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Mother-infant social gaze dynamics relate to infant brain activity and word segmentation

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A B S T R A C T

The ‘social brain’, consisting of areas sensitive to social information, supposedly gates the mechanisms involved in human language learning. Early preverbal interactions are guided by ostensive signals, such as gaze patterns, which are coordinated across body, brain, and environment. However, little is known about how the infant brain processes social gaze in naturalistic interactions and how this relates to infant language development. During free-play of 9-month-olds with their mothers, we recorded hemodynamic cortical activity of ́social brain` areas (prefrontal cortex, temporo-parietal junctions) via fNIRS, and micro-coded mother’s and infant’s social gaze. Infants’ speech processing was assessed with a word segmentation task. Using joint recurrence quantification analysis, we examined the connection between infants’ ́social brain` activity and the temporal dynamics of social gaze at intrapersonal (i.e., infant’s coordination, maternal coordination) and interpersonal (i.e., dyadic coupling) levels. Regression modeling revealed that intrapersonal dynamics in maternal social gaze (but not infant’s co-ordination or dyadic coupling) coordinated significantly with infant’s cortical activity. Moreover, recurrence quantification analysis revealed that intrapersonal maternal social gaze dynamics (in terms of entropy) were the best predictor of infants’ word segmentation. The findings support the importance of social interaction in language development, particularly highlighting maternal social gaze dynamics.

1. Introduction

Language development happens in social interactions, where infants and caretakers exchange social signals such as gaze, facial expression, speech, and gestures. Social interactions can boost learning for a variety of reasons, such as arousal, sustained attention, attunement, and shared intentionality (De Felice et al., 2022). Moreover, the ‘social brain’, regions associated with the processing of social information, is argued to gate language learning (Kuhl, 2007). Dynamic social exchanges are bidirectional (Elmlinger et al., 2019), and interpersonal coordination creates a structure within the interaction, allowing partners to predict the other’s behavior and respond to it. Communication is coordinated through multimodal processes at neural, bodily, and behavioral dimensions; however, little is known about how these dimensions connect (Pouw et al., 2021). Here, we follow dynamical systems approaches (Gordon et al., 2023) and use (cross-)recurrence quantification analysis (C/RQA; Coco and Dale, 2014; Wallot and Leonardi, 2018; Wallot and Mønster, 2023) to examine (1) which of three types of social gaze dynamics (i.e., intrapersonal coordination of infant’s or mother’s gaze, interpersonal dyadic coupling of infant’s and mother’s gaze; see Fig. 1) connects most to the temporal dynamics of 9-month-olds’ ‘social brain’ activity (measured by fNIRS) in a free-play interaction. In a second analysis, we connect this to infants’ language development and analyze (2) whether the social gaze dynamics type connected with infants’ ‘social brain’ activity is also the one most associated with 9-month-olds’ performance in a word segmentation task. We aim to understand

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whether and how the (intrapersonal or interpersonal) dynamics of mothers' and infants' social gaze creates a predictable social interaction, which can support infants' 'social brain' activity and (language) learning.

Social and language development are intertwined: Social interactions offer opportunities to develop language skills, and language skills affect how people interact. At around 9 months of age, infants increasingly coordinate social attention with others, evidenced through joint attention (Carpenter et al., 1998). Around the same age, their perception of foreign language input significantly improves when interacting with a real person compared to when receiving the same input from a video or a sound recording (Kuhl et al., 2003). Moreover, 7.5–12-month-olds increase their ability to segment words from continuous speech—an important prerequisite for word learning, with individual variability that predicts their later vocabulary size (Junge et al., 2012; Newman et al., 2006). Infants' word segmentation is linked to social aspects, such as infants' emotional synchrony with their mothers (Vanoncini et al., 2022) or speaker's gaze (Çetinçelik et al., 2023). Hence, word segmentation at 9 months is an ideal test case for examining links between social and language development.

Among various social signals characterizing a social interaction, eyes are powerful communication tools due to their dual function of receiving information from others and signaling information to others (Cañigueral and Hamilton, 2019). Gaze informs about another person's attention, communicative intentions, and future behavior. For the present study, it is important that infants are sensitive to eyes from an early age (Farroni et al., 2002) and use this sensitivity to learn a language (for a review, see Çetinçelik et al., 2021). Looking behavior during social interactions is one of the first ways to gather information, and to select and discriminate learning input (Hendry et al., 2019). It has been suggested that mutual gaze with another person triggers infants' expectations that semantic knowledge is transmitted (Csibra and Gergely, 2009). Accordingly, when looking at an object together with an adult, 9-month-olds' brain activity increased only if mutual gaze was involved (Hoehl et al., 2014).

Later, at 18–21 months of age, acquisition of word-object associations is reinforced through mutual gaze (Hirotani et al., 2009). Social gaze, that is an individual's gaze to an interlocutor's face, is beneficial for those who perceive it as well as for those who use it. For example, a speaker's social gaze increases 6-month-olds' brain activity when perceiving multimodal communicative signals (i.e., speech and gestures; Lloyd-Fox et al., 2015). Regarding infants' social gaze, looking-at-face preference was positively associated with 14-month-olds' receptive vocabulary (Portugal et al., 2022). One aim of the present study was to investigate the role of different types of social gaze, and its dynamics (i.e., on-off patterns of occurrence) within a naturalistic context, in infants' language development.

1.1. Rhythmicity and predictability in early interactions

Caregiver-infant interactions are characterized by a dynamic rhythmical social dialogue (Elmlinger et al., 2019; Tamis-LeMonda et al., 2014). Coordination of behaviors benefits learning, because rhythmical information enhances infants' attention and stimulates interactions (Markova et al., 2019). This coordination also boosts predictability in the interaction, which allows the members to anticipate the other person's upcoming behavior. From early on, infants are sensitive to predictable aspects experienced in daily routines (e.g., being picked up), and they enact anticipatory responses to facilitate the coordination of actions with the caregiver (Reddy et al., 2013). Regular family routines associate with development of language, academic and social skills (Spagnola and Fiese, 2007). Overall, predictable environments support learning due to children's increased sensitivity to the predictable aspect, such as an object or feature (Wass, 2022).

Social gaze provides an important cue for interpersonal coordination in adult-infant interactions (Leong et al., 2017) and could therefore play a role in infants' language learning. Hence, the present study asks whether the (intrapersonal or interpersonal) dynamics of mothers' and infants' social gaze during free play also creates predictable environments in social interactions that are associated with the activity of the

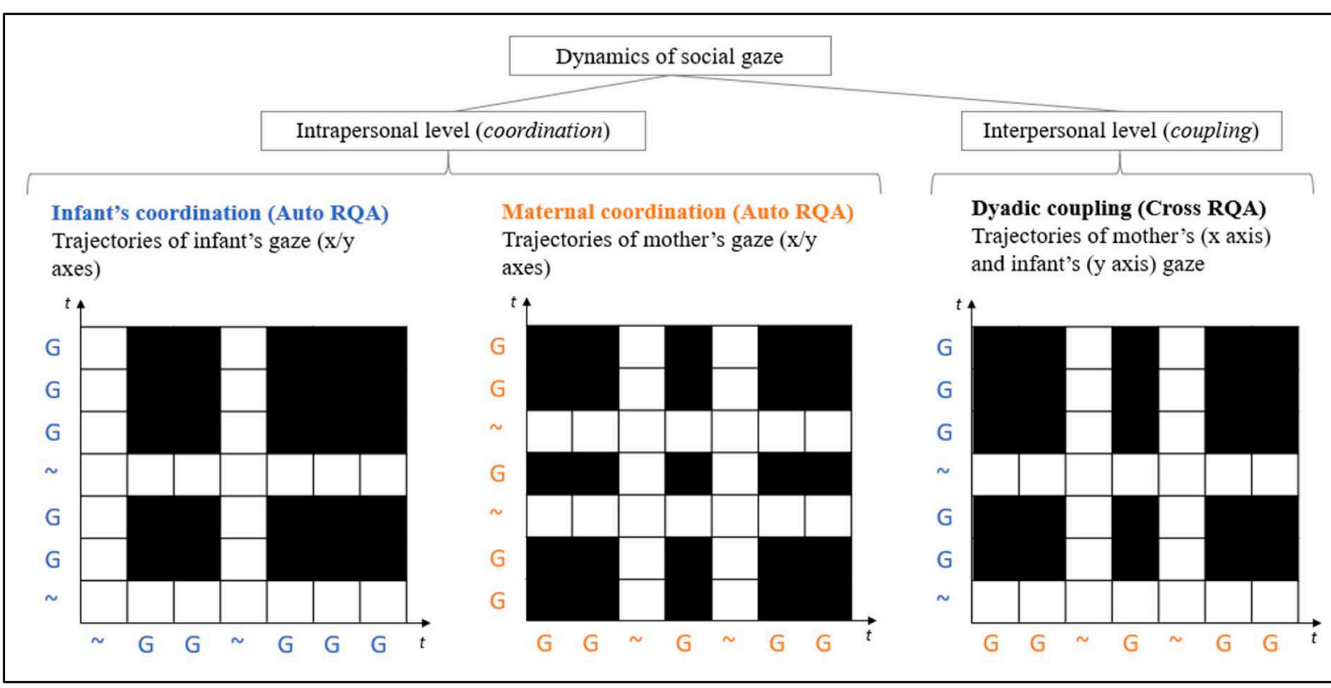

Fig. 1. Recurrence plots of social gaze (G) with left and middle: coordination within system; right: coupling of two systems. *Note.* Through C/RQA, the dynamics of social gaze can be examined at both intrapersonal (i.e., within infant in blue [left], within mother in orange [middle]) and interpersonal (i.e., between mother and infant [right]) levels. C/RQA quantifies a recurrence plot, a bidirectional matrix that captures how often and for how long a dynamic system along a time line (t) on the x-axis repeats the system along t on the y-axis. For each time point along t, we coded whether a participant used social gaze (G) or not (~). Recurrence (black square) is defined when we observe G on both t. From recurrence plots, we can extract different measures characterizing the dynamics of social gaze (see Methods).

infants' 'social brain' and with language learning, in particular infants' word segmentation performance. For our analyses, we used C/RQA (Coco and Dale, 2014; Wallot and Leonardi, 2018; Wallot and Mønster, 2023), which can capture the dynamics of coordination during dyadic interaction across different dimensions (e.g., neural, behavioral) and timescales. C/RQA is based on recurrence plots (Webber and Zbilut, 1994; see Fig. 1), which display the points in time at which a data point, for example the mother or the infant looking at the other person's face, returns to previous states (i.e., intrapersonal level, *coordination*), or at which two individuals enter the same state, such as mother and infant looking at each other (i.e., interpersonal level, *coupling*).

In Analysis I, we used joint C/RQA and compute recurrence rate (RR) to determine the percentage of time points with shared temporal patters in 9-month-olds' 'social brain' activity and in three types of social gaze dynamics (i.e., intrapersonal coordination of mother / infant, interpersonal infant-mother coupling; see Fig. 1) during mother-infant free-play interaction. In Analysis II, we used RQA and compute entropy (ENTR), which indicates the predictability of the recurrences for each of the three social gaze dynamics types during free play. We then analyzed whether the ENTR/predictability of the social gaze dynamics type most strongly linked with infants' brain activity (Analysis I) is also associated with infants' performance in the word segmentation task.

1.2. Hypotheses

We used functional Near-Infrared Spectroscopy (fNIRS) to measure local hemodynamic changes in brain regions associated with processing of social information (i.e., medial prefrontal cortex, left/right temporo-parietal junctions; Nguyen et al., 2020, 2021; Piazza et al., 2020). We hypothesized that infants' 'social brain' activity would connect more with dynamics (expressed by RR) of their own gaze at the mother's face (i.e., infant's coordination and dyadic coupling) than of the mother's gaze at the infant (i.e., maternal coordination). Second, we predicted that experiencing lower entropy/higher predictability in social gaze dynamics, ensuring more regular and coordinated 'social brain' engagement, would be beneficial for language development and therefore related to infants' word segmentation performance. These hypotheses were pre-registered (AsPredicted #124906).

2. Material and methods

2.1. Participants

The full sample consisted of 70 dyads of mothers and their infants aged 9 months ($M = 302$ days; $SD = 11$ days; 30 females). All infants were born full-term (> 36 weeks of gestation) and healthy (10-min APGAR Score > 9), with no history of hearing problems or known developmental delays, and were raised in German-speaking environments. Of this sample, for Analysis I, we excluded 44 infants due to refusing the fNIRS cap ($n = 3$), poor signal quality ($n = 21$), or experimenter or technical error ($n = 20$). Thus, Analysis I included 26 infants ($M = 301$ days; $SD = 12$ days; 10 females) who provided both fNIRS and gaze data. For Analysis II, we excluded 30 infants due to not performing either free play or word segmentation ($n = 5$), technical issues ($n = 12$), fussiness ($n = 6$), not providing 3 word segmentation test trials per condition ($n = 3$), or never engaging in mutual gaze ($n = 4$). Thus, Analysis II included 40 infants ($M = 301$ days; $SD = 12$; 19 females) who provided both gaze and word segmentation data. Forty percent of the infants who were included in Analysis I were also included in Analysis II. Mothers provided written informed consent. Participants received travel cost reimbursement and either a 15 € voucher or a children's book. The study was approved by the Ethics Committee of the University of Vienna.

2.2. Procedure

Mothers and their infants were invited to our lab. Each infant performed a 5-minute free-play interaction with the mother while fNIRS and gaze were recorded, and a word segmentation task. The order of tasks was counterbalanced across dyads.

For the 5-minute free-play interaction, mothers were instructed to play with their child as they would naturally do at home. Adhering to Covid-19 regulations, mothers could use some available toys (e.g., stacking ring, ball, doll) or toys they brought from home. Breaks were given if the infant got fussy. Mothers and infants sat face-to-face in a chair and a Maxi-Cosi. One camera recorded the mother's face and upper body, another one recorded the infant's face and body, and a third camera recorded the interaction overall. The video data (25 frames per second) was later coded for social gaze (see below).

During the free-play interaction, we measured infants' brain activity using NIRSport 88 / 2.01 (NIRx Medizintechnik GmbH, Germany) with a probe set consisting of 8 sources and 8 detectors. We recorded from 18 channels across the temporo-parietal junction (left hemisphere: Channel 1–7; right hemisphere: Channel 12–18) and prefrontal cortex (Channel 8–11). Absorption of near-infrared light was measured at wavelengths of 760 and 850 mm, with a sampling frequency of 7.81 Hz. Data was recorded through NIRStar 15.3 and Smarting Streamer 3.3. The start and end of each condition were sent through MATLAB (R2018b).

Before or after free-play, infants underwent the same word segmentation task as reported in Vanoncini et al. (2022) with a central fixation paradigm (Cooper and Aslin, 1990). The dependent measure was looking times (LTs) to a colorful blinking checkerboard presented on a screen while listening to familiar vs. novel test trials, recorded via eye-tracking (EyeLink 1000 Plus). For further details, see Supplementary Material 1.

2.3. Data preprocessing, coding

The fNIRS data were processed using MATLAB-based functions derived from Homer-2 provided by Ngyuen et al. (2021). First, raw data was converted into optical density. Motion artifacts were removed using a wavelet-based algorithm with an interquartile range of 0.5. Next, motion-corrected series were visually inspected for quality. We removed 18% of the channels from further analyses because of bad signal-to-noise ratio and motion artifacts. Then, we low-pass-filtered (0.01 Hz) and high-pass filtered (0.5 Hz) the signal to remove physiological noise and signal drift. Finally, we converted the data to changes in oxygenated (HbO) and deoxygenated hemoglobin (HbR) based on the modified Beer-Lambert Law. For the subsequent analysis, we used HbO because a study presenting naturalistic story stimuli found correlations of fMRI BOLD response to be larger with HbO than HbR concentration changes (Liu et al., 2017). We also analyzed HbR, for the results, see Supplementary Material 2.

Videos were coded offline for social gaze type using Mangold Interact (version 16). For both infant and mother, social gaze was defined as one person looking at the other person's face. Following Vanoncini et al. (2022), each instance of social gaze needed to last at least 1 s to be coded. Inter-rater reliability was achieved for 20% ($n = 9$) of the coded dyads ($kappa = 0.79$ for infant's social gaze; $kappa = 0.82$ for mother's social gaze).

For the word segmentation task, we discarded trials with looking times < 1 s and, to be included, infant needed to provide at least 3 test trials for novel and familiar words (cf. Junge et al., 2020). Because LTs were not normally distributed, they were log-transformed.

3. Analyses and results

3.1. Analysis I

Fig. 2 summarizes the steps followed in Analysis I. First (Fig. 2, Step

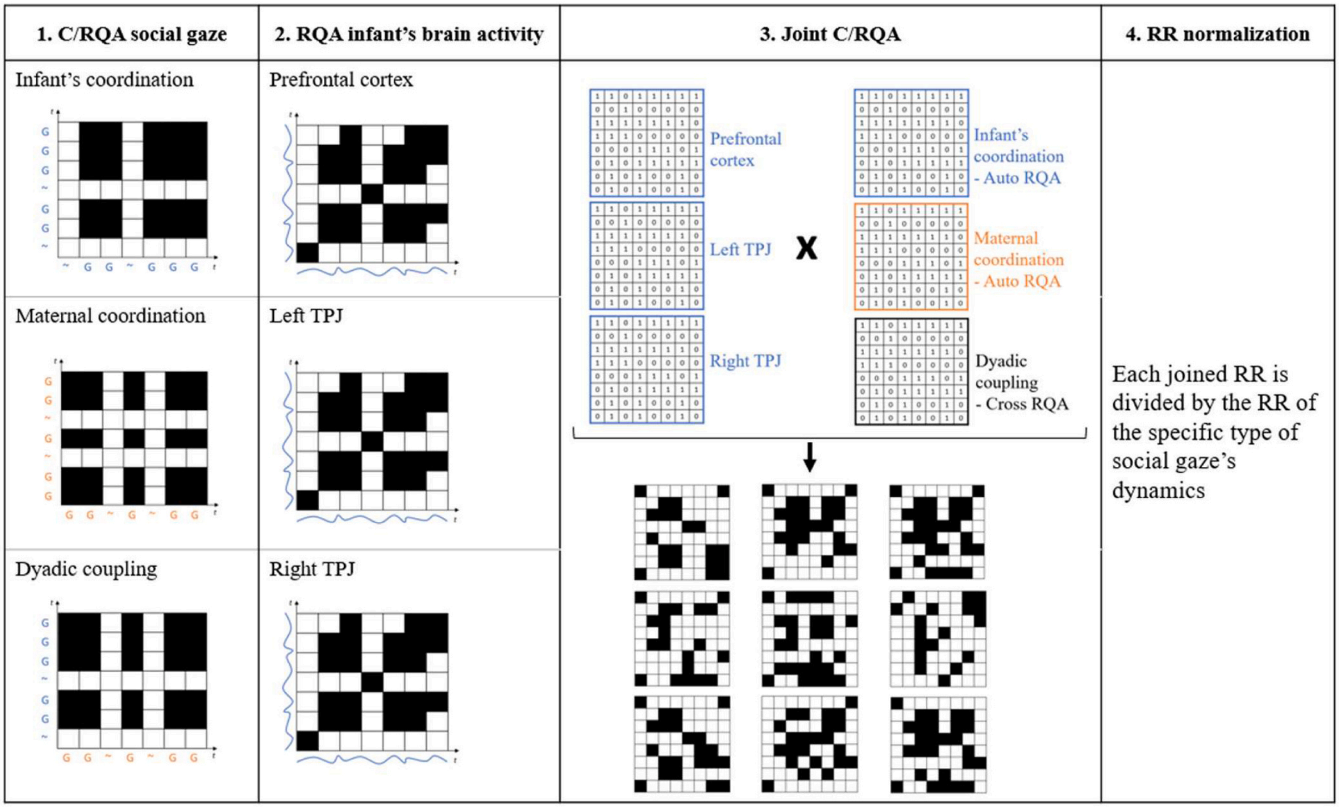

Fig. 2. Analysis I - Steps.

1), we ran separate C/RQA for categorical data, namely the occurrence (present vs. absent) of social gaze at intrapersonal (auto RQA; maternal coordination, infant's coordination) and interpersonal (cross RQA; dyadic coupling) levels. Second (Fig. 2, Step 2), we ran RQA for continuous data for fNIRS-recorded infant HbO, for three ROIs (prefrontal, left TPJ, right TPJ). Third (Fig. 2, Step 3), through joint C/RQA (Wallot and Mønster, 2023), we examined the recurrence of two factors across time, namely categorical data of three types of social gaze, and continuous infant HbO data. We gained nine joint recurrence plots by multiplicating each of the three social gaze dynamics recurrence plots (i.e., infant's coordination, maternal coordination, dyadic coupling) with each of the three infant-HbO recurrence plots (i.e., prefrontal, left TPJ, right TPJ). From each joint recurrence plot, we extracted RR as the percentage of time points in which we observe shared temporal patters of social gaze and brain activity. That is, the higher the RR, the more coupled are the dynamics of a social gaze type with the dynamics of infants' 'social brain' activity.

Last (Fig. 2, Step 4), we calculated nine normalized RRs (as suggested by Wallot and Mønster, 2023), by dividing the RR of each of the nine joint recurrence plots by the RR of the respective type of social gaze dynamics (see Step 1). The normalized RR controls for a potential bias, namely that the compared joint RR (between gaze and fNIRS data) might be influenced by the frequency of occurrence that affects the RR of the (unembedded) categorical-binary gaze data.

We conducted the data analysis with RStudio (RStudio Team, 2021) and R package lme4 (Bates et al., 2015). The dependent variable was normalized RR (log-transformed) of infants' brain activity and social gaze. We entered an interaction of social gaze dynamics type (i.e., infant's coordination, maternal coordination, dyadic coupling) and brain regions (i.e., prefrontal, left TPJ, right TPJ) in the fixed part. Participants were added as random intercept with a random slope for dynamics type by participant. Additionally, we applied Helmert contrast coding to compare normalized RRs for: (1) infant's coordination versus dyadic coupling, and (2) maternal coordination versus pooled infant's coordination and dyadic coupling. The intercept reflects the grand mean.

3.2. Results I

During the free-play, normalized RR of infants' brain activity and social gaze ranged from 0.005 to 0.88 ($M = 0.16$; $SD = 0.11$). Normalized RR was highest for the gaze type maternal coordination ($M = 0.25$; $SD = 0.12$), followed by infant's coordination ($M = 0.14$; $SD = 0.16$) and dyadic coupling ($M = 0.09$; $SD = 0.08$; see Fig. 3). Normalized RR was consistent across ROIs: prefrontal ($M = 0.17$; $SD = 0.16$), left TPJ ($M = 0.14$; $SD = 0.11$), right TPJ ($M = 0.15$; $SD = 0.13$).

The model (see Supplementary Material 3), including Helmert contrast coding, estimated that intrapersonal maternal coordination of social gaze had a higher normalized RR with infants' 'social brain' activity than the pooled social gaze data of intrapersonal infant's coordination and interpersonal dyadic coupling ($\beta = 0.93$; $p < .001$). No other main effects nor interactions reached significance. A follow-up model, using sum coding (see Supplementary Material 3), estimated that maternal coordination of social gaze had a higher normalized RR with infants' 'social brain' activity than both infant's coordination ($\beta = -0.83$; $p < .05$) and dyadic coupling ($\beta = -1.03$; $p < .001$). Thus, other than predicted, intrapersonal dynamics of maternal coordination of social gaze connected more with infants' concurrent hemodynamical 'social brain' activity during free play than intrapersonal infant's coordination or interpersonal dyadic coupling of social gaze.

4. Analysis II

We investigated whether the social gaze dynamics type most connected with infants' 'social brain' activity (i.e., intrapersonal maternal coordination; see Analysis I) is also the one that best predicts infants' LTs in the word segmentation task. We assumed that predictability in this dynamics type would be optimal for language learning. Hence, infants

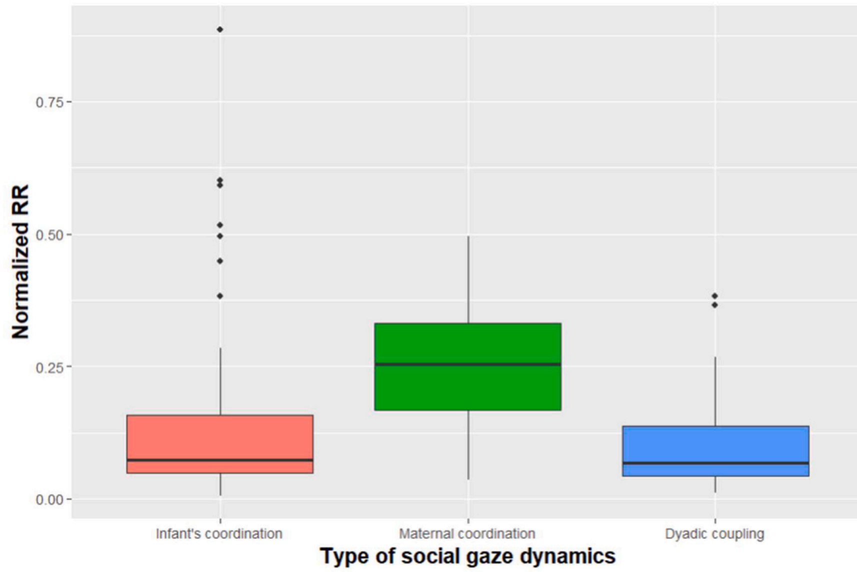

Fig. 3. Normalized RR of infants' brain activity and social gaze by types of social gaze dynamics.

who experience higher predictability in the intrapersonal coordination of maternal social gaze should also show advanced word segmentation.

We calculated entropy (ENTR) as index of predictability in a recurrence plot (Coco and Dale, 2014). Based on Shannon's entropy, lower levels of ENTR characterize more deterministic systems with less complex dynamics and a more predictable system trajectory; in contrast, higher levels of ENTR characterize less deterministic systems with more complex and disordered dynamics. We calculated ENTR based on the length of recurrence intervals in the three social gaze recurrence plots of Analysis I, Step 1: infant's coordination (auto RQA), maternal coordination (auto RQA), and dyadic coupling (cross RQA). Here, low ENTR entails a more predictable length of the recurrence intervals in the gaze dynamics type.

In the word segmentation task, the dependent variable was accumulated looking time (LT; in milliseconds) to the screen while hearing the test words (familiar vs. novel). Speech segmentation is shown by a difference in the looking time between novel vs. familiar test trials and/or b) a novelty preference (DePaolis, 2016). The model included the interactions of the categorical independent factor trial type (i.e., familiar vs. novel word; contrast coded as $1/-1$), with the continuous, mean-centered covariates ENTR of infant's coordination, ENTR of maternal coordination, ENTR of dyadic coupling, and participant as random intercept.

4.1. Results II

During test phase of the segmentation task, at the group level, infants' average LTs were 7.88 s ($SD = 6.97$) for familiar, and 8.06 s ($SD = 6.55$) for novel words.

The model (see Supplementary Material 4) showed that ENTR of intrapersonal maternal coordination of social gaze significantly predicted LTs ($\beta = -0.80$; $p < .05$): Infants who experienced higher entropy in their maternal gaze during free-play tended to overall show shorter LTs. Moreover, the model yielded a significant interaction between trial type and ENTR of maternal coordination of social gaze ($\beta = 0.87$; $p < .01$). In detail, while infants' looking during hearing the novel test words was unaffected by entropy, LT during the familiar test trials was negatively related to entropy (see Fig. 4). Thus, higher entropy (i.e., lower predictability) of maternal social gaze coordination was related to infants' longer looking during novel than familiar test trials, while for lower entropy, infants looked longer during familiar than novel test trials (see Fig. 4). None of the other effects nor interactions reached significance. These results confirmed our hypothesis that the social gaze dynamics type connected with infant 'social brain' activity, is linked with language learning.

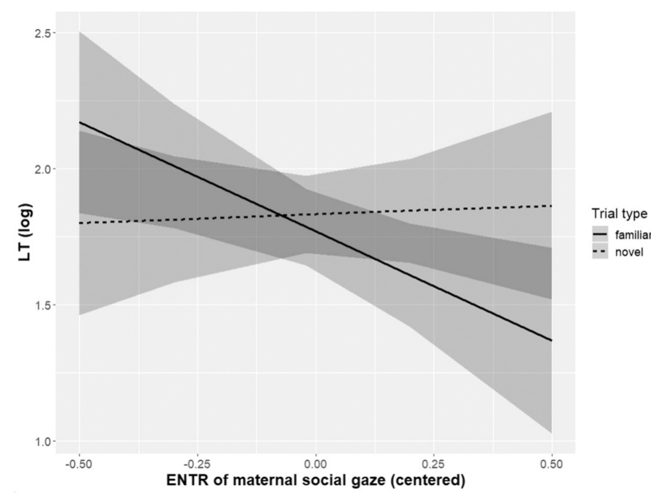

Fig. 4. Looking times in the word segmentation test trials by trial type (familiar, novel) as a function of the ENTR of maternal coordination of social gaze. *Note.* Effect plot of log transformed Looking Times by trial type (regression line continuous: familiar word; dashed: novel word) as a function of the entropy of maternal coordination of social gaze during the free-play interaction. Shaded areas indicate confidence intervals. For a plot with individual data points, see Supplementary Material 5.

5. Discussion

We examined (1) which type of social gaze dynamics that infants experience in a free-play interaction with their mother is connected with the dynamics of their 'social brain' activity, and (2) whether this social gaze dynamics type is linked with infants' performance in a word segmentation task. We approached this in two analyses. For both Analysis I and Analysis II, we used social gaze data of 9-month-old infants and their mothers during a 5-minute free-play interaction. For Analysis I, by means of joint C/RQA (Wallot and Mønster, 2023), we measured the connection between social gaze dynamics types and simultaneously recorded infant fNIRS data (HbO), from brain regions associated with processing of social information (i.e., prefrontal, left TPJ, right TPJ). For Analysis II, we used infants' data from a word segmentation task, and used RQA (Wallot and Leonardi, 2018) to test whether the entropy/-predictability of a certain type of social gaze dynamics during free play was more associated with infants' behavior at test than another. The results of both analyses indicated that the dynamics of intrapersonal maternal coordination of social gaze plays a crucial role.

For Analysis I, we found that the dynamics in intrapersonal maternal coordination of social gaze were connected with the dynamics of infant's 'social brain' activity. Our result contradicts what we previously hypothesized, namely that the dynamics types in which the infant played an active role (intrapersonal infant's coordination, interpersonal dyadic coupling) would be more connected to infant brain activity, than maternal social gaze coordination. At least two mechanisms could explain this result. First, the result is in line with assumptions of social gaze having a dual function, namely benefitting when using it but also when perceiving it (Cañigueral and Hamilton, 2019). Here, we observed that infants' 'social brain' activity is linked with the maternal social gaze dynamics, regardless of the infants' gaze. This is consistent with a previous study showing that infant-directed speech leads to increased brain activity in infants only when accompanied by the other person's social gaze (Lloyd-Fox et al., 2015). Possibly, if the mother spends time looking at the infant, she might share her interest in interacting with the infant. In turn, the infant might feel fully involved in the interaction. The lack of relevance of the infants' own social gaze dynamics may also be explained by the fact that social gaze behavior in infancy is not yet adult-like: In naturalistic interactions, 12-month-olds looked equally to partner, toy, or were inattentive, whereas parents spent most of their time looking at the infant (62%), then at the toy (31%), with 7% of the total interaction being inattentive (Marriott Haresign et al., 2023). Hence, future studies should investigate older children to understand if the role of their own social gaze dynamics in interactions and learning increases with age.

In Analysis II, we probed the hypothesis that predictability of the type of social gaze dynamics most strongly associated with the infant's concurrent brain activity in Analysis I, namely intrapersonal maternal coordination of social gaze, would be connected to 9-month-olds' performance in a word segmentation task. The result supports this: predictability in the maternal coordination of social gaze, but not in the other two dynamics types, interacted significantly with infants' looking while listening to familiar versus novel test words. This result matches previous research, suggesting the importance of social interactions, caregivers' input, social signals, and their contingency for language learning (Kuhl, 2004; Kuhl et al., 2003; Goldstein et al., 2003; Hoareau et al., 2019; Tamis-LeMonda et al., 2001, 2014). Likewise, a recent study on word segmentation found different processing of familiar vs. novel test trials as a function of the speaker's direct vs. adverted gaze (Çetinçelik et al., 2023).

One aspect was, however, in contrast with our predictions based on a previous study: Vanoncini et al. (2022) found that *lower* ENTR in mother-infant emotional synchrony was linked with an advanced word segmentation performance. Hence, we expected that word segmentation would also benefit from experience of lower ENTR in the dynamics of social gaze. However, we found that *higher* ENTR of maternal social gaze coordination during free-play interaction was connected to longer infant looking while listening to novel as compared to familiar test words, and novelty preferences are generally assumed to reflect more mature processing performances (DePaolis et al., 2016; Hunter and Ames, 1988).

This could be due to the following: First, there may be context-specific differences in the beneficial effects of low versus high entropy. In word learning, infants benefit from a language input characterized by low entropy (i.e., high predictability) (e.g., Lavi-Rotbain and Arnon, 2019), while high entropy supports learning in complex environments and prepares, for example, rule generalization (Radulescu et al., 2020, 2021). Hence, possibly the beneficial aspects of entropy also depend on the specific social signal (e.g., eye gaze, facial expressions). Notably, perception of gaze develops earlier than perception of facial expressions, and gaze direction influences how facial expressions are processed by infants (Hoehl and Striano, 2008, 2010). Hence, at 9 months, the age tested here and in Vanoncini et al. (2022), infants may have gathered more experience and efficiency in gaze perception than in facial expression perception. Therefore, 9-month-olds' emotion perception may still benefit from low entropy, while their more mature gaze perception already benefits from high entropy environments. Notably, Vanoncini et al. (2022) only examined entropy of the interpersonal dyadic coupling of facial expressions between mothers and their infants. This is a more complex level of interaction, as compared to entropy based on intrapersonal coordination (i.e., auto recurrence) of only the maternal gaze, where only one person plays a role. Thus, it is plausible that lower entropy may be beneficial with regard to a more complex social signal (e.g., facial emotional expression synchrony), while higher entropy may be beneficial in the context of a simpler and more easily processed social signal (e.g., gaze).

To sum up, the benefits of high versus low entropy or predictability of a specific aspect of a social interaction seem to depend on its developmental trajectory (i.e., eye detection occurs earlier than discrimination of facial expressions), complexity (i.e., eyes could be directed or averted vs. facial expressions have various emotional meanings), and the involved agents (i.e., one person vs. a dyad).

The main limitation of the current study is the high dropout rate due to our ecological approach to register fNIRS during free play, where the risk for artifacts and bad channels is much higher than in designs where participants sit motionless and watch or listen to presented stimuli. Hence, our findings await further replications. Future studies may consider replicating the study in a setting where infants are inclined to not move as much to avoid track loss. Moreover, it would be interesting to investigate the causal direction of the link between maternal coordination of social gaze and language development. Future research is also needed to further disentangle the role of the dynamics of intrapersonal maternal coordination of social gaze from the dynamics of other behavioral components present in interactions that can be relevant for language development, such as maternal speech.

6. Conclusion

In sum, the present study established that in mother-infant interactions, infants' dynamics of 'social brain' activity more strongly reflect the experience that their mother looks at them than their own coordination of social gaze toward their mother or of mutual social gaze between mother and infant. Moreover, lower predictability in maternal coordination of gaze behavior predicted infants' performance in word segmentation. By this, our study provides further evidence on how dynamics of social cues connect with infants' concurrent brain activity, and that this is in association with language development. This finding suggests that social gaze, together with its dynamics, is a powerful tool for communication that directs infants' attention and learning. Hence, this study adds further evidence on the link between predictability of social behaviors in mother-infant interaction and learning across development. Last but not least, this study presents a concrete application of a novel method for assessing recurrence and predictability, namely joint C/RQA, which can be pursued with any other categorical data (e.g., vocalizations, facial expressions) in combination with continuous data (e.g., HbO).

CRediT authorship contribution statement

Vanoncini Monica: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Visualization, Writing – original draft, Writing – review & editing. **Elsner Birgit:** Funding acquisition, Supervision, Writing – review & editing. **Hoehl Stefanie:** Conceptualization, Methodology, Resources, Software, Writing – review & editing. **Boll-Avetisyan Natalie:** Conceptualization, Funding acquisition, Methodology, Supervision, Writing – review & editing. **Wallot Sebastian:** Methodology, Writing – review & editing. **Kayhan Ezgi:** Conceptualization, Data curation, Funding acquisition, Methodology, Project administration, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.dcn.2023.101331.

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