Constructing interaction: the development of gaze dynamics

Keywords:

temporal dynamics ; gaze development ; cross-recurrence ; mother-infant
interaction

Abstract

Gaze is one of the first and most important means of communication and coordination in parent-infant dyads. In the present paper we used a novel method, designed to discover patterns in time-series, to investigate the dynamics of gaze in dyads and its developmental change. Using a longitudinal corpus of natural interactions, mutual mother-infant gaze was coded when the infants were 3, 6 and 8 months old and subjected to recurrence analysis. The cross-recurrence profiles obtained for the three time points show systematic differences: While the engagement in mutual gaze decreases with age, the behavior becomes more tightly coupled as a more regular temporal structure emerges. We suggest that this stronger interdependency of gaze behavior may indicate the development of a social feedback loop enabling engagement in interaction.

Visual fixation communicates attention. Early in development, infants rely on it to a large degree, whereas later in development, it becomes optional as other resources become available to the infant, such as gesture or language (Bullock, 1979). Filipi (2009, p. 3) suggests that gaze is the infant's early "way of starting to do interaction" as it allows the infant to take part in conversation and maintain his or her participation. In these early interactions, mothers are very responsive to their infants' gaze behavior and "fit" (Filipi, 2009, p. 3) their behavior to that of the infant (Fogel, 1977 ; Stern, 1974). According to Filipi (2009 ; also Nomikou, Rohlfing, & Szufnarowska, 2013), the responses to infant gaze reinforce this behavior of the infant, setting the foundation for protoconversations (Bateson, 1979 ; Bruner, 1983) thus "setting the stage for talk" (Filipi, 2009, p. 3). The value of looking at each other's face as an experience of interpersonal attention has been emphasized for the development of triadic attention and the emergence of referentiality (Bakeman & Adamson, 1984 ; Bruner, 1975 ; 1983 ; Nomikou, 2015). Mutual gaze bears, thus, ostensive power (Csibra, 2010) as it signifies to the infants that an interaction is explicitly designed *for* them and addressed *to* them.

In general, studies have shown a positive relationship between responsiveness to children's attentional focus and the development of infants' communicative and linguistic skills (Tomasello & Todd, 1983 ; Harris, Jones, Brookes & Grant, 1986 ; Carpenter, Nagell, Tomasello, Butterworth & Moore, 1998 ; Tomasello & Farrar, 1986). Yet, given the primary nature of infants' focus of attention for interaction, it is surprising that little work has been devoted to elucidate the development of this skill (but, see Bakeman & Adamson, 1984 ; Rossmanith, Costall, Reichelt, López, & Reddy, 2014 ; De Barbaro,

Johnson & Deák, 2013), as most studies concerned with infants' focus of attention have investigated infants from 9 months on. In addition, visual attention has mostly been considered as a signal but barely as an interactional skill. Yet, in interaction, it influences others' behavior and elicits feedback. Analyzing the sequential organization of the interactions of mothers and their infants at 3 and 6 months of age, Nomikou et al. (2013) found that during naturalistic interactions with their 3-month-old infants, mothers set the pace for the organization of gaze, as they switch between gazing at the infant's face and gazing at the objects involved in a diapering activity while the infants do not switch their gaze away, but remain focused on the mother's face for longer periods of time. At 6 months of age, the infants' increasing curiosity towards the surroundings is responded to by mothers attentively monitoring infant gaze and actively seeking for opportunities to engage in eye contact with them. This points to the dynamic, collaborative construction of mutual attention, which, together with the infants' increasing attention span and memory skills, brings changes within the mother-infant system, affecting the behavior of both participants.

In support of this argument, Keller and Gauda (1987) found that parents who were responsive to infants' gaze had "high gazers" (Keller & Gauda, 1987, p. 135), i.e., infants whose eye contact with one or both parents at 3 months exceeded the mean values of the sample. In a similar vein, Nomikou (2015) found a positive correlation between mothers looking at their infants' face and the infants looking at their mothers' face. This suggests that gaze feedback motivates infants to engage in mutual attention.

Research on responsiveness has focused on the possible influence of caregiver responses to infants' initiatives within interaction sequences, yet pertaining mostly to other modalities than gaze. For vocal development, Papoušek and Papoušek (1989, p. 149) have stressed the value of imitation: By imitating infant vocalizations, mothers "provide models which may most easily elicit matching responses". For language acquisition, this acts as a reinforcement of particular sounds, carving infants' language production.

Sensitivity to feedback has been studied also with respect to multimodal social cues. Hsu, Fogel, and Messinger (2001) found that infants produced more speech-like vocalizations when mothers were smiling and making eye contact with them. Harris, Jones, and Grant (1983) found that changes in the infants' gaze were an aspect of infant behavior to which the mothers greatly responded. This strategy faded with time. This suggests that feedback to gaze is especially appropriate for investigating interactions with young infants, as gaze is one of the earliest communicative skills infants acquire and is considered as the "first dyadic system in which both members have almost equal control over and facility with the same behavior" (Stern 1974, p. 188). For 3-month-old infants, Koester, Papoušek, and Papoušek (1989) found that the modality which mothers chose to respond to infants, and the tempo with which it was employed, were related to differences in infant gaze. This highlights the fact that, within interaction, caregiver feedback is selective, as it is influenced also by infant's feedback. In a study in which caregivers demonstrated actions to their 8-to-12-month-old infants, Pitsch, Vollmer, Rohlfing, Fritsch, and Wrede (2014) showed that infants' feedback in the form of their eye gaze (signaling their attention or

anticipating subsequent actions) modified the movements that caregivers made when demonstrating the actions, forming an interactional loop.

Methodologically, research has looked at responsiveness as a step-by-step process. More specifically, Bornstein, Tamis-LeMonda, Tal, Ludemann, Toda, Rahn, et al. (1992) define it as a recurring three-step sequence: the child acts, the parent reacts, and this has an effect in the child. By being responded to, infants learn that their behavior has an effect and this can be a motivator to learn (Watson, 1985). Yet, there is a growing number of researchers who suggest that interaction is not just the context in which development takes place. Interaction is a part of the cognitive processes themselves (De Jaegher, Di Paolo, & Gallagher, 2010). Researchers embracing a dynamic systems view (e.g. Thelen, 2000 ; Smith & Thelen, 2003 ; Chiel & Beer, 1997), suggest that development emerges from an embedded system, in which world and body are coupled dynamic systems. Accordingly, elements composing the system, apart from standing in some relation to one another, are affected by their participation and cooperation in the system (Wilson, 2002). To investigate development means to take into account not only how individual cognitive mechanisms work, but also how they influence each other. Also, to investigate interaction means to abandon the view according to which the mother or caregiver is seen as a competent sender of information and the infant as a receiver. Such a view reflects discrete state communication systems in which development takes place by transmission of messages.

In contrast to the sender-receiver view above, Fogel (1993) points out the way in which interaction unfolds with the engagement of the participants. Infants do not process information passively. Rather, they are active learners who are treated as participants and

influence the unfolding of the interactions they participate in. This is best explained in a continuous information system in which both partners are active and engaged in communication. Here, there are opportunities to modify the actions of partners as they occur, without the need to wait until they are finished. Thus, development proceeds as the coordination between interacting parties “produces a net gain of information in the system” (Fogel & Garvey, 2007, p. 252). This engagement of the partners is achieved because interactions are shaped by continuous mutual adjustments.

The coordination dynamics operate on two time-scales (Nomikou, 2015): On a first time scale they entail the moment-to-moment, real-time adjustments necessary to maintain an interaction going, a coupling of agents and world (Clark, 1999). These are not planned ahead of time, but are constructed online “out of the fabric of the present” (Fogel, 1993, p. 28). Rączaszek-Leonardi, Nomikou & Rohlfing (2013, p. 211) describe this online mutual responding to each other’s behavior as a coupling mechanism, enabling mother and infant to enter an interaction and maintain or stabilize it, serving as a flexible “glue” between them. According to such an approach, feedback is co-regulated (Fogel, 1993) and constructed interactionally, as one cannot discern who is acting and who is reacting to whom.

On a second time-scale, the dynamics act on multiple repeated interactions within a cumulative history of interactive experiences (Hsu & Fogel, 2003). On this time scale, interactants form expectations about each other’s behavior. Out of repetitive routinized interactive formats (Bruner, 1983), a constrained, systematic, predictive setting is constructed within which the infant can learn to be communicatively effective without, and

eventually with, language. The interactional experience, along with the transforming ecology (Rossmanith et al., 2014) continually increases the skillfulness of the participants.

In sum, this view has focused not only on *what* happens in interaction, but also *when* it happens. Accordingly, timing and especially infants' sensitivity to timing has been a significant research focus. This sensitivity has been underlined in studies in which a temporally contingent reaction was manipulated: e.g., Masataka, 2003 ; Striano, Henning, & Stahl, 2006 have shown that infants modified their behavior as their temporal expectations were violated. This evidence suggests that participation in interactions implies an engagement in repetitive interactive patterns, resembling turn-taking, and this allows for the development of expectations about the activity. This temporal alignment is most evident in vocal behavior. Jaffe, Beebe, Feldstein, Crown, Jasnow, Rochat & Stern, (2001) showed that infants' timing of the pauses of their vocalization were influenced by their mothers' timing and vice versa. Furthermore, they found that 4-month-olds changed the timing of their vocal behavior depending on whether they were interacting with their mothers compared to when they were interacting with a stranger. This suggests that temporal coordination within interaction is a marker of the quality of the interaction. As studies have revealed, this temporal coordination enables mothers and infants to anticipate each other's behavior in time and to "play" with each other's expectations (Jaffe et al., 2001 ; Gratier, 1999 ; Malloch, 1999 ; Robb, 1999 ; Trevarthen, 1999).

Yet, this timing sensitivity extends beyond the vocal modality. Gaze is also tightly coordinated with other multimodal actions in interactive episodes, and it can serve as an indication of an emerging interaction structure (Hsu & Fogel, 2003 ; Crown, Feldstein,

Jasnow, Beebe & Jaffe, 2002). As previously discussed, gaze can act as a motivator to engage in mutual attention (Keller & Gauda, 1987 ; Nomikou, 2015). Yet the timing of gaze may also form an emerging interaction structure, as shown recently by Nomikou and colleagues (2013). Analyzing longitudinal data for 3 and 6-month-old infants, the authors found that between the two time points, both mother and infant significantly reduced the duration of the gaze intervals to each other and to the surrounding objects, suggesting that the temporal characteristics of gaze behavior change with development. This is evidence of gaze becoming a resource for “alive communication” (Fogel & Garvey, 2007), i.e., a mutual adjustment during a coordinated joint activity that becomes visible at around 6 months of age (Nomikou, 2015).

With the present study, we argue that emerging patterns of mutual adjustments in gaze constitute a feedback loop, engaging mother and infant in interaction. These mutual adjustments are not a matter of one person reacting to the other, but rather a process of constructing a way of ‘doing gaze together’, which becomes an emergent property of the mother-infant co-action, keeping the interaction going. If this argument is correct, then we will find a coupling between infant gaze patterns and maternal gaze patterns early in development. With this coupling, we mean that there should be no clear leader of interaction in the sense of one person reacting to another. Instead, the contributions to the interaction should be distributed among the participants. Given the previous findings on the relationship between caregivers’ and infants’ gaze patterns reported above (Keller & Gauda, 1987 ; Nomikou, 2015), our first hypothesis was that at 3 months of age, there should be a temporal coupling of mothers’ and infants’ gaze at the partner’s face. In our

study, the coupling of gaze was operationalized as a repetition of a gaze switch to the partner's face within the same temporal window. The prediction here is that even in the earliest interactions mother and infant will mutually adjust the timing of their gazes.

Also, given the finding reported in Nomikou et al. (2013) that the duration of gaze intervals of both mother and infant become shorter, the second hypothesis was that with the development of the infant, this coupling should undergo some change. On the one hand, as infants become more and more interested in objects, they have to allocate their gaze towards increasing number of gaze locations, i.e., both the mother's face and the objects of interest. This reduces the proportion of the time available to them for looking at the face. For this reason, gaze at each other's faces should decrease. On the other hand, in time mothers and infants should become more experienced in interacting with each other, as their interaction history shapes their behavior, and, thus, gaze coordination should become more efficient. The second hypothesis, therefore, was that with infants' development, the coupling will change and give rise to tighter and more structured interactive episodes. Here, the tight and structured coupling was operationalized as a less variable timing of a gaze switch to the partner's face. The prediction here is that although mothers and infants should gaze less at each other, the timing of their gaze will become more predictable.

To test these hypotheses, we applied cross-recurrence analysis, a dynamical method which allows us to capture the temporal organization of gaze just before the onset of joint attention to reveal the developmental characteristics of the dynamics of interactional coupling.

Method

Participants

Participants were recruited through a number of different visits to courses for mothers and infants in Bielefeld (North Rhine-Westphalia, Germany). Seventeen mothers and their infants participated in our study. All infants were born between December 2009 and April 2010. Out of nine boys and eight girls, 12 were firstborn, (five boys and seven girls). Infants' average age at the first visit was 3;12 (months ; days); at the second visit 6;4, and at the third visit 8;0. The average age of the mothers was 33 years (ranging from 28 to 40). All mothers had finished secondary school, 50% had had some kind of professional training, and 50% had an academic degree. All mothers were native speakers of German and spoke German to their infants. Due to a camera failure during the third visit, one dyad was not registered and could not be coded, leading it to being discarded from further analysis.

Procedure

We aimed to collect ecologically valid data outside laboratory conditions. Therefore, the study took place within a naturalistic setting. More specifically, mother and infant dyads were filmed when changing the infant's diaper. Families were visited in their homes. For the purposes of the present study, the experimenter brought a foldable changing table. This was placed in the center of a spacious room, either the living room or the child's room.

Two HD video cameras (Canon HF10; Sony 3CMOS HDV 1080i) were also brought into the setting. They were mounted on camera stands. One camera was positioned behind the changing table (opposite to where the mother was standing), filming from the bottom and slightly offset from the center. This camera was aimed toward the mother's face and her upper body. The second camera was set up in front of the table behind the mother, thus filming on a higher level over her shoulder. This camera captured the mother's arms and the infant's body from the side, making her or his hands, body, and face visible. An external microphone was mounted on one of the cameras in order to guarantee high-quality audio recording for future phonetic annotations and analysis. The second camera recorded sound via its built-in microphone. The cameras were always set and adjusted at the beginning of the session and then no longer modified, because the experimenter left the room to make sure that mother and infant were not distracted during their interaction.

Once the equipment was set up and the cameras were turned on, the experimenter invited mother and infant to approach the table. The mother was asked to change the infant's diaper "*as she normally did, when she wasn't in a hurry.*" Mothers were encouraged to bring into the interaction any game, song, or other diaper-changing routine that they normally use. No toys were provided by the experimenter. However, because many objects (such as diapers, wet tissues, lotion, clothing, toys, etc.) were a natural part of the interaction within this situation, mothers were allowed to bring along and use any object they wanted if these were a part of the routine. Mothers were always assured that they could pause or stop at anytime they felt it to be necessary. As soon as the task was

completed, the experimenter was called back into the room and had a short discussion about the procedure with the mother. Small presents were then given to the mother for the infant as a form of gratitude for their participation.

Recording was carried out at 25 frames per second. Films were cut and edited with Final Cut Pro® film editing software. The two camera perspectives were then synchronized and rendered in a split-screen view.

Data coding

Data were coded manually using micro-analytical continuous coding with INTERACT®9 an observational data transcription software. Frame-to-frame analysis was used to mark the onset and offset of gaze intervals. Gaze direction was coded for both mother and infant. Three possible gaze locations were coded:

- gaze at face: this includes intervals in which the participant's gaze was directed towards the other participant's face.
- gaze away: this includes intervals in which the participants' gaze was directed outside the camera's field of view.
- gaze at object: this includes intervals in which the participant gazed at parts of the other participant's body beyond the face, i.e., the hands or torso, or at objects within the cameras' field of view.

Intervals during which the eyes were blocked from the cameras' view were not coded or coded as hidden. For the present analysis we used the gaze at face codes.

Data analysis

We applied cross-recurrence analysis as a method to assess the coded data. This method indicates how much the behavior of a participant, in this case gaze at the other's face, matches (repeats) the behavior of the other participant. Warlaumont and collaborators (2010) have used this method for the study of mother-infant vocalizations. We applied it to the analysis of gaze (for adults, see also Richardson & Dale, 2005). Recurrence analysis (Webber & Marwan, 2015) is a relatively novel analytic method stemming from dynamical systems theory, which among other things allows for an analysis of coupling and synchronization of signals evolving in time (see e.g. Dale, Warlaumont & Richardson, 2011). One way cross-recurrence analysis can be used to capture the coupling of behavioral signals is by means of the so-called diagonal-wise recurrence profile of those signals. In simple terms, this analysis extracts the level of recurrence rate (or recurrence percentage, indicated by %REC) in two signals as a function of the temporal lag, where a lag = 0 would indicate the status of the two signals at the same moment. That is, the analysis proceeds in comparing every point in time of the two signals, registering if the behavior at these points in time matches and finally computing the amount of matching of the behavioral events at every possible lag between the various points. This measure, %REC, is then essentially the proportion of matching behaviors against total possible comparisons, and it is typically interpreted as a measure of coupling of the two signals (see e.g. Shockley, Santana & Fowler, 2003 ; Richardson & Dale, 2005)

By plotting %REC as a function of the lag, we are able to establish if the coupling significantly concentrates at one specific lag (or delay) in the behavior of the interacting dyad or if on the contrary no such coupling takes place at all, in which case the observed recurrence would distribute rather uniformly across lags. In the case the coupling is observed, we can also determine if and who of the interacting subjects (here mother or infant) was leading the behavior. This is done by looking on which side of the recurrence profile, with respect to lag zero, the point of maximal recurrence takes place and/or if there is an asymmetry in the profile. Alternatively, no leader/follower pattern may occur and coupling will tend to distribute symmetrically around the central, zero lag.

From the video recordings of mother-infant interaction, we identified and coded the periods at which each one of them gazed at the other's face as explained in the Data Coding section. This process produced two time series, one for the mother and one for the infant, coded in binary terms, where "gaze-at-face" behavior was given a code of 1 and any other behavior was given a code of 0 at every single point in time. Sample individual behavioral streams from a dyad are shown in Figure 1. The temporal resolution of the sampled time series was 10 Hz (or one data point every 100 ms).

FIGURES 1A and 1B HERE

Time series from each dyad at each of three different time points or visits (at the age of 3 months, 6 months and 8 months), were first analyzed with the R package *crqa* (Coco & Dale, 2014). We used the *drpdfromts* function to extract the recurrence profiles in a lag window of ± 10 seconds. Studies in gaze coordination in speaker-listener pairs (e.g.,

Richardson & Dale, 2005) showed a peak in recurrence at a lag within ± 3 sec., so a window of 10 seconds seemed a plausible and sufficiently large one in order to observe the key coordination region of our mother-infant dyads.

After computing the %REC windowed lag profiles, we submitted them to a distribution analysis, treating the profiles as density distributions of temporal data. Following the procedure outlined in Dale et al. (2011), the extracted measures were: average total recurrence and maximum recurrence in the lag window, kurtosis, standard deviation and expected value (mean) of the distribution.

- *Average recurrence*: this measure tells us how much in average the behavioral signals of mother and infant match in the chosen lag window. High average recurrence would indicate a generally high level of similar behavior in the two signals (mother's and infant's).
- *Maximum recurrence*: this is the value of the highest point in the distribution (profile), corresponding to the moment in the lag window where recurrence, i.e., coordination, peaks.
- *Kurtosis*: this is a measure of how the density distribution peaks, and so high values of kurtosis would indicate a higher concentration of recurrence in a smaller interval of lags, i.e., a narrower distribution, that in our interpretation of recurrence would also mean a more punctual or effective coordination around some specified lag.
- *Standard deviation*: this has a similar interpretation as kurtosis, i.e., it is an index of how punctual/effective coordination is in the given window lag, although here

narrower distributions would be indicated by lower values of standard deviation, an inverse relationship than that of kurtosis.

- *Mean of the density distribution*: this measure tells us at which lag the center of gravity of the profile falls. With means significantly different from 0, we would have evidence that recurrence tends to concentrate more on one side of the profile meaning one member of the dyad significantly lagging behind the other.

In the following analyses, each measure was modeled as the dependent variable in a growth curve modeling framework (Mirman, 2014) using infant's age as the continuous underlying time variable and as the only fixed effect. After visual exploration of the time evolution of those measures for the individual dyads, which hinted at some nonlinear form of the growth curves, the fitted model considered orthogonal polynomials of age up to the quadratic term, the maximum allowed with just three visits. Age of child at time of visit (in days) was then appropriately transformed in orthogonal linear and quadratic terms through the function *poly* in R. We also modeled dyads' idiosyncratic variability as the only random effect in the model, allowing each dyad to have variable starting points (random intercept) and linear growth rates (random slopes). Analyses were performed in R using the *lme4* package (ver. 1.1-9, Bates et al., 2015) complemented by the *lmerTest* package (ver. 2.0-29; Kuznetsova et al., 2015) which computed p-values for the parameters' tests based on degrees of freedom estimates (Satterthwaite's approximation). Additionally we report marginal (associated to the fixed effect) and conditional (for the complete model) R^2 statistics (Nakagawa & Schielzeth, 2013) measuring the effect size for each analysis in terms of explained variance.

Results

Aggregate data

TABLE 1 HERE

The behavior of interest was “gaze-at-face”. This was in general a very frequent behavior, certainly favored by the particular constraints of the diaper-changing routine. Mothers and infants engaged in such a behavior almost half of the total time (46%) spent in the interaction. The pattern across visits indicated a difference between mothers and infants in the rate of change of this behavior (in aggregate value; see table 1). While for both this behavior significantly decreased in time, infants showed a steeper negative slope than mothers (infants = -0.63, $t(15) = -4.63$, $p < .001$, $R^2_m = .33$, $R^2_c = .65$; mothers = -0.22, $t(29) = -2.74$, $p < .01$, $R^2_m = .05$, $R^2_c = .74$). Additionally, infants (but not mothers) showed a significant effect on the quadratic term, indicating that the decrease in the behavior is possibly temporary and deemed to non-linear fluctuations with the passing of time.

Apart from a general gaze-at-face behavior, analyzed separately for infants and mothers, a measure of joint-face-attention was also derived from the video coding, summing up the periods of time in which mother and infant gazed at each other’s face at the same time. When comparing the aggregate value of such behavior across visits, joint-face-attention occupies a consistent portion of the dyad behavior (25%) but shows a clear decrease with age (see table 1) which is significant in the linear but not in the quadratic term (-0.55, $t(16) = -5.71$, $p < .001$, $R^2_m = .28$, $R^2_c = .80$)

Cross-recurrence analysis

While aggregate data on various dyad members behaviors are important to have a hint on what is going on in the interaction during development, a dynamic analysis of the behavior of the dyad members seems crucial to observe the fine grained changes in the gaze-at face coupling. We thus turn to the results of the cross-recurrence analysis of dyads' gaze-at-face behavior.

Shuffled baselines

As a first step, a shuffled baseline analysis contrasted lag recurrence profiles with a shuffled version of the same signals. A shuffled signal maintains the statistical properties of the collected data but disrupts the temporal structure of the data, which generates the dynamical information that recurrence analysis is able to detect. So if we can ascertain a significant difference of mother-infant recurrence profiles from randomly shuffled data, we are more confident that the profiles reflect real coordination processes being at work in the dyads' behaviors.

Total recurrence was computed for the shuffled and the original recurrence profiles for each visit and then entered a series of paired t tests. All three tests (one for each visit) showed significant differences ($ts > 2.2$ $ps < .05$) indicating a higher total recurrence in non-shuffled vs. shuffled lag profiles. This indicates a significant coordination pattern in the gaze-at-face behavior compared to the shuffled baseline. In the next section we explore then *how* this coordination is organized.

FIGURE 2 A-B HERE

Gaze-at-face behavior profiles

Figure 2.A shows the recurrence lag profiles averaged across dyads for each visit, at 3, 6 and 8 months of infants' age. A first obvious and notable difference is evident in the average amount of recurrence, which is definitely higher at 3 months (34%) compared to 6 and 8 month (in both cases 19%). A way to visually compare the main features of the three profiles in a single plot is to take the normalized recurrence rate as a ratio of the non-shuffled over the shuffled baseline profiles introduced previously. If at every lag point we compute the ratio of the real recurrence and the shuffled recurrence for every dyad and visit, we will obtain a measure of the relative gain of the recurrence rate profile compared to the randomly shuffled version. The result is shown in Figure 2.D. Quite evidently, the general pattern already notable in Figure 2.A is even more clear in the normalized plot, where we see a relatively flatter distribution for the first visit, while the distribution for the second visit peaks at about a lag of 0 as well as that of the third visit, which seemingly shows an even smaller variability around the peak.

Statistical analyses compared the five individual distribution measures discussed above (Average Recurrence, Maximum Recurrence, Kurtosis, Standard Deviation and Mean of the distribution; for detailed descriptions see Data Analysis section) across the 16 dyads, using growth curve analysis (lme4 package in R) treating Dyads as a random factor and Age as the only fixed effect. Given that several of the individual dyads curves in most of the dependent measures showed a noticeable curvature when plotted against time, we included a linear and a quadratic term in the fitted models, using the orthogonal polynomial method (Mirman, 2014), to evaluate possible nonlinear growth effects. In general, the

measures were fitted by significant linear (and in certain cases quadratic) decrement/increment with age with the only exception of the mean lag of the distribution profiles.

First of all, as it is already apparent from Figure 2, Mean Recurrence at age 3 months is in average much higher if compared to 6 and 8 months ($M_1 = 34\%$, $M_2 = 19\%$, $M_3 = 19\%$) and both the linear (-0.38 , $t(16) = -4.07$, $p < .001$) and the quadratic term (0.18 , $t(16) = 3.41$, $p < .01$) showed to be significant in this analysis (effect sizes: $R^2_m = .23$, $R^2_c = .85$). A similar pattern repeats in the analysis of the peak of Maximum Recurrence (linear slope = -0.36 , $t(16) = -3.85$, $p < .01$ and quadratic term = 0.19 , $t(16) = 3.52$, $p < .01$; $R^2_m = .22$, $R^2_c = .85$) which is maximal at 3 months (36%) and stabilizes at lower values at 6 months (21%) and 8 months (22%).

Our main hypothesis regarding structuring of behavior has been operationalized as a difference in the measures of Kurtosis and Standard Deviations across visits. We observe significant linear growth curves both in the Kurtosis and in the Standard Deviations of the distributions. Kurtosis increases from 3 months of age (-1.16) to 6 (-1.09) and 8 months (-1.08 ; slope = 0.24 , $t(19) = 2.99$, $p < .01$, $R^2_m = .11$, $R^2_c = .70$) while Standard Deviation is higher at 3 months (5.74) and shows a significant linear decrement with age (6 months = 5.63 and 8 months = 5.57 ; slope = -0.46 , $t(20) = -2.87$, $p < .01$, $R^2_m = .13$, $R^2_c = .55$). In both cases the quadratic term for the growth curves did not reach significance. In other words, these results tell us that during development, from the 3rd to the 8th month of age, recurrence concentrates in an even smaller lag interval around the point of maximum peaking of the distribution. For all three distributions, the peaks are close to lag 0 and not

significantly different from it. This is demonstrated by the fact that the fitted growth curve model for the Means of the three distributions ($M_{3\text{ mos.}} = -0.01$, $M_{6\text{ mos.}} = -0.14$, $M_{8\text{ mos.}} = 0.16$) do not show any significant effect in the linear or quadratic parameters. The general meaning of these results is that in average neither infant nor mother leads the interaction, i.e., on-line synchronization is in place.

Overall, these findings show that the lag dependent recurrence of the gaze-at-face behavior of mother-infant dyads is in average very high in the first visit (at about 3 months of age of the infants) but also flatter, more evenly distributed along the lag-dependent profile. Although the point of maximal coordination is centered at a lag of 0 ms meaning that the dyad members tend to gaze at each other if one is doing it already, the coupling is looser, distributed across lags. A much stronger coupling appears in the second visit (at about 6 months), where we observe however a much lower overall recurrence, probably fostered by the increased curiosity of infants towards other external stimuli and greater activity. Such recurrence is still concentrated around the point of online synchronization, i.e., once again at lag 0 ms, and stronger coupling is manifested by higher Kurtosis and lower Standard deviation in the recurrence profile. The third visit at 8 months confirms observations from the previous one.

Discussion

While infants' gaze is commonly investigated as the ability to react to a social cue and to follow somebody's attention, the present study addresses the development of gaze

coordination applied in early interactions. Drawing on data from a longitudinal corpus of everyday mother-infant routine interactions, we focused on the temporal coordination of eye contact at three time points, when the infants were 3, 6 and 8 months of age. Starting from the assumption that mutual gaze is an engagement process (Fogel, 1993 ; Reddy, 2003 ; Reddy & Uithol, 2016) that extends beyond a mere reaction of the caregiver to infant behavior, we analyzed temporal characteristics of multiple instances of gaze behaviors in interaction. This approach gives us insights into the online interactional loop, in which establishing and maintaining joint action takes place.

Applying cross-recurrence analysis, we aimed at creating a more complete picture of the development of temporal gaze coordination just before the onset of joint attention (Bakeman & Adamson, 1984). Given the freedom that we left to the dyads' behavior, which from a purely statistical and analytical point of view is bound to generate noisy datasets possibly masking the sought effect, our results reveal a convincing pattern: Our results show the gradual “getting into synch” (Bloom, 1993, p. 84), a process of engagement and mutual feedback to each other. In our data, the finding was that the center of the lag distribution was around the 0 lag, which points to the fact that there is no clear leader or follower of the interaction. This finding reflects the unfolding of mutual attention as a co-regulated process within a continuous information system (Fogel, 1993). Accordingly, feedback should be seen as continuous dynamics in a loop, a coupling in which the behavior of one person has an instantaneous effect on the behavior of the other, while at the same time being influenced by the other.

More specifically, we found that at 3 months, the infants showed a main interest in the mother's face, as they gazed at her for more than half of the interaction time on average. The mothers too spent a lot of time looking at the infant's face (about half of the interaction time). This finding has been addressed in depth in the qualitative sequence analysis presented in Nomikou et al. (2013). There, it was shown that infants spent prolonged periods following their mother's face as she moved during the diapering activity. This behavior can be explained by the development of infant visual and motor skills and how these may constrain or foster different ways of participating in interaction (Fogel, Messinger, Dickson & Hsu, 1999). At 3 months of age, infants have good oculomotor control and increasingly look at and track objects in their environment (Von Hofsten & Rosander, 1997). Yet at the same time, their movement repertoire is still restricted: they can hold and move their head, but most infants cannot move their body, turn, or manipulate objects with ease (Adolph & Berger, 2005), but as they participate in face-to-face dyadic attention (Bruner, 1983 ; Bakeman & Adamson, 1984) they are already experienced in proto-conversations with their caregivers through gaze, facial expressions and vocalizations (Trevvarthen, 1974 ; Bateson, 1979 ; Snow, 1977 ; Bullowa, 1979 ; Bruner, 1983 ; Masataka, 2003).

At 3 months, as the mothers change the diaper of the baby, they switch to and away from the infant's face during dressing and undressing the infant, wiping the infant clean etc. It seems that they provide 'rewarding' experiences for the infant when she or he is gazing at their face, through multimodal practices such as facial expressions, playful

intonation and repetitive patterning of their behavior, which might be attractive for the infants (Nomikou et al. 2013 ; Nomikou & Rohlfing, 2011 ; Lavelli & Fogel, 2013).

The manifestation of this gaze-at-face behavior in such a big percentage is confirmed in our dynamical analyses, where it inflates the recurrence rate at the first visit. For Sander (1962), this is a period of initial regulation, in which as Trevarthen (1977) observed, the interaction is not about ‘something’, rather it is about ‘interacting’, about the “exchange itself” (Trevarthen, 1977, p. 241). Our findings support existing literature by showing that when infants are 3 months of age, mother and infant engage in and maintain gaze at each other’s face to a great extent.

Yet, these levels of recurrence do not turn into better coordination as shown in the lag-dependent profile, where recurrence is rather uniform. This means that coordination is rather loose, as reflected by large standard deviations of the profile and low kurtosis. At 3 months, although mother and infant repeat each other's behavior often, the timing of this repetition is still very variable as repetition takes place in a broad time window. From a dynamic systems perspective (e.g., Thelen & Smith, 1994), this variable participation in an interaction pattern could be interpreted as evidence of the self-organization process of the dyad around an emerging attractor, i.e., engaging in eye contact. At 3 months of age, we may be witnessing the stabilization of eye contact as an interactional resource which is still in negotiation and therefore, large variability is visible. Yet already at this early point, the data reveal an emerging coupling of the mother-infant dyad as suggested by the comparison of the time series with a shuffled (random) one, indicating the emergence of eye contact as an attractor (Fogel, 1993) of the system at this age.

At the time of the second visit, when the infants are 6 months old, we see that the infant's attention is increasingly often attracted by different objects or the mother's hands and less by the mother's face; this is even more pronounced in the 8-month-old infants (third visit). This decreasing interest in the mother's face goes hand in hand with a general reduction of his/her gaze-at-face behavior, which is consistent with the developing ecology of the interaction (Rossmanith et al., 2014): At 6 months, as infants are keen in manipulating objects, can turn their body and in some cases, can even sit without support (and at 8 months, as some infants can even stand or crawl), the configuration of mother and infant in the diaper situation changes. Rossmanith et al. (2014) made similar observations when looking at the situation of early book reading longitudinally. At this age range of 6 to 9 months, they observe a shift in the constellation of the interactions from being more static (more sustained, very little movement of participants and objects) to becoming much more dynamic and unstable (shorter engagement, more movement and change in the setting). Our findings thus point to the changing configuration of the participation framework (Goodwin, 2007) as the mother–infant system develops. The mothers' gaze at the infants' face is also reduced in the second and third visit, but the growth curve slope is much smaller. This suggests that, whereas infants are evidently showing a shift in the allocation of their gaze to different locations, mothers do not change their behavior in a radical way. Similarly, Nomikou et al. (2013) showed that in the interactions with the 6-month-old infants mothers increase the use of the facial modality when engaging in eye contact with the infants. It seems that although the infants are starting to disengage from the face-to-face configuration (see Bakeman & Adamson, 1984), the mothers continue to

use the facial modality, which is a resource conveying social feedback, i.e., a smile, a frown, or a surprised face.

As a consequence of this development, analyzing the dynamics of gaze at each other's face, we observe a reduction of the average recurrence rate in the explored lag window. Interestingly though, the coupling of dyads' gaze is more effective and concentrates in a narrower time window as testified by the lower standard deviation of the profile and by higher values of kurtosis. Thus, although mother and infant repeat each other's behavior less, this does not mean that the coupling is reduced. Instead, the coordination becomes more efficient with probably more predictable structuring of gaze, since the time that it takes to repeat the behavior of the other becomes much more concentrated around lags closer to 0. This is consistent with Messer and Vietze (1984) who suggested that with age, infants' gaze becomes more efficient as they need shorter glances to obtain information. At 6 months, the ostensive meaning of eye contact can be perceived (Senju & Csibra, 2008).

Our finding points to the emergence of a structure in the interaction, supporting research which suggests that gaze behavior is “conversational” in that it regulates preverbal social interactions and shows similar temporal regularities to verbal communication (Jaffe, Stern & Perry, 1973 ; Richardson, Dale, & Kirkham, 2007). Accordingly, at 3 months of age there is more recurrence but also more variability in timing, whereas at 6 and 8 months there are less instances of gaze behavior at the face (less recurrence) but these instances are more correlated, more structured around a more predictable temporal pattern. Our research complements investigations documenting the decrease of face-to-face attention and the

shift to object-focused attention (e.g. Bakeman & Adamson, 1984 ; de Barbaro et al., 2013). We suggest that infants do not just lose interest in face-to-face attention. Gazes become shorter—and perhaps more effective—and there is a shift in the interaction dynamics, which provides infants with the resources to direct their attention to both the face of the mother, as well as the interesting objects in their surroundings (de Barbaro, Johnson, Forster & Deák, (2015). Here again, from a dynamic systems perspective, what we might be witnessing is the dyadic system having reached a stable state—gaze at the face becomes more effective. At the same time, instability in other attractors—such as the increasing gaze at the surroundings—may be shifting the system towards a transition and an eventual organization in a new stable state—that of coordinating attention to objects and then, finally, to joint attention.

One further aspect of the data worth addressing is the between-dyad variability of the extracted measures. In our sample, we found that dyads varied both in the extent to which they repeated each other's behavior, as well as in the time window within which this repetition occurred. Finally, dyads also slightly differed in the center of gravity of their recurrence profile, indicating that in individual dyads there might be a slight leader-follower role-distribution. Hsu and Fogel (2003) criticize common research practice of predicting variability in development for using individual mother measures and infant measures. In doing so researchers have paid little attention to within-dyad factors. In their work, they showed that communication is shaped not only by individual characteristics (e.g., infant sex and maternal parity) but also by the dyad's communication history (Hsu &

Fogel, 2003). Accordingly, addressing the developmental trajectories of gaze coupling in individual dyads may reveal different routes to similar developmental outcomes.

Furthermore, since the assumption is that gaze coordination is shaped by the interaction then variability in this shaping process could be reflected in the later behavior of the infant. This assumption echoes socio-cultural theory, which suggests that interaction characterizes development prospectively. For vocalizations, Jaffe et al. (2001) found that infants and mothers who showed “optimal” (p. 95) coordinated interpersonal timing at 4 months were more likely to be securely attached at 12 months than were other infants (for a more recent account, see also Beebe et al., 2010). Expanding on these findings, future research should address whether recurrence measures of gaze coupling can help further explain differences in developmental outcomes.

Finally, it remains an open question whether gaze coupling could be used as a predictive measure of impairment. As mentioned in the introduction, Warlaumont et al. (2010) used cross-recurrence analysis on vocalizations in a study comparing children diagnosed under the classic autism subtype and typically developed children. They found differences in the time adults needed to respond to vocalizations in the autism population. Children in the autism group also tended to follow more and lead less relative to the control group. In a recent review, Hurwitz and Watson (2015) reveal that children with autism spectrum disorder employ joint attention significantly less often even though they understand how to use it. The relation to language development becomes apparent—as already suggested by Mundy and colleagues for typically developed children (Mundy et al., 2007)—when comparing children who did not employ joint attention with children who

employed joint attention; the latter had better scores in language surveys. In connection to our approach, these findings raise further questions of how the coupling of early gaze could also be informative for the detection of coordination deficits/ breakdowns as a potential risk factor for autism.

In conclusion, our contribution focuses on the continuity of development. To this notion we propose the idea that early engagement in mutual gaze creates shared, attuned, interactions of emotionally involved participants (Stern, 1985) and that this is more than the analysis of others' behavior as cues (Reddy & Uithol, 2016). Out of the emerging coordination of gazing at each other's face, out of these co-constructed affective experiences a capacity of sharing emerges, which is relevant for the transition to new patterns of interaction (Adamson & Bakeman, 1982), involving coordinated joint-object attention and later on verbal communication.

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Figure 1. Section of the whole session of the coded behavioral streams of gaze-at-face behaviors in dyad 10 in visit 2 (6 months of age).

	Visit 1	Visit 2	Visit 3
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Gaze-at face	MEAN (SD) in %		
Infant	60% (21%)	34%(17%)	35%(16%)
Mother	54% 16%)	48% (19%)	45% (17%)
Joint-face attention	39% (19%)	21% (14%)	16% (13%)

Table 1. Average proportion (and standard deviations) of time spent in specific behaviors by the dyads' members in the three different visits (3rd, 6th and 8th month of infants' age).

A

B

Figure 2. A. Lag dependent profiles of absolute recurrence rate averaged across dyads at every of the three visits.. B. Normalized averaged recurrence profiles at different ages. It becomes clear from this image how recurrence rates at 6 and 8 months tend in average to be more concentrated around the point of on-line coordination while recurrence distribution at 3 months is less structured.