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Co-regulation of movements during infant feeding

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ABSTRACT

The process by which infants move from liquid feeding to caregiver-assisted spoon feeding of semi-solid food is quite a dramatic transition. In previous studies, we observed that in the weeks after the introduction to solid food, mother-infant dyads showed increased co-regulation and synchronization of their respective feeding behaviors (e.g. offering food, accepting/refusing, timing). Learning this new way of feeding and eating requires that infants coordinate their position and movements with the complementary position and movements of the caregiver. The present study augments the category-based analysis of this co-regulation by the analysis of coupling in the dyads based on automatically extracted movement data. Previously collected video data from 10 mother-infant dyads were re-analyzed for the purpose of this study. Movement trajectories of mother's hand and infant's face were obtained by applying an automatic movement detection algorithm (TLD, Kalal et al., 2012; for applications to mother-infant interactions see López Pérez et al., 2017). Coordination was assessed by the method of Diagonal Cross Recurrence Profiles (DCRP), which expresses the degree of synchronization at different time lags. Profiles for each dyad from two different occasions –with one visit in the first week of solid feeding and one approximately 4–5 weeks later– were compared. The results showed that, on average, most synchronization occurred in the first visit at lag 0. In the second visit there was an average delay in synchronization of about 1 s, with leading behavior starting from the infant. This suggests that the coordination was initially closely synchronized and became somewhat looser over time. Possibly, infants have begun to anticipate and guide the feeding movements enacted by the mother. However, our findings underline the idiosyncratic and complex nature of co-regulation of movements during the introduction of solid food. Whereas some dyads showed signs of increased organization, others seemed to disorganize, re-organize, or showed no organization at all. Many (interacting) factors –both individual and contextual– may be responsible for the observed differences between dyads. Further research is needed to understand why specific synchronization pathways emerge and whether and how these might relate both to later feeding and eating and to the emergent patterns of participation.

The moment at which infants move from liquid feeding to caregiver-assisted spoon feeding of semi-solid food is a crucial milestone in feeding. This transition involves many changes, and requires –among other things– that infants and caregivers synchronize their

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position and movements with the complementary position and movements of the other. Caregiver-infant synchrony is seen as the foundation for socio-emotional bonding and is linked to many long-term developmental outcomes (Harrist & Waugh, 2002; Evans & Porter, 2009). It involves the coordination of micro-level behavior in various modalities, such as touch, gaze, affect, and bodily expressions (Feldman, 2006). Ideally caregivers are sensitive to the needs of their infants and adapt their behaviors to the behaviors of the infants, whereas the infants are sensitive to the regularities and the structure of social exchanges scaffolded by the caregivers (e.g., Murray & Trevarthen, 1986; Rochat et al., 1999).

Dyadic partners become synchronized because they co-regulate (or co-adapt) their behavior to the expressed and anticipated behavior of the other (Fogel, 1993; Harrist & Waugh, 2002). Co-regulation[1] and synchronization are dynamic constructs, because they come into existence as the result of the ongoing moment-to-moment interactions. Caregiver-infant synchrony and processes of co-regulation are highly relevant for feeding in infancy. This is particularly the case for the adaptations that have to be made when infants start feeding on solids (Toyama, 2013; van Dijk, van Voorthuizen, & Cox, 2018). This transition involves many changes, also with regard to the timing and rhythm of caregivers and infant's bodily movements (Toyama, 2013). Although there are only few studies on the developmental changes in eating and feeding during this transition period, there are indications that this transition phase is of great importance, because at this point in time infants build the foundations of how they relate to food and eating (Lindberg et al., 1991). It is also relevant because at the same time, it is a highly cooperative joint action, in which infants are also building how they relate to caregivers and the social world in general, for instance forming their own agency, learning cultural-specific respect patterns, etc. (Rączaszek-Leonardi & Nomikou, 2015). It is the aim of the current study to explore the emergent synchronization patterns during feeding by investigating the coupling of caregiver's and infant's movements.

Both liquid feeding and spoon-feeding require a continuous temporal coordination of microlevel behavior of both infant and caregiver. In the first months of life, infants use their sucking and swallowing reflexes and skills for liquid feeding (breast and/or bottle) (Toyama, 2013). In the context of breastfeeding, it has been argued that although it seems that the mother is in control because she initiates the feeding, the infant has many possibilities for control during feeding (Young & Drewett, 2000). In fact, the observation that mothers of newborns attempt to stimulate sucking by 'jiggling' during sucking feeding pauses has been suggested to be one of the earliest forms of turn-taking (Kaye & Wells, 1980). During the transition to eating solid food –also referred to as 'the weaning period'– infants are exposed to various new flavors and textures and need to master new feeding skills. Smooth pureed foods are usually introduced first, followed by somewhat more lumpy food and finger foods (Vail et al., 2015). In Western countries, spoon-feeding is the most typical form in which solids are fed (see for instance Watson et al. (2020) and Negayama (2000)). Gradually, being fed is replaced by more independent feeding when the infant becomes more capable to bring food to their mouth (Pearcey & de Castro, 1997). Generally, there is an extended period of feeding on both milk and (semi-)solid food in which different types of feeding and eating (breast/bottle, spoon, and manual feeding) co-exist (Drewett & Young, 1998). However, the moment at which infants move from a feeding pattern based only on sucking to the spoon-feeding of semi solid food, requires an entirely different kind of synchronization with caregivers, because it demands coordination of the quality and timing of each individual give-and-take action (van Dijk, van Voorthuizen, & Cox, 2018).

The introduction of solid food is generally caregiver-led in the sense that it is the caretaker who determines the moment of introduction, chooses the type of food, and presents the food in a particular way. In addition, it is the caregiver who offers each individual spoon-full of food and relies on the responses of the infant for offering each consecutive bite. Infants are not passive recipients in this process, but they anticipate and follow actively (Toyama, 2014). With regard to this, Toyama (2013) argued that solid feeding involves a certain 'division of labor'. Infants have to open their mouths at just the right moment in time, which means that they have to pay attention to the arm movements of the caregiver. At the same time, caregivers have to carefully observe the chewing and swallowing movements of the infant.

Infants gain more advanced skills and become able to begin to feed themselves over time, and caregivers have to adapt to such rapid changes (Toyama, 2013). In this sense, spoon-feeding is an iterative process, in which each give-and-take action is causally dependent on the previous one(s), in which each feeding session is dependent on the previous one(s), and in which patterns of interaction emerge due to the repeated interactions at the micro-level. Successful spoon feeding requires a large degree of synchronization on many levels, both qualitatively and temporally. For instance, in order for efficient and enjoyable feeding to exist, the food needs to be presented not only at the right moment in time (the infant is no longer chewing on the previous bite and is ready for the next) but also in a sensitive manner (the spoon contains just the right amount of food, the spoon enters the mouth just deep enough, etc.).

In previous studies, it has been reported that the process of co-regulation takes place quickly after the introduction to solid food. For instance, in an earlier study, we observed that in the first 6 weeks after the introduction to solid food, increased behavioral synchrony with regard to the quality of the actions had emerged (van Dijk, Hunnius, & van Geert, 2012). In most dyads, sensitive, responsive, and efficient feeding interactions became more frequent over time, and this pattern became relatively stable in most dyads. However, there were also clear interindividual differences, and dyads who showed a relatively large day-to-day variability in the first weeks of eating solids, also exhibited a more diffuse ending of the meal in the sense that caregivers kept on trying to feed the infant when the infant had already stopped eating. A similar finding with regard to co-regulation of feeding was reported by Toyama (2014), who observed that whereas shortly after the introduction of solids infants usually opened their mouth after the caregiver pushed the spoon against their lips, they showed more spontaneous mouth opening one month later. This demonstrates that in the first few weeks after the

[1] Though, the terms 'synchronized' and 'co-regulated' are often used interchangeably, we will refer to 'synchronized' for those observable patterns that show a close temporal similarity (or complementarity) of behavior, and to 'co-regulation' as the underlying coordinative process by which this occurs.

introduction, infant and caregiver show increased behavioral synchrony during feeding, in the sense that their actions are complementary and well-timed.

1. Feeding as a complex dynamic system

The changes in eating and feeding during the transition of solid food can be seen as a new attractor state to add to the multi-stable landscape of possible interaction organizations that occurs in a complex dynamic system (van Geert, 1994; Thelen and Smith, 1993). Such systems consist of many different elements which interact on a moment-to-moment basis, generating in this way the emergence at a macroscale of new behaviors and skills. The interactions between these elements take many different forms and are therefore highly person-specific (van Geert, 1991, 1994). The theoretical framework of complex dynamic systems fits very well with the study of dyadic co-regulation. By taking the caregiver-infant dyad as a whole as the focus of investigation, and by moving away from studying individual behaviors or traits, we can, according to Paxton et al. (2017) *"[.] begin to explore the behavioral dynamics that emerge from the contextual pressures constraining the dyadic system"* (pp 2). During feeding, infant and caregiver can also be seen as such a complex system, with the infants' appetite, food preferences, feeding skills (etc.) and the caregiver's goals, concerns and behavior continuously and mutually influencing each other from moment to moment. In this system, the components self-organize into a functional unit, a behavioral synergy for each feeding interaction, characteristic for each individual infant-caregiver dyad. In van Dijk, van Voorthuizen, & Cox, 2018, we used these theoretical concepts to investigate how certain specific feeding behaviors became more temporally coordinated during the introduction to solid food. In a multiple case study of 5 mother-infant dyads, we analyzed the dynamical structure of the feeding behaviors of the caregiver (such as offering, inserting, and pulling back) and infant (such as chewing, rejecting, and mouth opening). We employed Cross-Recurrence Quantification Analysis (CRQA, e.g., Wallot & van Orden, 2011, Dale et al., 2011) to analyze the temporal structure of both qualitative matches in behavior (for instance offering in combination with mouth opening) and mismatches (for instance offering in combination with chewing). The method of CRQA has been used in various studies on child development, for instance in parent-child talk (Cox & van Dijk, 2013, in gaze coordination (Nomikou et al., 2016) and in infant-adult vocalizations (Abney et al., 2015) and offers unique information about coordination processes. The results of the analyses in van Dijk, van Voorthuizen, & Cox, 2018 showed that all five participating dyads showed optimal coordination when the caregiver leads the feeding interaction by approximately 1–2 s. In addition, all dyads demonstrated increased temporal coordination over time, but the complexity metrics showed clear interindividual differences with regard to the indicators of synchronization. In some of the dyads, the peak in the profile changed (indicating greater synchrony), whereas in other cases the temporal delay decreased (indicating temporally closer synchrony). In some dyads, it was most visible in changes in coordination in behavioral matches whereas in others it was in the mismatches.

One of the important new elements of spoon feeding is the way in which the bodily movements of infants and caregivers have to become synchronized to each other. In one of the very few studies on movement during feeding, Toyama (2013) observed a peak of non-fluent arm movements of the three participating mothers at 2–3 months after the introduction of solid food. At that time, the mothers had stopped wiggling the spoon in the infant mouth in order to take the food from the spoon, as the infants became able to actively take foods in one bite. Whereas, the movements of mothers and infants were initially slow, they increased in tempo as a result of the increased abilities of the infant. According to Toyama, it is natural that the movements of both dyadic partners are constrained by each other during feeding, and this results in the matching of the mother' arm movements to the child's mouth movements. In a second study on the same three mother-infant dyads, Toyama (2014) focused on the exact timing of mothers' arm movements and infants' mouth-opening and the role of rhythmic body movements of both infant and mother. The results of the analyses showed that these rhythmic body movements preceded coordinated feeding, which suggests that mother-infant synchrony in body movements plays a role in practicing and constructing a sense of 'shared timing' of feeding. She argues that in order to fully understand the relationship between coordinated feeding and synchrony of body movements, further research is needed.

1.1. *The present study*

The present study builds upon these earlier findings and aims to further explore changes in movement synchronization between caregivers and infants during the transition to solid food. Learning to eat from a spoon requires that infants, among other things, coordinate their position and movements with the complementary position and movements of the caregiver. The infant learns to perceive the caregivers movements in a way that enables participation. The dyad's movements reveal important information about who is leading and who is following and this may be indicative of more general concepts such as agency and participation. For this reason, dyadic movements reflect embodiment of emerging relations and analyzing them offers further insight into the emerging dynamics of feeding. We investigated this in the current study by tracking the coupling of mother's and infant's movements during feeding sessions in the first weeks of the introduction of solid food. We also aimed to describe the interindividual differences in movement synchronization.

In our analysis, we use 'synchrony' as a specific case of coordination, in the same way as Paxton and Dale (2017) did. We consider infants and caregivers to be synchronized to the extent that they tend to exhibit the 'same' behavior at the same time. We use time series analyses of movements to quantify whether this 'sameness' in behavior is structured in a particular way. In the current study, the movements of caregiver and infant were measured directly from the videos, and they were not categorized into functional units as in previous studies (e.g. Toyama, 2014, van Dijk, van Voorthuizen, & Cox, 2018). While not meant to substitute, but rather complement valuable qualitative analyses and coding, this approach is less time-consuming and less burdened by subjectivity than forms of categorical coding. In addition, the behaviors are captured in precise time series data that are highly suitable for analyzing temporal structure of behaviors.

Considering the above, we posed the following research questions:

Research Questions:

1. Can we detect systematic changes in patterns of movement synchronization during the introduction to solid food?
2. To what degree do these possible changes exhibit interindividual differences?

2. Method

2.1. Participants

The study was based on the videos of the First Bites Project (data collected in 2005/2006 and reported on in earlier publications (van Dijk, Hunnius, & van Geert, 2009, 2012; van Dijk, van Voorthuizen, & Cox, 2018) which were re-coded for the purpose of the current study. Ten mother-infant dyads were video-taped during two home visits: 1) in first week of solid feeding, 2) approximately 4–5 weeks later. The dyads came from the general population, were from middle to upper SES, and lived in the Netherlands. At the start of the study, the infants were feeding solely on milk. For the current analyses, the dyads were selected from a larger dataset (n = 25) on the basis of quality of recording. The main criterion for selection was the absence of faces and spoons moving in and out of view.

In the selected videos, most infants were fed in a face-to-face situation, but some were fed while sitting on the lap of the mother (see Table 1 for details). The duration of the videos was 8.95 min (SD = 3.79) for the first visit and 9.74 min for the second visit (SD = 3.27). There were 6 boys, 4 girls. In the first feeding session, the average age was 5.5 months (SD = 0.72), in the second session, this was 6.7 months (SD = 0.76). Two of the infants ("Charlotte" and "Bowen") were fraternal twins and had separate 1-on-1 feeding sessions each with the same mother. Aside from the twins (who were first- and second-born), there were four first-born children, three second-born children, and one fourth-born child. Four infants were exclusively breast fed at the moment of the introduction of solid food, three were exclusively bottle fed, and three were given a combination of both.

2.2. Measurements

The first step was to obtain the movement trajectories of mother's hand and infant's face by applying an automatic movement detection algorithm onto the videos (TLD, Kalal et al., 2012; for applications to mother-infant interactions see López Pérez et al., 2017). We choose hands and faces because these are the instrumental complementary effectors engaged in feeding and at the same time easy and reliable to track (the algorithm is not sensitive enough to recognize only mouths instead of faces). TLD returned a set of 2D coordinates for each one of the tracked features, i.e. the hand with the spoon of the caregiver and the face of the infant. However, in some cases, the tracker was unable to follow for some frames the hand movement or the position of the infant's face. Due to the specificity of the analyzed episodes, where, for instance, the caregiver normally moved the spoon from left to right and vice versa, a linear movement was assumed in those missing frames. Therefore, a linear interpolation was calculated between the last correctly tracked point and the first one available after that. Next, a moving average was applied to avoid one-point outliers. The second step was to code the movements of each individual into a 5-category directions Cartesian scheme on a frame-by-frame basis (see Fig. 2), where each frame was 0.04 s. This resulted in categorical time series, for each dyad appropriately time-aligned between each mother and infant. These categorical time series were analyzed with cross-recurrence quantification analysis (CRQA) (see 'Analyses').

2.3. Procedure

The videos were collected in 2005 during home visits. The feeding sessions were naturalistic in the sense that they took place at the same location as usual (kitchen or living room), and took place with the caregiver who fed the infant most frequently in daily life. The same caregiver participated in both sessions of the same infant. Though one father participated in the total sample, the current sample consisted of only female biological mothers. The choice of food was free, but the observations were scheduled around fruit or vegetable feedings. Other common weaning foods are porridge and bread (crust), but these were not observed in the current analysis. At the time of the study, the baby-led weaning technique was relatively popular in The Netherlands. Since this technique is based on the infant self-feeding, such feedings were also excluded.[2] The position in which the infant was fed was determined by the mothers (high chair, baby seat, lap). In three dyads, this seating position changed between the first and second visit. In most cases, the bowl (or jar) that contained the food was held by the mother, as is shown in Fig. 1. In 4 cases, it was placed on a table in front of the mother (Matteo/V2, Bowen/V1, Charlotte/V1, Femke/V1). The video-recordings were made by researchers (or assistants) who knew the participating families. After each recording, a short questionnaire was filled in stating for how long the infant had been awake, and the time and type of the previous meal. The amount of consumed food was estimated by weighing the bowl and bib before and after feeding. Situational variables (such as the number of people present at mealtime and recent illnesses) were also noted, but showed no relation with the feeding behavior. In total, the participants were filmed on 15 feeding occasions throughout the weaning period, starting with the first introduction of solids till after the transition to solid food. There were three waves of five observations, one wave immediately after the

[2] The proportion of each type of feeding during the transition to solid food warrants its own study, which was not the main goal of the current analysis.

Table 1
Infants synonyms, visits numbers and background information for participants selected for the current analysis.

ID	Pseudonym	Visit 1 (wave-session)	Seating V1	Visit 2	Seating V2	Sex	Feeding history	Birth order
1	“Bowen”	1–1	lap (FM)	2–1	baby seat	male	combined	first/second (twin)
3	“Floris”	1–3	high chair	2–2	high chair	male	breast	first
4	“Femke”	1–4	high chair	2–3	high chair	female	breast	first
5	“Ivan”	1–2	baby seat	2–2	baby seat	male	bottle	ourth
6	“Jonathan”	1–3	baby seat	2–4	baby seat	male	breast	second
7	“Lola”	1–4	lap (BW)	2–2	lap (FF)	female	combined	second
8	“Charlotte”	1–2	lap (FM)	2–3	baby seat	female	combined	first/second (twin)
9	“Lewis’	1–3	high chair	2–2	high chair	male	bottle	first
10	”Milou”	1–1	lap (BW)	2–1	lap (FF)	female	bottle	second
11	“Matteo”	1–1	baby seat	2–2	high chair	male	breast	first

Note. Infants “Milou”, “Femke” and “Floris” were also analyzed in van Dijk, van Voorthuizen and Cox (2018)
Note. “Combined” refers to a combination of breast feeding and bottle feeding
Note: Lap position was sideways in all cases.. In some cases the infant was mostly facing mother (indicated as FM), in some cases they were mostly facing front (FF), in some they were flexibly turning both ways (BW)

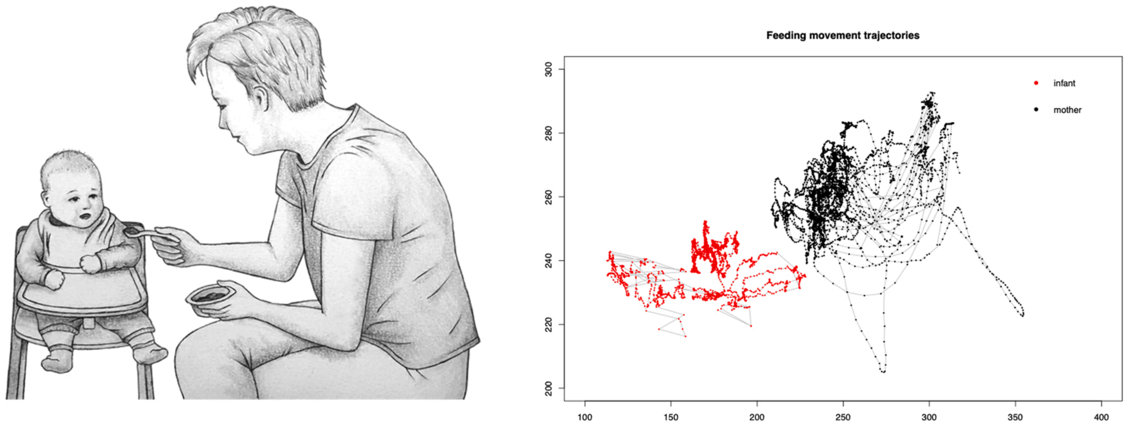

Fig. 1. A typical feeding situation (left) and example of the resulting movement trajectories (red line= infant face, black line = hand mother) (right).

introduction, one wave that started approximately one month later, and one wave roughly 3 months after the introduction. For the current analyses, one video of the first and one video of the second wave was selected. This selection was made basing on two criteria. The first was that the infant was placed in such a position that the head could be moved. This means that a few videos with the child sitting on the lap of the caregiver in an almost horizontal position where the infant could not freely move their head were excluded. The second criterion was the quality of the videos. Because the recordings were not made with the purpose of movement analysis in mind, many were not usable because of hands moving out of frame, camera angles that blocked the infants’ faces momentarily, poor lighting conditions, unstable camera positions, etcetera. When we had one suitable video for each wave for each dyad, we stopped the selection. Ethical guidelines of the respective universities were the original study took place were followed and the ethical approval was gained (OUNL-U2006–219CBO (for the original data collection) and PSY-1819-S-0099 (for the current analyses)).

2.4. Analyses

CRQA. The categorical time series that were obtained by coding the movements in the cartesian coordinates (see Fig. 2) were first categorized into ‘matches’ and ‘mismatches’. This was based on the movements that infant and mother made, from one moment (frame) to the next (from t to t + 1). If the infant and mother both went into the ‘2′ or the ‘4′ category (on the vertical axis) at the same time, this was considered a ‘match’. This was also the case if both remained in ‘0′. However, for the horizontal dimension, a match was a synchronized move towards each other. This means that if both infant and caregiver moved to ‘1′ this was also considered a match, but not if they moved in opposite directions (i.e. the ‘3′ and ‘5′ categories do not match) since this combination of movements is not functional to achieve synchronization for feeding. All other combinations were also considered as ‘mismatches’.

As a second step, based on these matches and mismatches, a Cross-Recurrence Plot (CRP) was constructed, which is in this case a graphical representation of recurrence points with the infant’s time series along the x-axis, and the caregiver along the y-axis (see Fig. 3). When the categorical time series of the infant’s and the caregiver’s movements match in value, at any given time, a dot is marked at the intersection of those two time points. A CRP then emerges as a bidimensional representation of all the possible ‘matching values’ at any combination of the time points in the two time series. The thick red diagonal broken line in Figure 3 indicates a special

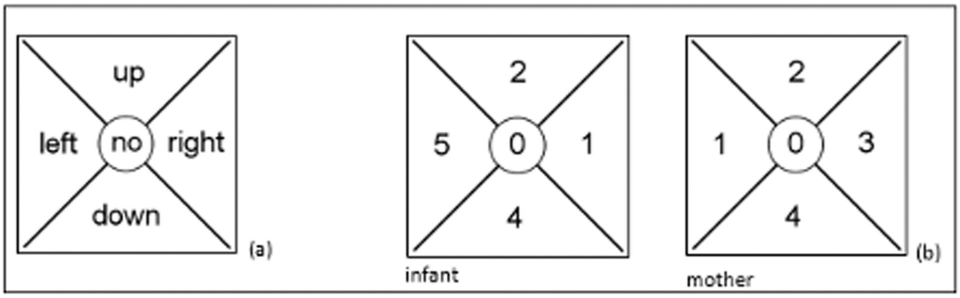

Fig. 2. Coding scheme for categorical time series.

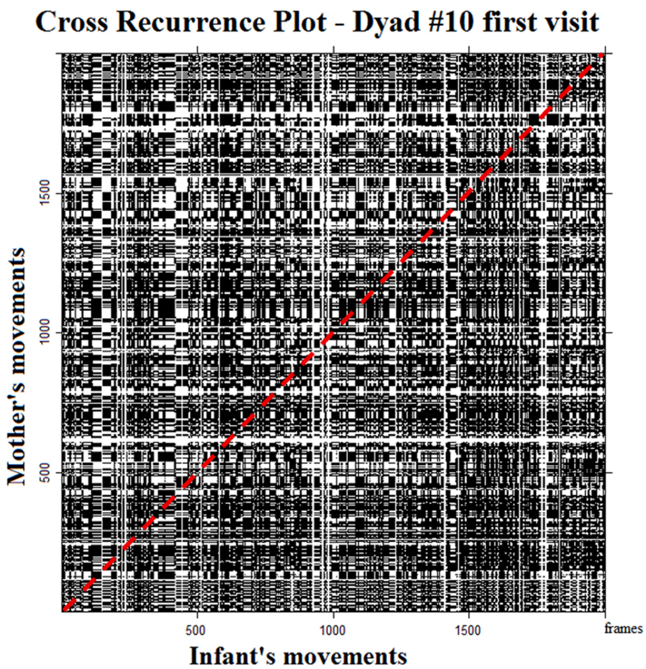

Fig. 3. Recurrence plot of dyad 10. The main diagonal represented with a red broken line added on top of the cross-recurrence plot is called the Line of Synchrony.

location in the CRP, the Line of Synchrony (LOS). Along the LOS, the presence of recurrent points would indicate a synchronic movement of infant and caregiver without any time delay, i.e. infant and caregiver perform matched movements at the same time. All other dots represent matches between caregiver and infant with a particular time lag between them (1 frame, 2 frames, etc.). More specifically, all dots above the LOS represent moments where the infant precedes the caregiver with his/her actions and all dots below the LOS represent moments when the caregiver precedes the infant. CRQA provides various measures of coordination based on the number and the distribution of the matching and mismatching dots in the CRP (Webber & Zbilut, 2005). For instance, the Recurrence Rate (RR) is used as a measure of global recurrence/coordination. The RR is the ratio of all recurrent states (recurrence points) to all possible states and is therefore seen as the probability of matching states during the interaction (Marwan & Kurths, 2002).

The third step consisted of constructing Diagonal Cross-Recurrence Profiles (DCRPs or LOS-profiles, see Dale and Spivey, 2006 and De Jonge-Hoekstra et al., 2016) for each individual dyad, which allows to investigate the temporal coordination around the LOS (see Fig. 4 for an example). A DCRP displays the Recurrence Rate (RR) on the vertical axis, for 6 s around the LOS (from −3 s to 3 s). The middle of the horizontal axis (0-s delay) represents the RR exactly on the LOS.

As a final step, after constructing the DCRPs on the basis of the empirical data (see the red line in Fig. 4), baseline profiles were constructed for each session, based on a randomization of the data of both the infant and the caregiver in the original categorical time series (the blue line in Fig. 4). The empirical profiles were compared to baseline profiles for each individual dyad (= 'Profile type').

First, at the level of the group of dyads, linear mixed effects model analysis were used to test the effect of two variables: Profile type (baseline profile vs empirical profile) and Visit (first visit, right after the introduction of solid food vs second visit, 4-5 weeks later). The models were fit by using the maximum likelihood, the t-tests used Satterthwaite's method.

Second, visual inspection was performed on the individual DCRPs. Here, we evaluated whether: 1) the profile shows indications of

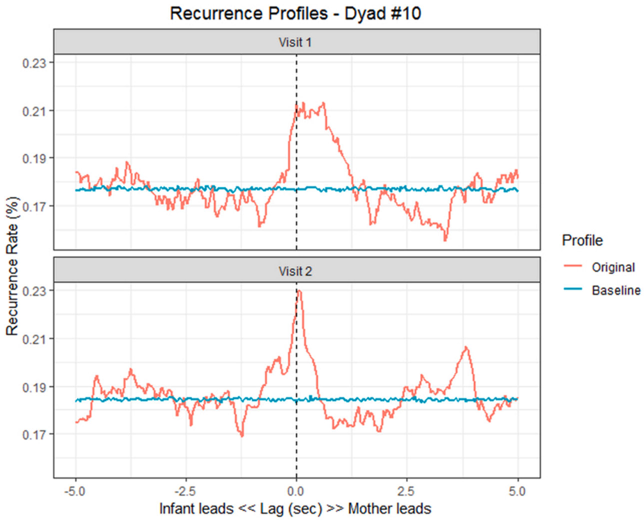

Fig. 4. Example of a Diagonal Cross-Recurrence Profile (dyad 10/"Milou").

global synchronization (the question whether the RR is higher than the baseline, and if so, whether this is higher in one of the two sides of the DCRQ), 2) whether there exists some sort of peak in synchronization and where it is located, and, 3) whether some sort of qualitative change is observable between visit 1 and 2.

3. Results

3.1. Group analyses

On average, most synchronization seemed to occur in the first visit at lag 0 (see Fig. 5, top, line for 'original data'), where the RR peaks exactly at the line of synchrony. In the second visit there was a delay in synchronization by about 1 s (see Fig. 5, bottom, line for original data), with leading movements starting from the infant. Generally, the overall recurrence seemed to be higher in the left part of the graph, suggesting that the infant is somewhat ahead of the caregiver. In addition, the RR appeared to be generally lower in the second visit, which suggests that the coordination became somewhat looser over time. Fig. 5 also shows that the RR of the baselines were much lower than that of the empirical data, although this seems to be more pronounced during the first visit.

These group observations were tested by means of linear mixed effects model analysis, with both Visit (visit 1 versus visit 2) and Profile type (original versus baseline) as coefficients. A linear mixed model analysis, is a development of the 'traditional' linear model (e.g. ANOVA and linear regression). The method is increasingly used for its efficiency and elegance with certain data. It operates by giving structure to part of the random component of the estimated linear model (the residual component), by leveraging on the fact

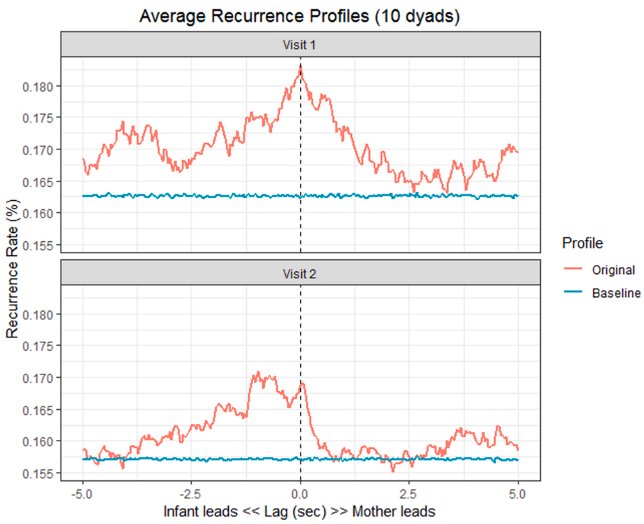

Fig. 5. Diagonal cross recurrence profiles –averaged for all dyads (original empirical data versus randomized/baseline data).

that there may be nested or repeated measures ascribable to some identifiable sources contributing to this error component (different participants, different items and so on). In this case we have repeated measures of recurrence rate for each of the dyads analyzed, which are clearly correlated. By taking into account the idiosyncratic variation due to individual differences (the dyads) we can estimate a better model for the fixed effects represented by the posed factors, in this case Visit and Profile. While traditional analyses that average such influences (e.g. across the multiple measures collected from the same dyad) may be legitimate, mixed models give researchers more flexibility and take the full data into account.

The results of the full model (RR ~ Visit * Profile + (Visit + Profile | Dyad)) are described in Table 2.

The results showed that there was a significant effect of Profile, which means that there is a significant difference between the empirically found RR and the baseline. However, the effect of Visit was not significant ($p = 0.283$), indicating that the average RR did not significantly differ across visits, whereas the interaction effect between Profile and Visit was significant ($p < 0.001$). This means that while there is no evidence for an effect of Visit by itself, there is evidence for an effect in combination with Profile. In particular, after running a simple effects analysis, we can conclude that there is a significant difference between Profiles (original vs. baseline) at the first level (visit 1) of the factor Visit ($t(9.08) = 3.87$; $p = 0.004$), while the difference is only marginally significant at the second level of the factor (visit 2: $t(9.08) = 2.08$; $p = 0.067$), which substantiates, in statistical terms, what we could already observe in the two panels of Fig. 5.

3.2. Individual analyses

When inspecting the DCRPs of each individual dyad, large inter-individual differences were present. Some sessions showed no signs of synchronization at all (see Fig. 6: Jonathan/first visit for an example), whereas others showed diverse patterns of synchronization. In many cases changes between visit 1 and visit 2 were visible (see Fig. 7 for some examples). In total, in 7 out of 10 dyads a general decrease in RR was visible, which suggests less similarity in movements.

There was a high degree of idiosyncrasy, which we attempted to interpret in a synthetic way by describing the main characteristics of the profiles. On the basis of visual inspection, we evaluated whether the profile shows indications of global synchronization, whether a peak in synchronization occurred, and whether a change can be observed between visit 1 and 2. A summary of these description is given in Table 3.

Based on these observations, four out of ten mother infant-dyads can be described as “organizers”. These dyads are either moving from a “no synch”-pattern to an infant leads or synch pattern, or moving from an infant leads pattern to an even stronger infant leads pattern. Two other dyads were already organized in the first visit, but changed their temporal organization over time, from a pattern in which one of the two was leading, to a synch pattern. We can call them “re-organizers”. Furthermore, there were two “disorganizers” (dyads changing from any synchronized pattern to a non-synchronized), and finally two dyads who we call “not organized” because they show no coupling or synchronization at all. We also checked whether there was a relation with feeding history (breast, bottle or combined) but there seemed to be no such pattern. We noted that the two disorganizers were also infants who had changed seating position between visits (either from lap to baby seat or from baby seat to high chair). In addition, both dyads who were characterized as ‘disorganizers’ and one of the ‘not organized’ dyads (Charlotte) had a change in the place of the feeding bowl (in the hand vs on the table).

4. Discussion

In this study, we explored co-regulation of synchronized bodily movements of caregiver and infant during the introduction of solid food. The group analysis showed that there was an effect of Profile, which means that the movements of the infant’s face and the hand of the caregiver are already synchronized at the moment of the introduction of solid food in the sense that they are different from random movements. This was expected because of the goal-directed nature of the feeding situation and the natural constrains that follow from it. On average, the movements were initially closely synchronized, whereas the infant was leading by approximately 1 s at this later point in time. This may be caused by anticipatory behavior of the infant (Reddy, 2015) reactive behavior of the caregiver

Table 2
Results of the Linear mixed effects model (full model) with Visit and Profile as coefficients.

Fixed effects					
	Estimate	Std. Error	df	t	p-value
(Intercept)	1.63e-01	6.34e-03	9.00	25.65	< 0.001*
Visit	-5.53e-03	4.84e-03	9.02	-1.14	0.283
Profile	8.96e-03	2.32e-03	9.08	3.87	004*
Visit* Profile	-4.15e-03	3.12e-04	6009	-13.30	< 0.001*
Random effects					
Groups	Name	Variance	SD		Correlation
Dyad	(Intercept)	4.02e-04	0.02004		
	Visit	2.34e-04	0.01529		-0.29
	Profile	5.32e-05	0.00730		0.05/– 0.49
Residua		3.67e-05	0.00606		

* = $p < 0.05$

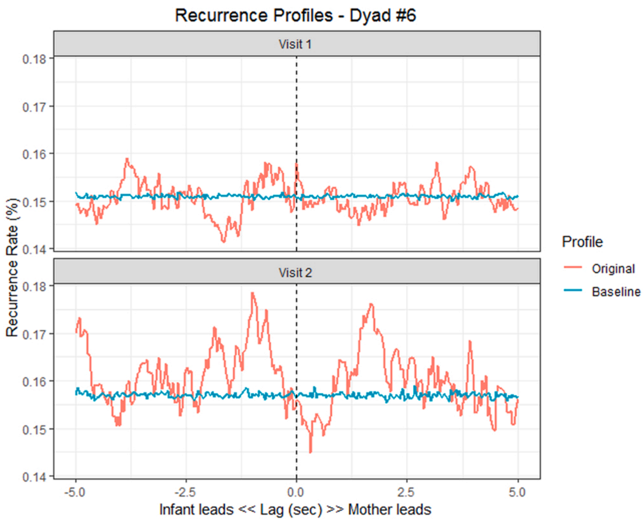

Fig. 6. DCRPs of Jonathan.

(Rączaszek-Leonardi et al., 2013) or both.

The results also showed there was a difference between the original data and the baseline at Visit 1, while the difference is only marginally significant at visit 2. This suggests that the patterns of synchronization undergo some sort of change between the moment of the introduction and several weeks later. These findings are in line with earlier results from studies on weaning that showed that caregivers and infants co-regulate their behaviors in this time frame in various ways. For instance, dyads also show a general increase of 'smooth' feeding actions (van Dijk, Hunnius, & van Geert, 2012; van Dijk, van Voorthuizen, & Cox, 2018) and an increase of spontaneous mouth opening by the infant (Toyama, 2014). This implies that the introduction of solid foods triggers a process of co-regulation in many different modalities, that include not only different types of feeding behaviors, but also the bodily movements of caregiver and child during feeding. The suggestion that the infant's movements lead the movement of the caregiver particularly would fit with earlier observations of Rączaszek-Leonardi et al. (2013) demonstrating how mothers give meaning to infants' actions. It supports the theoretical view that caregivers often enact actions around the baby's natural moves and co-create meaningful patterns of interaction (ibid.). Such interpretations can be seen as extending an ecological psychology approach (Heft, 1989; Gibson, 1950, 1966; Reed, 1996)() into the social domain, showing that early forms of intentionality arise from initial 'moving with others', which after repeated experiences to become 'acting with others'.

Within the general pattern that could be distinguished at the group level, we observed large inter-individual differences in synchronization. In fact, the 'general' pattern that infants would increasingly lead the movements could hardly be generalized to any of the individual dyads. Instead, we observed at least four distinctive characterizations: some dyads showing no signs of co-regulation at all, and others showing increasing, decreasing or re-organizing patterns. In the current study, four dyads (Femke, Jonathan, Charlotte, and Matteo) did not show any signs of organization or disorganized over time. The other six dyads were quite different from each other as well, but were similar in the sense that they all did show signs of organization or re-organization. Multiple (interacting) variables may have influenced the dyads organization caused why the dyads have organized in the way they did and their interplay might explain the interindividual differences in synchronization patterns. In fact, it is likely that situational factors in the immediate context in which the feeding takes place function as 'constraints' on the on-the-spot synchronization process and influence the co-regulation over time. First, a likely candidate to contribute to a lack of synchronization between visits is change in seating position. We had already noted that the two 'disorganizers' had both changed seating position between visits (lap, baby seat, high chair) and both changed the location of the bowl containing the food (hand versus table). The latter change was also observed in one of the 'not organized' dyads. This suggests that changes in the immediate context of feeding (i.e. the location of the individuals in relation to each other and the food) can influence the process of movement synchronization. However, the process of selecting, over time, the best settings (i.e. the best configuration in which the feeding takes place), is a part of the process of feeding in infancy. This means that the causal paths between parent-child synchronization on the one hand and the immediate setting of the feeding are complex. Secondly, we may speculate that the amount of food refusal by infant may also greatly contribute to the interindividual differences in synchronization. Food refusal can be particularly challenging for caregivers, and may cause a breakdown of synchronization (van Dijk, van Voorthuizen, & Cox, 2018). In an earlier analysis (van Dijk, Hunnius, & van Geert, 2009), we computed the frequency of food refusal in the first four minutes of each meal. When we inspected these percentages for each of the observations in the current study, we noted that only the observations of Femke (both visit 1 and 2), Mateo (visit 1 and 2), Jonathan (visit 1), and Bowen (visit 2) these were larger than 4%. Femke had a particularly high refusal rate (33% and 59% of bites were refused for visit 1 and 2 respectively). However, one of the dyads who was characterized as 'disorganizer' was Charlotte and she did not show *any* food refusal in the earlier analysis. Also, Bowen was characterized as 'reorganizer', and he refused more than 8% of all bites in the second visit, which is relatively high. This suggests that food refusal may relate to synchronization or the lack of it, but it does not explain all individual differences.

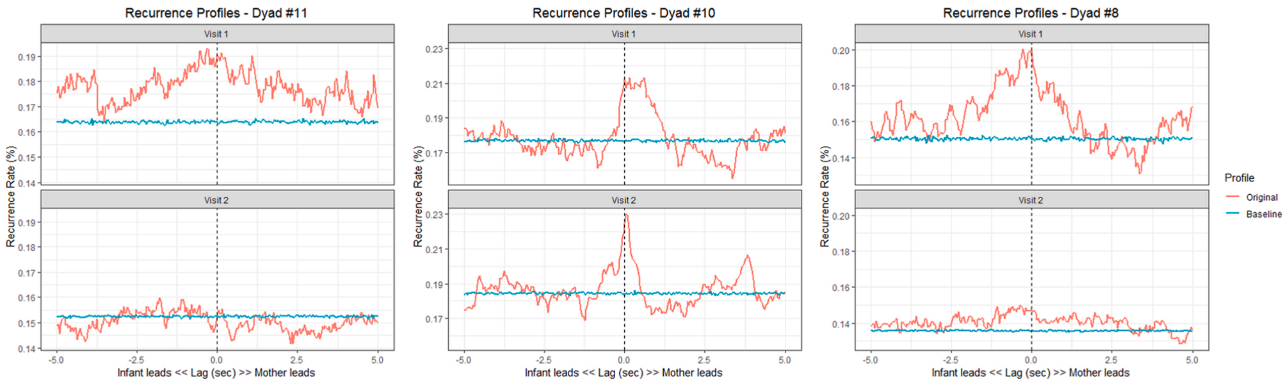

Fig. 7. DCRPs of Floris, Milou and Charlotte.

Table 3
Qualitative description based on visual inspection of the DCRPs of all individual dyads (including feeding history).

ID		Visit 1	Visit 2	Type	Change in seating V1-V2
8	"Charlotte"	synch	around baseline, no synch	disorganizer	yes
11	"Matteo"	synch	around baseline, no synch	disorganizer	yes
4	"Femke"	no synch	no synch	not organized	no
6	"Jonathan"	around baseline, no synch	around baseline, no synch	not organized	no
3	"Floris"	infant leads	infants leads with peak	organizer	no
5	"Ivan"	no synch	infant leads	organizer	no
7	"Lola"	around baseline, no synch	synch	organizer	no
9	"Lewis'"	around baseline, no synch	infant leads	organizer	no
1	"Bowen"	infant leads	move towards synch	re-organizer	yes
10	"Milou"	mother leads	synch	re-organizer	no

Notes. "Infant/mother leads" refers to a generally higher RR on the left/right side of the LOS, "synch" refers to the presence of a peak at the LOS, "no synch" refers to a flat or chaotic profile.

When we inspected the way in which the dyads *did* synchronize, we also noted some clear differences with regard to timing of bodily movements. In some of these observations, the infant was leading, whereas in others the movements were 'in synch' (that is: infant and mother were moving in the same direction at the same exact moment). In only one observation the mother was leading the movements. These findings are in line with findings from earlier analyses of the same dataset. In the analysis reported in van Dijk, van Voorthuizen, and Cox (2018), we included repeated measures of a subset of five dyads from the original dataset and also observed large individual differences in the behavioral matches and mismatches in the feeding interaction. These behavioral matches were defined in terms of qualitative behaviors of the mothers and infants (e.g. moving the spoon towards the mouth combined with mouth opening, retracting the spoon combined with infant refusing, etc.). It is worth noting that three of the dyads (Milou, Femke and Floris) from the study reported in van Dijk, van Voorthuizen, and Cox (2018) were also included in the current analyses. With regard to infant Milou and her mother, the earlier analysis showed that mother was leading the interaction with regard to the behavioral matches. For the bodily movements, we observed that Milou's mother was also initially leading, but that over time the movements became more closely synchronized in time. In contrast, for Femke and her mother, the earlier analysis showed that the timing of matching behaviors remained variable, suggesting that Femke and her mother were still exploring. This fits with the current result that the movements of Femke and her mother did not exhibit any type of movement synchronization. Finally, for Floris, the previous analysis demonstrated that mother was strongly leading the interaction with regards to the behavioral matches, which became less pronounced over time. In the current analysis, this was the other way around: it was Floris' movements that were initially leading. This suggest that Floris and his mother initially had a certain task division during feeding (Floris initiated movements, mother initiated the feeding actions such as offering, entering the mouth, and pulling back), which changed into a more 'in synch' interaction over time. These case-by-case comparisons illustrate that the combination of dyadic bodily movements analysis with other feeding behaviors description provides a broader perspective on the (changing) feeding system whereas in some cases, but not all, the results converge into a general pattern. Despite the individual variability and the apparent difficulty in finding regularities we have to note that the method we used allows us to ask meaningful questions and make meaningful observations about the overall coordination while feeding.

Earlier studies have already indicated that interindividual differences are characteristic of feeding and eating in infancy (Young & Drewett, 2000). The current study showed that this is also the case for the synchronization of bodily movements during feeding. It may be argued that the observed differences in the current study are also due to uncontrolled feeding environment settings. However, the results are compatible with a complex dynamic systems perspective that feeding interactions self-organize into qualitatively different patterns due to many different parameters within the system (see van Dijk (2021)). As such the emergence of coordinated feeding interactions resides in the ongoing interactions among the components of the system that are observable in the moment-to-moment actions of the individuals. This means that different individual and contextual factors lead to qualitatively different configurations within the interpersonal dynamics (Paxton & Dale, 2017). We have discussed above that there are two factors in the immediate context of feeding –seating position changes and food refusal by the infant– that may have contributed to the observed interindividual differences in synchronization patterns. We can also speculate on the role of various other individual variables such as differences in the momentary emotional state of the infant and mother (mood, tiredness, etc.).

A more distal factor that may influence the synchronization of bodily movements during feeding is the cultural background of the dyads. A recent study has demonstrated that differences exist between Scottish and Japanese mother-infant dyads, with regard to the temporal structure of the feeding interactions (Negayama et al., 2021). More specifically, the Japanese mothers displayed relatively long and deliberate movements in the way moved the spoon towards the infant's mouth, whereas the Scottish mothers did this more quickly and showed greater initiative and leadership in the feeding interaction. Though it is unclear how this relates to the finding of the current Dutch sample, it is reasonable to assume that (cultural and individual) differences exists in caregiver's tendency to initiate actions or follow the actions of the infant which might also influence patterns of synchronization.

It should be stressed that the current study was explorative in nature and further research on the topic is certainly needed. The transition to solid food is an important milestone in early development and is relevant for the way children relate to food and eating later in life. This transition also necessitates action coordination of both parties and is thus one of the first true "joint actions" with a clear division of labor. This means that it might be a particularly interesting ground for studying development of participation, agency and development of early relations. In addition, feeding is an indispensable context for studying caregiver-child synchronization because of the importance of feeding for survival and the way this forms a foundation in infant-caregiver bonding (Else-Quest et al., 2003). Because of the idiosyncratic nature of the feeding dynamics such future studies should include larger samples. The small sample of the current study prohibited any conclusions with regard to which variables may have contributed most to the emergence of the characteristic patterns of synchronization (or lack of synchronization). Organizing which factors (situational, individual, cultural) are most important in explaining the inter-individual difference should be a topic of further work and exceeds the scope of this paper. In the current study, we already found remarkable inter-individual differences. It may be speculated that many more developmental patterns might exist, and that these patterns relate in some way to later eating behavior. Aside from the small sample, another limitation of the current study is the fact that the videos that were used were not collected for the purpose of movement analyses. As a result, many of these videos in the original dataset had to be excluded for the current study, due to hands moving in and out of view, inconvenient camera positions, etcetera. For future studies on bodily movements, it may be advised to standardize the feeding situation at least to some degree with regard to feeding position (baby seat, high chair, lap), angle of the movements, and camera position. In the current study, these differences may have also contributed to the observed differences between dyads.

Another limitation is that only two feeding sessions per dyads were included in the analyses due to the fact that many of the videos could not be used for the movement tracking. Earlier studies have shown that not only do individual dyads differ from each other, they also differ from *themselves* at a different moment in time (van Dijk, Hunnius, & van Geert, 2012). Immediately after the introduction of solid food, day-to-day variability in eating and feeding behavior is typically large, and over time the interactions stabilize in most cases. This shows that information on the day-to-day (or meal-to-meal) variability is important because it provides insight on the degree to which the synchronization patterns are stable over time or whether they are still rather vulnerable. Studies with more repeated measures of feeding interaction are therefore indispensable. Such studies should also aim to understand the degree of stability of the characteristic synchronization patterns over time and possible associations with feeding later in life. It should be noted that the weaning period involves a rather long period of combined feeding (Drewett & Young, 1998), in which infants increasingly start self-feeding and start eating more ‘adult like’ meals. At this time, different types of feeding and eating (liquid, spoon/manual, self/caregiver-led feeding) co-exist. It is to be expected that during this period, the interaction between caregiver and infant remains highly adaptive to these changes.

In conclusion, the results from this explorative study suggests that during the introduction to solid food, bodily movements of infant and caregiver are synchronized to a certain degree. However, the way in which they are synchronized and how this changes over time varies from dyad to dyad. This underlines the embedded, embodied, and enacted nature of feeding.

CRediT authorship contribution statement

Marijn van Dijk: Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Giuseppe Leonardi:** Conceptualization, Methodology, Formal analysis, Writing – review & editing. **David López Pérez:** Methodology, Formal analysis, Writing – original draft, Writing – review & editing. **Joanna Rączaszek-Leonardi:** Conceptualization, Writing – original draft, Writing – review & editing.

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