





“Dancing” Together: Infant–Mother Locomotor Synchrony

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Pre-mobile infants and caregivers spontaneously engage in a sequence of contingent facial expressions and vocalizations that researchers have referred to as a social “dance.” Does this dance continue when both partners are free to move across the floor? Locomotor synchrony was assessed in 13- to 19-month-old infant–mother dyads ($N = 30$) by tracking each partner’s step-to-step location during free play. Although infants moved more than mothers, dyads spontaneously synchronized their locomotor activity. For 27 dyads, the spatiotemporal path of one partner uniquely identified the path of the other. Clustering analyses revealed two patterns of synchrony (mother-follow and yo-yo), and infants were more likely than mothers to lead the dance. Like face-to-face synchrony, locomotor synchrony scaffolds infants’ interactions with the outside world.

Behavioral synchrony is fundamental to social interaction (Bernieri, Reznick, & Rosenthal, 1988; Condon & Ogston, 1967; Kendon, 1970; Marsh, Richardson, Baron, & Schmidt, 2006). Precise coordination with a social partner underlies the ability of two children to time the swings of their jump ropes in double-dutch, campers to paddle a canoe in a straight line, and friends to pivot a couch around the landing of a flight of stairs. Ballroom dancing is perhaps the clearest example—both partners must maintain temporal and spatial synchrony as they move across the dance floor.

Behavioral synchrony often emerges as the result of a shared goal, but it can also occur unintentionally (Schmidt & O’Brien, 1997). Indeed, adults are so sensitive to each other’s behaviors that partners spontaneously synchronize their gait while walking (Zivotofsky & Hausdorff, 2007), their postural sway while speaking (Shockley, Santana, & Fowler, 2003), their to-and-fro motions while sitting in rocking chairs (Richardson, Marsh, Isenhower, Goodman, & Schmidt, 2007), and can even form stable patterns of four-legged coordination when visually or mechanically coupled as a two-person “horse” (Harrison & Richardson, 2009). Intentional or not, behavioral synchrony requires the ability to coordinate perception and action. One or both partners

must have visual, tactile, or auditory access to the other’s behavior and move accordingly (Demos, Chaffin, Begosh, Daniels, & Marsh, 2012; Richardson et al., 2007).

Although behavioral synchrony underlies many forms of social interaction, its development has been studied primarily during stationary, face-to-face interactions between infants and caregivers or other adults (Cohn & Tronick, 1987; Cuadros, Hurtado, & Cornejo, 2019; Kaye & Fogel, 1980; López Pérez et al., 2017; Stern, 1971, 1974). While held in their mother’s arms or seated across from one another, pre-mobile infants and their caregivers spontaneously engage in a sequence of contingent facial expressions and vocalizations that researchers have referred to as a social “dance” (Bernieri et al., 1988; Feldman, 2007; Harrist & Waugh, 2002; Jaffe, Beebe, Feldstein, Crown, & Jasnow, 2001; Provenzi, Scotto di Minico, Giusti, Guida, & Müller, 2018; Stern, 1997; Yale, Messinger, Cobo-Lewis, & Delgado, 2003). Infants are acutely sensitive to these contingences and become distraught when the dance is disrupted. If mothers stop responding and present a frozen “still face,” infants fuss, cry, and eventually disengage (Tronick, Als, Adamson, Wise, & Brazelton, 1978; Weinberg & Tronick, 1996). Conversely, when mothers smile, make exaggerated facial expressions, and bob their heads, infants are more likely to smile, vocalize, and laugh (Kaye & Fogel, 1980).

Like most dances, the coordination between partners starts out a little messy. Early on, asynchrony

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is more common than synchrony (Tronick, 1989). Typically developing 3- to 9-month olds and their mothers spend more than 70% of their interaction time in mismatched states and cycle frequently between periods of coordination and discoordination. “Interactive repairs” (i.e., transitions from mismatched to matched states) are therefore characteristic of infant–mother interactions (Tronick & Cohn, 1989). With development, coordination between partners increases (Tronick & Cohn, 1989), and the time to repair interactive errors decreases (Feldman, Greenbaum, & Yirmiya, 1999). Of course, infants and mothers do not always aim to behave in synchrony. Infants can decide to engage with or disengage from their mothers (Beebe & Stern, 1977), and partners can have differing interactional goals (Ruvolo, Messinger, & Movellan, 2015). Thus, descriptions of infant–mother interactions as coordinated, reciprocal, synchronous, coherent, or dance-like aim to characterize periods of time when things, in Tronick’s (1989) words, are “going well” (pg. 115).

Developmental changes in face-to-face synchrony accompany changes in infants’ motor skills (Feldman, 2007). Around 2–3 months of age, before infants can hold up their heads or sit unsupported, they begin to demonstrate the repetitive, rhythmic behavioral cycles characteristic of face-to-face interactions (Beebe, 1982; Cohn & Tronick, 1988; Feldman, 2007; Kaye & Fogel, 1980; Messer & Vietze, 1984; Stern, 1971, 1974; Trevarthen, 1979; Weinberg & Tronick, 1996). For such young infants, behavioral synchrony is necessarily limited to facial expressions, vocalizations, and patterns of gaze. These early interactions are considered bidirectional, but asymmetrical—mothers are generally considered responsible for maintaining dyadic synchrony (Beebe et al., 2016; Harrist & Waugh, 2002). Although infants can attune to their caregivers, infants tend to drive the interaction: Infants behave and mothers respond (Beebe et al., 2016; Chow, Haltigan, & Messinger, 2010; Cohn & Tronick, 1988; Van Egeren, Barratt, & Roach, 2001). As infants acquire postural and manual skills between 3 and 9 months of age, infants and mothers look less at each other and begin to jointly focus their attention on objects (Bakeman & Adamson, 1984; Feldman, 2007). This period is marked by increased variability in who leads and who follows and reflects a more mutual pattern of synchrony where both partners respond to each other’s behaviors (Feldman, Greenbaum, Yirmiya, & Mayes, 1996; Feldman et al., 1999; Kaye & Fogel, 1980).

Although the onset of independent mobility is an important milestone in the development of both motor and social behavior (Adolph & Hoch, 2019; Campos et al., 2000), previous studies did not quantitatively analyze whether or how locomotor actions are synchronized when both infants and mothers are mobile. This omission is striking because locomotor skills dramatically alter infants’ opportunities for social interaction (Karasik, Tamis-LeMonda, & Adolph, 2011). Pre-mobile infants can only interact with those in sight or in earshot. But after infants can crawl or walk, they become true social partners who can travel across the room to initiate social interactions or reject them. What happens to infant–mother synchrony after infants become mobile and both partners are free to move around the “dance floor?”

There are good reasons to suspect that behavioral synchrony might differ between stationary and mobile interactions. Coordinating locomotor behavior poses practical constraints. To communicate effectively, caregivers and infants must distance themselves appropriately to keep the other in view (Yamamoto, Sato, & Itakura, 2019) or have a good guess about where their partner is going. However, compared to stationary interactions where mothers and infants are often seated face-to-face, mobile mothers and infants rarely look at each other (Franchak, Kretch, & Adolph, 2018). When free to move in a large laboratory playroom, mothers look at infants’ bodies about 50% of the time and infants’ faces about 30% of the time. Infants look at their mothers even less: 15% of the time to mothers’ bodies and less than 5% to mothers’ faces. Instead, infants look at toys and other objects in the playroom.

Locomotor synchrony is further complicated by differences in infant–mother body size. Infants are smaller than adults, so their steps are necessarily shorter, and it takes them longer to cover the same ground. Thus, infants must take more steps to keep pace with their mothers, or mothers must move excruciatingly slowly to maintain proximity with their infants. And, as any parent of a toddler knows, infants move more than their caregivers. Prior work confirms that infants accumulate more distance, cover more area, and interact with more objects than their mothers while dyads play together, and the distance between partners steadily increases from pre-crawling to independent walking (Rheingold & Eckerman, 1970; Thurman & Corbetta, 2017). However, whether and how infants and mothers coordinate their locomotor activity is unknown.

Current Study

As a first step, we compared the accumulated locomotor activity of thirty 13- to 19-month-old infants and their mothers during free play in a large laboratory playroom (Figure 1A). If infants and mothers are synchronized, dyads' accumulated locomotor activity should be correlated. However, accumulated measures of locomotor activity do not necessarily reflect synchrony in real time. Indeed, each partner could accumulate related amounts of locomotion asynchronously—the infant breakdancing stage left and the mother pirouetting stage right, both dancing furiously, but to completely different beats. Alternately, mothers and infants might not move together at all—partners might take turns sitting out the dance while the other goes solo. To describe the real-time nature of infant–mother locomotor synchrony, we must also know how the partners move together in space and over time. Thus, we digitally tracked the step-to-step spatial coordinates of both infants and mothers (Figure 1B).

We used time-series analyses to test the real-time spatiotemporal relations between infants and

mothers. First, we calculated the moment-to-moment distance between infants and mothers by digitally tracking their spatial coordinates. If partners remained close throughout the session, we can infer that they moved in synchrony because they visited similar locations at similar times. We also asked whether the spatiotemporal sequence of each infant's path was most similar to his or her own mother's path using dynamic time warping. High similarity between dyads indicates that infants and mothers moved in synchrony because they visited similar locations in a similar order.

Finally, we investigated whether one partner was responsible for controlling the dyad's movements as they moved through the playroom—that is, whether infants or mothers were more likely to lead the dance. Even when partners are synchronized, one partner may be more likely to lead and the other to follow. Thus, we examined three forms of leading and tested whether the leading partner differed among dyads. First, we examined how infants and mothers changed the distance between each other. We identified different patterns of synchrony by clustering dyads into groups based on which partner was primarily responsible for increasing the

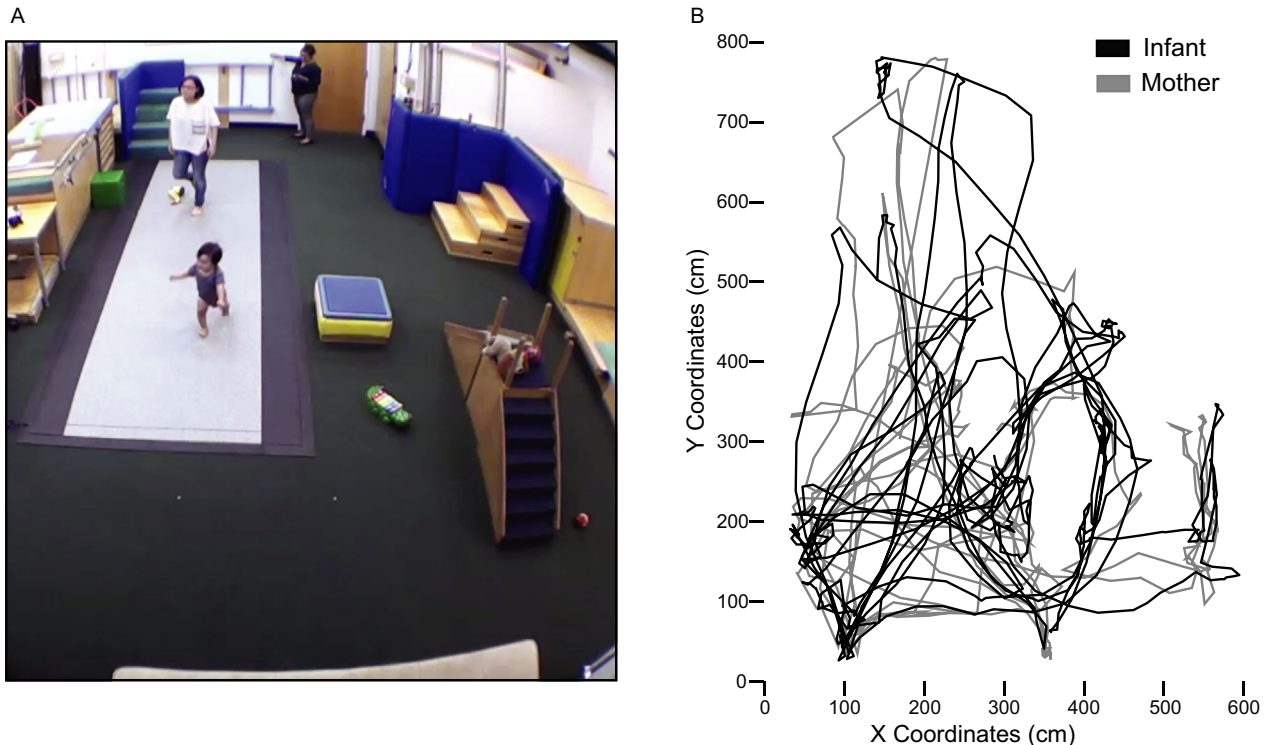


Figure 1. Experimental procedure. (A) Video frame from exemplar infant and mother in the playroom. (B) Exemplar plot of each partner's location in the room over the 20-min play session. Data are drawn from a "bird's eye" view. Overlap between lines signifies both members of the dyad visited the same location.

distance between partners (leading), and which partner was primarily responsible for decreasing the distance between partners (following). Second, we used cross-recurrence plots (Eckmann, Kamphorst, & Ruelle, 1987) to test whether one partner was more likely to initiate (lead) periods of joint movement (i.e., times when both partners were in motion). Third, we used Granger causality (Granger, 1969) to test whether one partner's spatial coordinates could predict the future location of the other during periods of joint movement (i.e., whether one partner led when both were in motion). Because the current study investigated locomotor synchrony, a novel domain of infant–mother synchrony, our hypotheses were non-directional, and all analyses were exploratory.

Method

Data Sharing

Videos of each dyad's play session and annotated coding spreadsheets are shared with authorized investigators (with caregivers' permission) in the Databrary digital library (<https://nyu.databrary.org/volume/943>). Exemplar videos of different types of infant–mother locomotor synchrony, the video coding manual, and the flat file processed data that support the findings are posted publicly in the Databrary volume. The code for the analyses is available publicly in the Databrary volume and on *github* (<https://anonymous.4open.science/r/d84b2b42-f6ce-4c6c-95ea-f555c97132eb/>).

Participants

We recruited 30 walking infants (16 girls) between 12.89 and 19.53 months of age ($M = 15.86$) and their mothers from maternity wards of local hospitals in the New York City area. Families visited the laboratory between October 2013 and March 2016. From parental report, 18 infants were White, 1 was Black, 2 were Asian, 7 were multiple races, and 2 infants' races were not reported; 6 infants were Hispanic or Latino and 1 infant's ethnicity was not reported. We used census data and families' home address to determine the mean family income for their zip code ($M = \$116,191$, range = \$44,634–\$214,946). All mothers (age $M = 34.85$ years, range = 28.29–48.68) identified as their infant's primary caregiver. Mothers reported their infant's walking experience during a structured interview using calendars or cell phone photos and videos to support their memories (Adolph et al., 2012). Walking experience was dated

from infants' first success at walking 3 meters independently without stopping or falling until the test date ($M = 2.57$ months, range = 0.23–9.01). Infants' heights ranged from 72.40 to 90.75 cm ($M = 78.62$) and mothers' heights ranged from 156.20 to 181.20 cm ($M = 164.47$). Families received a framed photograph and tote bag as souvenirs of participation. Participants in the current study are a subset of 97 infants from a larger data set, whose gait data were reported previously in Lee, Cole, Golenia, and Adolph (2018) and shared in the Databrary library (<https://nyu.databrary.org/volume/89>). The free play data and mothers' behavior were not previously reported. Prior to analysis, we selected the subset of infant–mother dyads quasi-randomly to achieve a wide spread in infant age.

We observed infants and their mothers for 20 min in a large laboratory playroom (6 × 8 m) filled with toys, a couch, and elevations designed for climbing (risers, pedestal, slide with stairs, and platforms; Figure 1A). For six infants, the slide was replaced with a large wooden platform. Mothers were instructed to play with their infants as they normally would at home. Sessions began with the toys in designated locations. Infants and mothers could move freely throughout the room. We aimed to collect 20 min of free play data. However, some infants had shorter sessions because they became fussy ($M = 20.43$ min, range = 15.32–23.44).

Following the free play session, we collected standard measures of walking skill. An experimenter placed infants at one end of a pressure sensitive mat (1.21 × 4.88 m, 120 Hz, 4 sensors/in.², protokinetics.com) and mothers encouraged infants to walk over the mat using toys and snacks as lures for six trials. We analyzed the two fastest walking trials as in Lee et al. (2018). Walking skill data from one infant were excluded due to equipment failure. As expected, mothers' reports of walking experience were validated by high correlations with standard measures of infant walking skill (speed, step length, step width; $rs(27) = .81, .70, \text{ and } -.74$, respectively, $ps < .001$; see Table S1). With walking experience, infants moved faster and took longer, narrower steps.

Video Coding

Four camera views captured dyads' location in the playroom: two fixed side cameras and one fixed overhead view recorded dyads from different vantage points. An experimenter followed dyads' activities using a handheld camera from the periphery of the room but did not interact with infants or mothers. Videos from the four camera views were

synced into a single frame using vMix software (vimix.com). Coders scored infants' and mothers' actions frame-by-frame using Datavyu (datavyu.org) video-coding software that links the onset and offset of user-defined events with the video.

A primary coder identified bouts of walking, knee walking, or crawling steps, although walking was predominant for both mothers (72% of all bouts) and infants (79% of all bouts). During stationary periods between bouts, both feet and knees were on the ground for at least 0.50 s. A second coder scored 25% of the data for each partner in each dyad to assess inter-observer reliability. Coders agreed on locomotor posture for 98% of bouts, all Cohen's κ coefficients $\geq .96$, $ps < .001$. For steps per bout, bout duration, and total number of bouts, correlations between coders were high; $rs \geq .98$, $ps < .001$. Disagreements between coders were resolved through discussion. Locomotion was only coded when infants were on the floor to make the measures comparable between infants and mothers. On average, infants spent 38.05% ($SD = 16.52\%$) of the session on elevations. These times were excluded from the session duration for measures of time in motion. Thus, for infants, percent time in motion, steps per hour, and distance per hour were calculated from the total amount of time spent on the floor (both moving and stationary). Mothers never locomoted on elevations, so percent time in motion, steps per hour, and distance per hour were calculated from the total session duration. We compared infants' and mothers' locomotor activity using paired samples t-tests and correlations (Figure 2).

Dyads' Spatial Coordinates

We tracked infants' and mothers' step-to-step location using the view from a stationary overhead video camera. Coders used the MATLAB DLTdv digitizing tool (Hedrick, 2008) to mark the location of the knees or feet for each step for each partner as in Hoch, O'Grady, and Adolph (2019). Between steps, infants' and mothers' locations were interpolated every 100 ms. These coordinates were used to generate each partner's locomotor path (Figure 1B) and to calculate the distance between partners (Figure 3). We also calculated the unique amount of area infants and mothers explored by amassing the area covered by a 15-cm radius circle centered between the feet or knees. Movement to a new part of the room that had not been previously covered was counted as an addition to the cumulative area explored over the course of the session. We interpolated infants' paths on elevations based on their starting and ending locations on the floor.

Path Similarity Using Dynamic Time Warping

Our goal was to compare every infant's path to every mother's path. However, because session durations differed among dyads, paths (x, y time series) from different dyads had different durations. Thus, to compare paths across dyads, we used a nonlinear sequence alignment algorithm called "dynamic time warping" (Berndt & Clifford, 1994), which allows for similarity to be measured between two time series. Dynamic time warping is widely used in machine-learning applications to compare time series with different durations (Muda, Begam, & Elamvazuthi, 2010; Myers & Rabiner, 1981; Tomasi, Van Den Berg, & Andersson, 2004).

For each infant–mother dyad, we tracked the (x, y) coordinates of each partner throughout the session in 100-ms intervals, creating two time series, P_{infant} and Q_{mother} of length n and m , respectively:

$$P_{\text{infant}} = [(px, py)_1, (px, py)_2, (px, py)_3 \dots (px, py)_n] \quad (1)$$

$$Q_{\text{mother}} = [(qx, qy)_1, (qx, qy)_2, (qx, qy)_3 \dots (qx, qy)_m] \quad (2)$$

where $(px, py)_i$ is the infant's spatial coordinates at time point i , and $(qx, qy)_j$ is the mother's spatial coordinates at time point j . We aligned the two sequences and constructed an $n \times m$ matrix where the (i th, j th) cell of the matrix contains the Euclidean distance $d(pi, qj)$ between the two points pi and qj . We then calculated the accumulated distance between infants and mothers across the session. Next, we applied the dynamic time warping algorithm to find the minimum cumulative distance between each pair of trajectories based on the constructed matrix. We defined the similarity index of each pair as 1 over the cumulative dynamic time warping distance divided by the normalization factor k (the length of the dynamic time warping path) to control for session duration (for examples of high and low similarity, see Figure S1).

After completing this procedure for all combinations of infants and mothers, we constructed a 30×30 similarity matrix in which the (i th, j th) cell is the similarity index of infant i and mother j (Figure 4A). To examine the level of spatiotemporal synchrony between infants and their mothers, we tested whether the highest similarities were located on the diagonal (indicating highest similarity between each infant and his or her own mother).

Clusters Based on Infant–Mother Distance

To test whether dyads could be sorted into groups based on how the partners changed the distance between each other, we used a clustering procedure based on “fast search and find of density peaks clustering” (Rodriguez & Laio, 2014). With this procedure, the number of clusters is derived from the data and is not pre-defined as in other, more common methods such as k -means clustering (Hartigan & Wong, 1979). Thus, we made no assumptions about the number of clusters or the number of dyads per cluster. More than one cluster of dyads would suggest multiple patterns of synchrony, and that the activity patterns of dyads within a cluster are more similar to each other than to the activity patterns of dyads in other clusters.

To calculate the measures used for clustering, we first divided the video into times when the distance between partners decreased (partners moved closer together) or increased (partners moved farther apart), regardless of the magnitude of the change. We then segmented periods of “closer” and “farther” movement into times when only the infant, only the mother, or both were in motion. For each dyad, we then calculated the following input measures: The percentage of “closer” segments where (a) infants moved independently toward their stationary mother; (b) mothers moved independently toward their stationary infant; (c) infants and mothers moved simultaneously and toward each other; and the percentage of “farther” segments where (d) infants moved independently away from their stationary mother; (e) mothers moved independently away from their stationary infant; (f) infants and mothers moved simultaneously away from each other. A segment ended when the distance between partners changed from increasing to decreasing (or vice versa) or when both partners stopped moving. We used these six values as input for clustering (Figure S2A).

Using the six outcome measures, we calculated the four-dimensional Euclidean “distance” between each pair of dyads (visualized in Figure S2B):

$$d_{i,j} = \sqrt{\sum_{i=1}^n (x_i - x_j)^2} \quad (3)$$

where i and j signify two different dyads, n is the number of independent input measures used ($n = 6$ in the current study), and x is the value of the measure. If the distance between dyads is low, the similarity between them is high, and vice versa.

Next, we identified dyads as “group centers.” To do this, we calculated a density coefficient ρ to reflect the number of dyads whose distance from dyad i in the similarity matrix was lower than a certain predefined cutoff distance. We detected this cutoff distance from the data set using the change in entropy with different distance cutoffs. We considered the most reasonable d_c to be the one that provided the lowest value of entropy, where uncertainty is the smallest. This procedure was tested and described in Wang, Wang, and Li (2015).

Formally, a density coefficient ρ was calculated as follows:

$$\rho_i = \sum_{j=1}^m \chi(d_{i,j} - d_c) \quad (4)$$

Then, we sorted dyads in increasing order according to their density coefficients to calculate a distance coefficient δ . This coefficient reflects the minimum distance between each dyad and the dyad with the next highest density. The dyad with the highest density was assigned the maximum value, which we conventionally set as $\delta_i = \max(d_{ij})$. Formally, the distance coefficient was calculated as follows:

$$\delta_i = \min_{j:\rho_j > \rho_i} (d_{ij}) \quad (5)$$

Next, the distance coefficient and the density coefficient were multiplied to create a γ score for each dyad. Thus, high γ scores reflect dyads who had both large density coefficients and large distance coefficients. From the γ distribution of all infants, outliers were chosen as values for which γ was at least 3 SD s above the mean γ . These outliers were chosen as the “group centers” (Figure S2C). That is, many dyads were relatively similar to the group center and the group centers were dissimilar to each other. The number of centers determined the number of clusters identified. Dyads were then assigned to the group center to whom they were most similar (Figure S2D). We visualized similarity among dyads using a 30×30 similarity matrix in which cell i,j is the “distance” between dyad i and dyad j based on the input measures (Figure S2E). Finally, we examined differences in the values used for clustering to describe and label each resulting cluster (Figure 5A; Figure S2F).

Cross-Recurrence Plots

For each infant–mother dyad, we created a cross-recurrence plot to identify joint movements (times

when both partners were in motion), determine which partner initiated each joint movement, and calculate the latency between the onset of movements. Figure 6A shows an exemplar cross-recurrence plot from one dyad (#10). Each time series in the figure shows stationary periods (white) and periods of movement (black) for the infant (x axis) and the mother (y axis) over the course of the session. Regions touching the diagonal indicate joint movements (shown in black). Light gray boxes show lagged movements. White regions represent periods of no movement. The location of the bottom left corner of each black box relative to the diagonal indicates whether the infant or the mother moved first, and the latency of their partner's movement (Figure 6B). Negative latencies (orange bands) denote times when the infant moved first. Positive latencies (green bands) denote times when the mother moved first. We then plotted the pooled distribution of latencies between the partners' movements across all joint movements and calculated the average latency for infants and mothers (Figure 6C).

Granger Causality

We used Granger causality to analyze whether one partner was leading when both were in motion. For each joint movement segment, we concluded that one partner was the "leader" if his or her time series "Granger-caused" the other partner's time series (Barrett, Barnett, & Seth, 2010; Bli-nowska, Kus, & Kaminski, 2004; Granger, 1969). Granger causality uses multivariate autoregressive models to test whether the ability to predict variable A (e.g., the mother's future location) can be improved by incorporating the information contained in variable B (e.g., the infant's location history). For example, if the mother's future location is significantly better predicted by her location history and her infant's location history than her location history alone, this means that the infant's location history contains additional information that helps to predict the mother's future location above and beyond her own location history. In this case, then the infant's location is said to Granger-cause the mother's location (for a tutorial using continuous values see Barnett & Seth, 2014; for a tutorial using discrete binary spike trains or point processes see Xu, de Barbaro, Abney, & Cox, 2020).

For both infants and mothers, causality was calculated on two time series independently—one series represents changes in x coordinates over time,

and the other represents changes in y coordinates over time. Because we assessed causality on the x and y dimensions separately, we added significance restrictions to ensure clear interpretations of leadership. We used four tests per joint movement segment and required that one partner led in the x or y dimension and that the second partner led in neither dimension. Thus, for each joint movement segment, we calculated four F -statistics: F_{inf_x} (infant leading on the x -axis), F_{inf_y} (infant leading on the y -axis), F_{mot_x} (mother leading on the x -axis), and F_{mot_y} (mother leading on the y -axis). We also calculated their corresponding critical values from the F -distribution (based on a significance level of .05): C_{inf_x} , C_{inf_y} , C_{mot_x} , C_{mot_y} . If, for example, we found that $F_{\text{inf}_x} > C_{\text{inf}_x}$ or $F_{\text{inf}_y} > C_{\text{inf}_y}$, and that $F_{\text{mot}_x} \leq C_{\text{mot}_x}$ and $F_{\text{mot}_y} \leq C_{\text{mot}_y}$, we considered the infant the "leader" of this joint movement segment. Infants and mothers could lead in only the x dimension, only the y dimension, or both dimensions. When a leader could not be determined in either dimension (x or y) because neither partner predicted the other, both partners were equally predictive, or the joint movement segment was too short to determine Granger causality, we labeled the segment as "inconclusive leading."

For segments with a conclusive leader, we compared the algorithm's result to human judgments of "leadership" to verify the validity of the analysis. Two human coders—blind to the output of the Granger analysis—watched all algorithm-defined conclusive leading segments and subjectively coded whether the segment was infant led or mother led. Coder 1 was in 93% agreement with the algorithm results, Cohen's $\kappa = .77$, $p < .001$; Coder 2 was in 99% agreement with the algorithm results, Cohen's $\kappa = .95$, $p < .001$; there was 93% agreement between coders, Cohen's $\kappa = .78$, $p < .001$.

Results

Overall, infants spent more time in motion, took more steps per hour, traveled greater distances, and covered more area than their mothers; paired t s ≥ 2.93 , $ps \leq .007$, Figure 2A. However, as shown in Figure 2B, accumulated measures of infant and mother locomotion were highly correlated, suggesting that the partners scaled their locomotor activity to each other, $rs \geq .68$, $ps < .001$. Tables S2 and S3 show infant–mother comparisons and inter-correlations between locomotor measures.

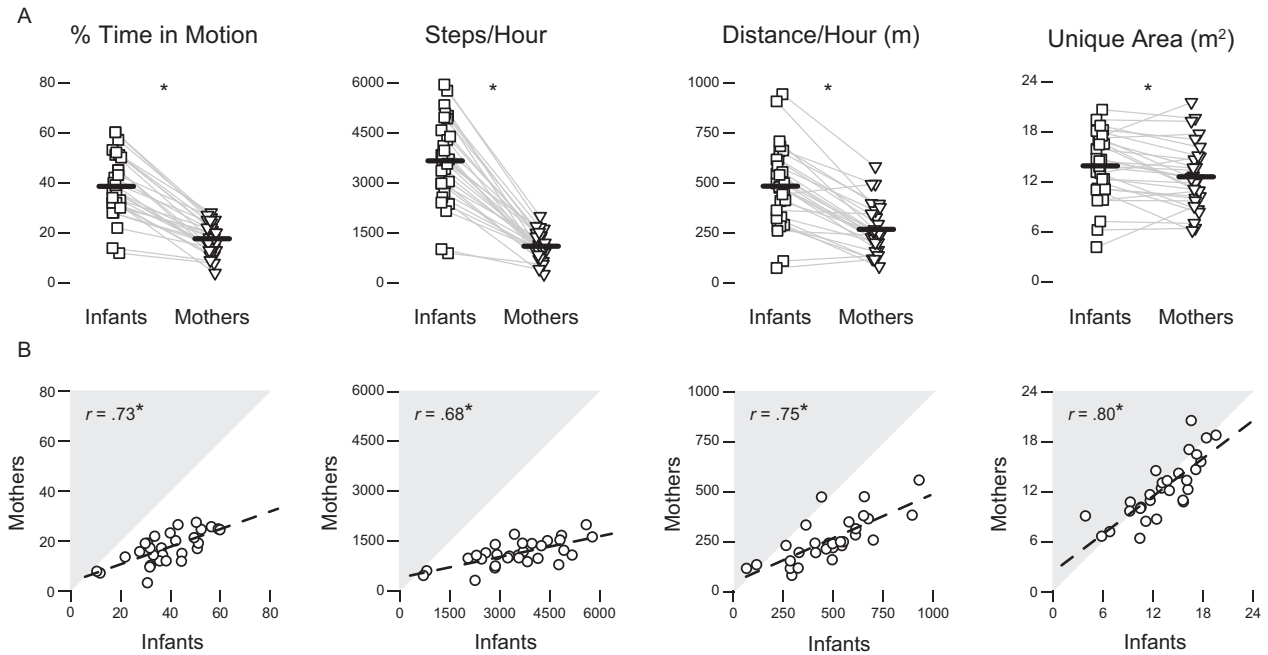


Figure 2. Accumulated measures of locomotor activity (denoted by each column). (A) Differences in locomotor activity between infants and mothers. Partners differed on all measures. Black bars denote group means. Gray lines connect each infant–mother dyad. (B) Correlations between infants’ and mothers’ locomotor activity. Partners were correlated on all measures. Gray diagonals show the identity line.

Real-Time Spatiotemporal Synchrony

Generally, infants and mothers played near each other, and mothers geared their spatial proximity to infants’ safety. Although infant–mother distance varied widely across dyads and within each session (range = 0.37–708 cm), partners maintained relatively close proximity (Figure 3A). When infants were on the floor, dyads were about one and a half adult steps, or five infant steps apart ($M = 120.89$ cm, $SD = 35.69$). However, when infants were on elevations, where presumably the consequences of falling were more serious, dyads were closer together—approximately within mothers’ arm reach ($M = 87.12$ cm, $SD = 35.44$; Figure 3B), paired $t(29) = 6.59$, $p \leq .001$. The average distance between partners on the floor and on elevations was not correlated with infants’ age, walking experience, walking skill, or accumulated locomotor activity, $r_s \leq .32$, $p_s \geq .08$.

Moreover, infants and mothers took similar paths as they moved through the playroom. Using dynamic time warping, we compared the spatiotemporal path of each infant to the spatiotemporal path of all 30 mothers (Figure 4A). High path similarity within dyads indicates that infants and mothers visited similar locations in a similar order

and suggests coordinated locomotion. Low synchrony indicates that partners took different routes. Nearly all (27 of 30) infants’ paths were most similar to their own mother’s paths (dark diagonal in similarity matrix in Figure 4A). The similarity between infants and their own mothers ($M = 0.016$, $SD = 0.005$) was significantly higher than the similarity between infants and all other mothers ($M = 0.009$, $SD = 0.002$), unequal variance t -test, $t(898) = 9.54$, $p \leq .001$. Two infants’ mothers had the second highest similarity to their own infants’ paths, and one infant was an outlier—the similarity of his path to his mother’s path was ranked 24th out of all 30 mothers (see Figures 4A and 4B, dyad #08). Thus, most partners could be matched solely on the basis of their locomotor paths, and high path similarity is consistent with infants’ and mothers’ close proximity during play. Path similarity was not correlated with infants’ age, walking experience, walking skill, or accumulated locomotor activity, all $r_s \leq .33$, $p_s \geq .08$.

Who Led the Dance?

We analyzed three different forms of “leading” and found that infants were primarily responsible for controlling the dyads’ movements through the

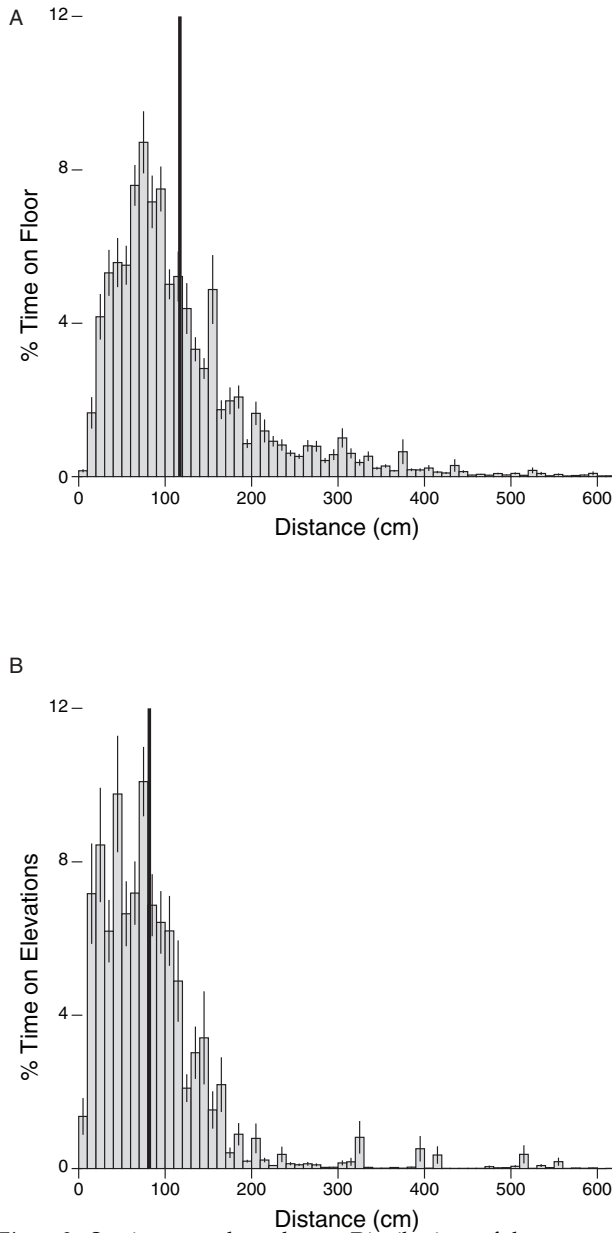


Figure 3. Spatiotemporal synchrony. Distributions of the percentage of (A) floor, and (B) elevation time that dyads spent at each distance from each other. Dyads were closer when infants were on elevations. Error bars denote standard errors in each 10-cm bin, black vertical lines denote means.

playroom. In the first analysis, we examined how infants and mothers maintained proximity. As dyads played together, the distance between them varied due to the movements of one or both partners. Thus, we determined whether infants or mothers were primarily responsible for increasing the distance (leading) or decreasing the distance (following) between partners and whether these roles differed among dyads. Across the data set,

infants' independent movements accounted for a greater percentage of "farther" segments ($M = 63\%$, $SD = 19\%$) than "closer" segments ($M = 38\%$, $SD = 27\%$), paired $t(29) = -4.28$, $p \leq .001$. Conversely, mothers' independent movements accounted for a greater percentage of "closer" segments ($M = 49\%$, $SD = 24\%$) than "farther" segments ($M = 27\%$, $SD = 21\%$), paired $t(29) = 4.43$, $p \leq .001$. When both partners moved simultaneously, their movements accounted for a greater percentage of "closer" segments ($M = 12\%$, $SD = 8\%$) than "farther" segments ($M = 10\%$, $SD = 7\%$), paired $t(29) = 2.03$, $p = .05$. In general, infants tended to lead by moving farther away from their mothers, and mothers followed by closing the distance between themselves and their infant.

To test for different patterns of synchrony among dyads, we used these data as input to a data-defined clustering procedure and identified two clusters of dyads (Figure 5A). We labeled one cluster the "mother-follow" cluster ($n = 16$), because infants moved away from their mothers (infants led), and mothers moved closer to their infants (mothers followed); see video exemplar #1 at <https://nyu.databrary.org/volume/943/slot/38662/-?asset=293050>. As shown in Figure 5B, infants' independent movements accounted for a greater percentage of "farther" segments than "closer" segments, paired $t(15) = 15.17$, $p \leq .001$. Conversely, mothers' independent movements accounted for a greater percentage of "closer" segments than "farther" segments, paired $t(15) = 15.10$, $p \leq .001$. When both partners moved simultaneously, their movements accounted for a greater percentage of "closer" than "farther" segments, paired $t(15) = 3.71$, $p = .002$. We labeled the second cluster the "yo-yo" cluster ($n = 14$) because infants' and mothers' movements brought the partners closer together and farther apart in equal proportions (see video exemplar #2 at <https://nyu.databrary.org/volume/943/slot/38662/-?asset=293060>). As shown in Figure 5C, infants' and mothers' independent movements, and the simultaneous movements of both partners, accounted for similar percentages of "closer" and "farther" segments, paired $t_s(13) \leq 0.71$, $p_s \geq .49$. Infants in the mother-follow and yo-yo clusters did not differ in age, walking experience, walking skill, or accumulated locomotor activity, $t_s \leq 1.71$, $p_s \geq .10$.

In the second analysis of leading, we found that infants initiated (led) the majority of joint movements—times when both partners were in motion (see black boxes touching the diagonal in Figures 6A and 6B). We determined the number of

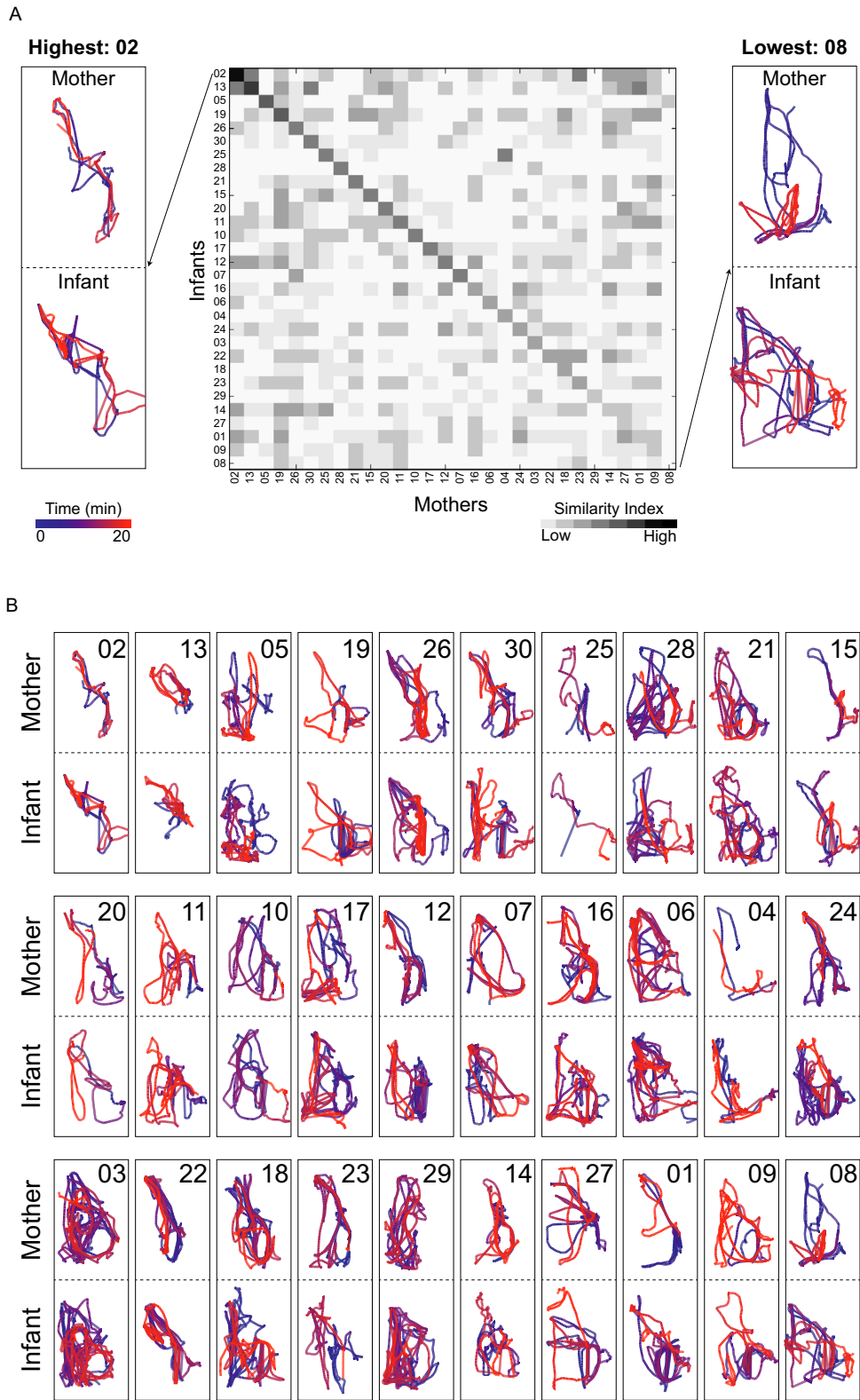


Figure 4. Similarity between infants' and mothers' paths ordered from most to least similar dyads. (A) Path-based similarity matrix. Numbers along the axes in the similarity matrix refer to each dyad. Darker shading denotes higher similarity. Dark diagonal in the matrix shows the high similarity between each infant's path and the path of that infant's mother. Exemplar paths show the most synchronized dyad (#02) and least synchronized dyad (#08). (B) Paths for every dyad. Colors denote the progress over the session.

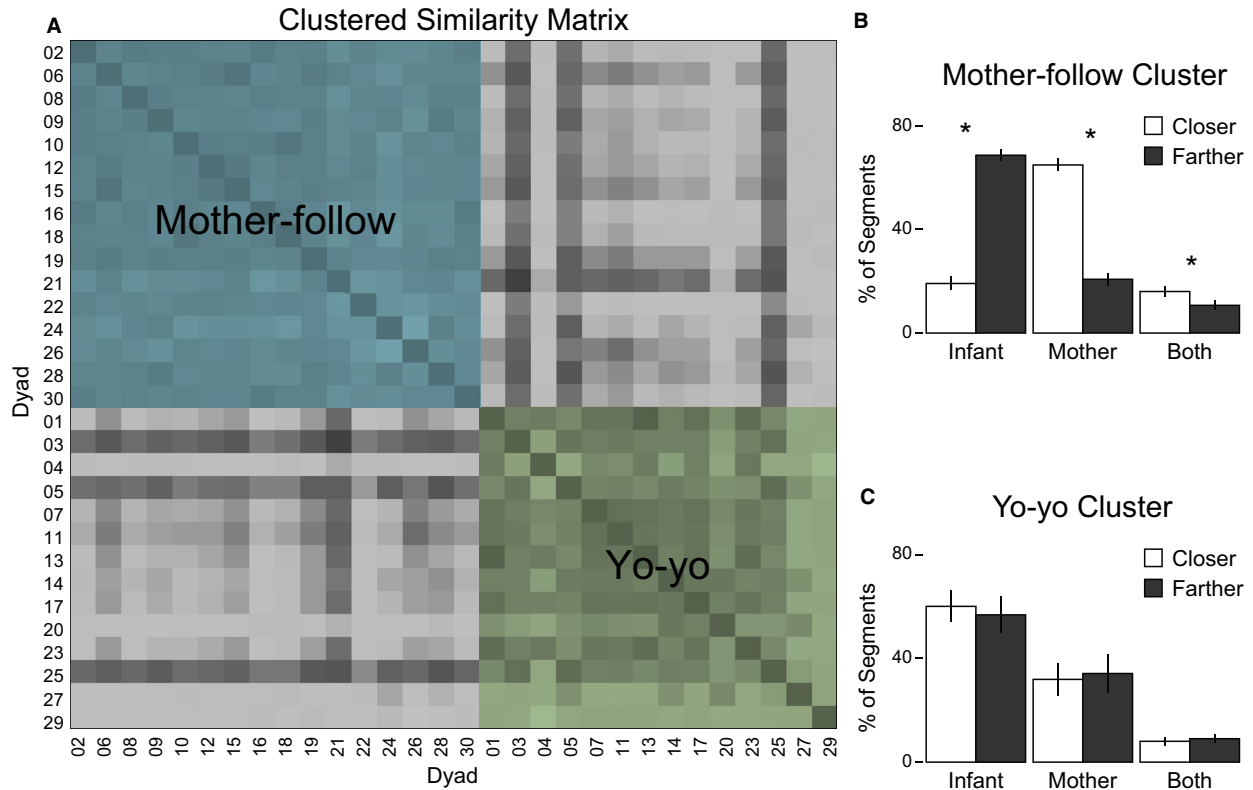


Figure 5. Clusters based on infant–mother distance. (A) Similarity matrix shows two clusters. Numbers along the axes in the similarity matrix refer to each dyad. Darker shading denotes higher similarity among dyads. Within clusters, dyads are ordered randomly. (B) In the “mother-follow” cluster, infants’ movements accounted for a greater percentage of “farther” segments than “closer” segments, and mothers’ movements accounted for a greater percentage of “closer” segments than “farther” segments. (C) In the “yo-yo” cluster, infants’ and mothers’ movements accounted for similar percentages of “closer” and “farther” segments. Error bars denote standard errors.

joint movement segments, which partner moved first, and the latency between the onsets of partners’ movements using cross-recurrence plots. Joint movement segments were generally short (0.2–31.3 s), and infants and mothers were rarely in motion at the same time ($M = 9.49\%$ of the session, $SD = 4.70\%$). Most infants (28 of 30) initiated the majority of their joint movement segments ($M = 64.44\%$, $SD = 10.01\%$ of segments). In other words, when infants and mothers were in motion at the same time, infants were more likely to move first (lead), and mothers to join in (follow). Two mothers (dyads #02 and #25) initiated more joint movement segments than their infants (55.10% and 54.54%, respectively). The percentage of infant-initiated joint movements did not differ between the mother-follow and yo-yo clusters ($t(28) = 0.48$, $p = .63$) and was not correlated with infants’ age, walking experience, walking skill, or accumulated locomotor activity, $r_s \leq .28$, $p_s \geq .15$. For joint movement segments, the average latency to follow

was generally short (1–6 s; see distribution in Figure 6C), but mothers were slower to follow ($M = 2.92$ s, $SD = 0.89$) than infants ($M = 2.43$ s, $SD = 0.88$), paired $t(29) = 2.36$, $p = .03$. Taken together, we find that infants were more likely to initiate periods of joint movement than their mothers, but both partners moved relatively quickly once the other was in motion.

In the third analysis of leading, we examined whether one partner was leading when both were in motion using two-dimensional Granger causality (Granger, 1969; Kaminski, Ding, Trucolo, & Bressler, 2001; Seth, 2010). To use this method, we examined segments of joint movement—times when infants and mothers moved together. For most joint movement segments (68.67%), the algorithm was inconclusive and therefore revealed no leader. Inconclusive leading can result from insufficient data (i.e., very short joint movement segments), equal prediction (high synchrony), or no prediction (low synchrony).

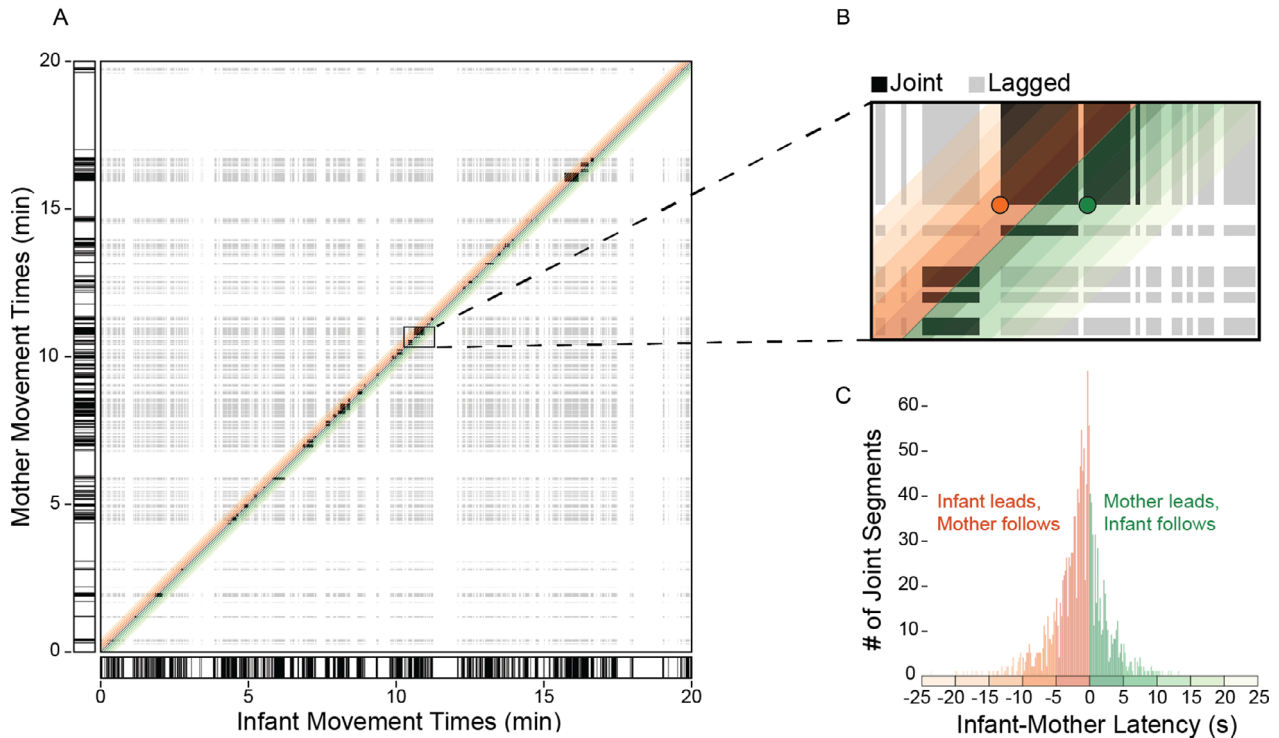


Figure 6. Leading based on cross-recurrence. (A) Exemplar cross-recurrence plot from one dyad (#10). Each time series shows stationary periods (white) and periods of movement (black) for infant (x -axis) and mother (y -axis) over the course of the session. Joint movements (times when the infant's and mother's locomotion overlapped in real time) are shown in black along the diagonal. Light gray boxes show lagged movements. (B) Close-up of joint movements in the cross-recurrence plot. The location of the bottom left corner of each joint movement (black) relative to the diagonal shows whether the infant or the mother moved first, and the latency of the other partner to join in (demonstrated by the graded colored bands). Orange bands denote times when the infant moved first, green bands denote times when the mother moved first. Darker bands indicate shorter time lags, and each band represents 5 s. (C) Histogram showing the # of Joint Segments versus Infant-Mother Latency (s). Negative latencies (orange) indicate that the infant moved first, and the mother followed. Positive latencies (green) indicate that the mother moved first, and the infant followed.

Thus, we provide no interpretation for inconclusive joint movement segments.

For joint movement segments with a conclusive leader, infants were more likely to lead than mothers (see video exemplar #3 at <https://nyu.databrary.org/volume/943/slot/38662/-?asset=293062>). The algorithm determined a leader for 293 segments ($M = 8.43$ s, range: 1.53–31.20). Most (81.9%) were scored as infant led, and infants led the majority of joint-movement segments in 28 out of 30 dyads. Relatively few segments were scored as mother led (18.1%), and mothers led the majority of joint-movement segments in two dyads (#03 and #04; see video exemplar #4 at <https://nyu.databrary.org/volume/943/slot/38662/-?asset=293064>). Thus, when both partners were in motion, infants were more likely than mothers to lead the dyad's path. The percentage of infant-led segments was not correlated with infants' age, walking experience, walking skill, or accumulated locomotor activity, $r_s \leq .24$, $p_s \geq .21$.

Discussion

Even before infants can lift their heads, they begin to learn about the social world through spontaneous, synchronous interactions with their caregivers (Cohn & Tronick, 1987; Stern, 1971). Over development, changes in behavioral synchrony accompany changes in infants' motor skills (Feldman, 2007). However, previous work did not rigorously examine whether or how infants and mothers coordinate their locomotor activity after infants become mobile and both partners are free to move. Using a combination of time-series analyses, we found that infant–mother dyads engage in a temporally and spatially coordinated locomotor “dance” as they move through the playroom.

As expected, infants moved more than their mothers while at play (Thurman & Corbetta, 2017). And although infants and mothers were rarely in

motion at the same time, accumulated measures of locomotor activity were correlated across dyads suggesting that infants and mothers scaled their locomotion to each other. Moreover, dyads spatially and temporally coordinated their locomotor activity in real time. Infants and mothers remained relatively close throughout the session, and both partners joined in quickly if the other began to move. In fact, infants' and mothers' spatiotemporal paths were so coordinated, that for most dyads, the path of one partner could uniquely identify the path of the other.

Such synchrony between young infants and their mothers is remarkable because maintaining spatial and temporal coordination during locomotor play is no easy task. The problem is complicated by unconstrained freedom to move, differences in infant–mother body size and activity level, and the necessity of keeping the other partner in sight. Although the precise timing of locomotor behaviors is likely less crucial than the timing of face-to-face interactions, to remain synchronized, even with a few seconds of delay, one or both partners must coordinate perception and action by tracking the location of the other and moving accordingly. Despite these challenges, infants and mothers managed to move through the playroom in synchrony.

Like face-to-face interactions (Stern, 1971), patterns of locomotor synchrony differed among dyads. For about half the dyads, mothers were responsible for keeping pace with their infants—when their infant ventured off, mothers followed. For the other half, infants and mothers “yo-yoed” to and from their partner’s location. Infants, however, did most of the yo-yoing (often to bid for mothers’ attention or to engage in social interaction). These two patterns of synchrony were unrelated to infants’ age, accumulated locomotor activity, walking experience, and walking skill. Likewise, although dyads varied in how much they moved, their average distance from one another, and the similarity of their paths, these differences were also unrelated to infants’ age, walking experience, and walking skill. Thus, dyadic differences in locomotor synchrony may reflect some unmeasured construct (e.g., infant temperament, attachment style) or state (e.g., energetic, tired), and developmental differences might only be observed across a broader time scale. Subjectively, all dyads in our sample seemed happy to play—in the dyad with the most similar paths (Figures 4A and 4B, dyad #02), the mother followed and spotted her infant on different climbing surfaces; in the dyad with the

least similar paths (Figures 4A and 4B, dyad #08), the mother watched her infant cheerfully play from a distance (occasionally while sitting on the couch).

As in face-to-face interactions, many locomotor activities initiated by the infant were “converted” into a dyadic experience by their mothers (Schaffer & Crook, 2017). Infants were more likely than their mothers to initiate segments of joint movement and to control the dyad’s path while in motion. Mothers, in turn, generally followed their infant’s lead. Thus, the onset of independent mobility provides infants with new opportunities to initiate the social dance, and mothers, like good partners, can respond. If mothers become unresponsive during mobile free play, infants notice the disruption and try to re-engage their caregiver (Myruski et al., 2018). In contrast to the typical still-face paradigm where infants are confined to a highchair, independent mobility gives infants the opportunity to “de-synchronize” and make their own fun when needed. Indeed, mobile infants readily leave their occupied, stationary caregiver to explore a room full of toys or to investigate a totally empty room (Hoch et al., 2019; Mahler, Pine, & Bergman, 1975; Rheingold & Eckerman, 1970).

Despite differences in modalities, we propose that face-to-face and locomotor synchrony serve a similar developmental function: to scaffold and support infants’ interactions with the outside world. Synchronous face-to-face interactions support infants’ developing social skills, ability to coordinate attention, and interactions with objects (Feldman, 2007). After infants become independently mobile, locomotor synchrony supports infants’ exploration of the larger environment, facilitates opportunities for learning, and keeps infants safe. Indeed, while playing on the floor, infants and mothers maintained a distance of 120 cm—an interpersonal distance that allows infants to explore but also affords high rates of gaze communication between infants and parents (Yamamoto et al., 2019). When infants climbed on elevated surfaces, mothers moved closer to support infants’ safety. Mothers may also guide infants toward interesting aspects of the environment. Infants who follow their mothers or siblings into an unfamiliar environment discover more objects and are more likely to investigate a new environment than infants who explore independently (Hay, 1977; Samuels, 1980). Importantly, the functional consequences of synchronous behavior do not rely on infants’ or mothers’ intentions. Neither member of the dyad must possess explicit knowledge of these functions nor deliberately engage in synchronous behavior, but

synchronous behavior can have functional consequences nonetheless.

Limitations and Future Directions

Most infants and mothers in our sample were engaged in what appeared to be a spatially and temporally coordinated locomotor dance. However, our observations were restricted to a 20-min session of free play in a laboratory playroom. In a different context, or over a different timescale, infants and mothers may coordinate their locomotor behavior differently. At home, for example, infants and mothers might move more independently than in a novel playroom, whereas their locomotion may be tightly coupled while walking down the street. Moreover, previous work on face-to-face interactions shows that synchrony is shaped by cultural norms, and specific patterns of asynchrony are associated with infant and maternal risk conditions (e.g., infant prematurity, maternal depression) and atypical infant development (Feldman, 2007). Thus, in cultures where children are expected to play independently, or in disrupted dyadic relationships, we might expect to observe less locomotor synchrony. Although dyads in our sample were healthy and relatively homogeneous, our methods were sensitive enough to characterize different styles of interaction. Thus, future work that includes culturally diverse or clinical samples in different contexts may reveal meaningful differences in synchronous locomotor activity.

Moreover, our data-driven approach and combination of analytic methods offer new tools for studying behavioral synchrony, and more broadly, behavioral development. Most behavioral research relies on a rigid “trial-based” structure that discretizes the behavioral stream into a series of brief events. But natural behavior is rarely discrete, and its spatial and temporal structure varies across individuals. This is especially true in the case of behavioral synchrony, which unfolds across multiple time scales. By analyzing continuous spatial and temporal data, we join others (e.g., Chow et al., 2018; Cuadros et al., 2019; López Pérez et al., 2017; Xu et al., 2020; Yu & Smith, 2013) in championing the feasibility and advantages of using real-time techniques to measure dyadic behavior.

Conclusions

By focusing on locomotor play in infants with a wide range of walking experience, we found that the infant–mother social dance continues after

infants are free to move around the floor. Dyads displayed behavioral synchrony, but like the variety in dance forms, they accomplished this feat through different means. Indeed, as infants gain new locomotor skills, early face-to-face interactions expand to a complex spatiotemporal social dance as infants literally learn the steps.

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Supporting Information

Additional supporting information may be found in the online version of this article at the publisher's website:

Figure S1. Example of Dynamic Time Warping Analysis, Comparing One Infant's Path to Her Own Mother's Path (Left) and a Different Mother's Path (Right)

Figure S2. Illustration of the Procedure for Clustering Dyads Based on Infant–Mother Distance

Table S1. Correlations Between Infant Walking Experience and Measures of Infant Walking Skill and Locomotor Activity

Table S2. Differences in Locomotor Activity Between Infants and Mothers

Table S3. Inter-Correlations for Infant and Mother Locomotor Activity