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Infant Locomotion Shapes Proximity to Adults During Everyday Play in the U.S.

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Abstract

Learning to walk expands infants' access to the physical environment and prompts changes in their communicative behaviors. However, little is known about whether walking also shapes infants' proximity to their adult social partners during everyday activities at home. Here we followed 89 infants (42 boys, 47 girls; 92% White, not Hispanic or Latino) longitudinally and documented connections between infant locomotion and infant-adult proximity on two timescales: (1) across developmental time, by comparing data from a session when infants could only crawl to a later session when they could walk (*M* walk onset = 12.15 months, range = 8–15); and (2) in real time, by testing whether the amount of time that infants spent in motion (regardless of their locomotor status) related to their interpersonal distance to adults. The developmental transition to walking corresponded to a significant, but modest, decrease in infant-adult proximity. Infants' moment-to-moment locomotion, however, was strongly related to patterns of interpersonal distance: infants who spent more time in motion spent less time near adults and instigated more proximity transitions, resulting in shorter and more dispersed bouts of proximity throughout sessions. Findings shed new light on how infants' motor achievements can reverberate across other domains of development, and how changes in infant development that researchers often observe over months arise from infants' moment-to-moment experiences.

Keywords

infant-adult proximity; interpersonal distance; infant locomotion; crawling; walking; developmental cascades

Learning to walk reorganizes how infants engage with the physical and social environment (see Adolph & Tamis-LeMonda, 2014). For example, walking allows infants to travel greater distances at faster speeds compared to crawling and provides them with an expansive view of their surroundings while they move (Adolph et al., 2012; Kretch et al., 2014). Accordingly, compared to crawlers, walkers visit more destinations, retrieve more distal objects, and carry them to share with caregivers and initiate play (Karasik et al., 2011; Thurman & Corbetta, 2017; Toyama, 2020). The onset of walking also co-occurs with changes in infant communication, including more frequent production of adult-directed

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vocalizations, gestures, and initiation of shared attention around objects (Clearfield et al., 2008; Clearfield, 2011; Walle, 2016; West & Iverson, 2021). In turn, walkers' social initiations elicit rich language and gesture input about infant action and objects from caregivers (Karasik et al., 2014; Schneider & Iverson, 2022; West & Iverson, 2021).

Prior work suggests that walking has a cascading effect on infants' social exchanges with their caregivers, but it is unclear whether walking similarly shapes the *physical arrangement* of infants' social interactions. As infants and caregivers move about their homes, they continuously increase or decrease their distance from one another. The space between infants and caregivers likely sets the context for their social interactions, either in seated object play near adults on living room floors or bursts of back-and-forth exploration as infants venture out to retrieve favorite toys for sharing. Thus, patterns of infant-caregiver proximity serve as an important contextual factor for infants' social interactions.

Several theoretical perspectives have stressed the importance of physical proximity for development, particularly to support the development of attachment and emotional regulation (Ainsworth, 1979; Bowlby, 1991; Brent & Resch, 1987; Mahler et al., 1975). Changes in proximity provide opportunities for infants to separate from their caregivers, explore their surroundings, and then return to play. Indeed, research shows that walking offers infants greater autonomy to venture away from caregivers and periodically return as a means of emotional "refueling" before continuing their travels (Mahler et al., 1975). This back-and-forth pattern of proximity may serve to regulate infants' emotional states—either to self-soothe infants when they are in distress, or to revitalize when arousal is low (Brent & Resch, 1987; Mahler et al., 1975).

Yet little is known about how infants' motor skills shape patterns of proximity. Does learning to walk co-occur with changes in infants' interpersonal distance to adults? To address this question, we investigated connections between infant locomotion and infant-adult proximity on two timescales: (1) across *developmental time*, by comparing longitudinal data from an observation when infants could only crawl to a later session when they could walk; and (2) in *real time*, by examining whether the amount of time that infants spend in motion (regardless of their locomotor status) shapes patterns of proximity to adults.

Infant locomotion and proximity to social partners

Several studies have measured infant-adult proximity in the context of infants' developing locomotor skills, with mixed results. Some studies report that infants spend less time near adults after they begin to walk. For example, a study examining infants and caregivers during play at home found that walking infants traveled beyond their mothers' reach more often and stayed in different rooms longer compared to age-matched crawlers (Biringen et al., 1995). And more generally, research shows that the interpersonal distance between infants and adults gradually increases as infants acquire new locomotor skills (Rheingold & Eckerman, 1970; Thurman & Corbetta, 2017). It is possible that walking infants' increased propensity to travel to distant objects may incur a reduction in their time spent near adults (Karasik et al., 2011; Toyama, 2020). And in fact, far-off toys are enticing destinations:

walkers spend less time playing near their caregivers in a room filled with toys compared to an empty room (Hoch et al., 2019).

In contrast, other studies find that infants spend more time near adults after they begin to walk as they increasingly approach caregivers to seek out social interaction. Some evidence suggests that unlike crawling, upright locomotion enables infants to approach their caregivers more often and engage in more proximal interactions. For example, Gustafson (1984) demonstrated that merely placing pre-walking infants upright in a mechanical walker increased the frequency with which they locomoted to adults and consequently, the amount of time infants spent near adults during play in a laboratory. This pattern of increased proximity was replicated in a longitudinal study, which showed that walking infants spent more time near adults in a laboratory playroom compared to prior sessions when infants were experienced crawlers (Clearfield, 2011).

More recent work suggests that infant-adult proximity may not change when infants learn to walk. For example, a longitudinal study measuring the interpersonal distance between infants and caregivers during play at home did not reveal significant change in proximity across the transition from crawling to walking (Yamamoto et al., 2020). Of course, proximity is a mutually determined behavior that is shaped by both members of the dyad. Walking infants and their caregivers often synchronize their movements, and the actions of one likely influence the actions of the other. Evidence suggests that infant and caregiver movements are coordinated: as infants explore a laboratory playroom, caregivers often followed in-step and close the distance (Hoch et al., 2021). Consequently, developmental change in infant locomotion may prompt a corresponding change in adult behavior. That is, if newly walking infants are increasingly on the go, adults may modify their actions to remain nearby, resulting in little change across time.

Finally, it is possible that infants' real-time locomotor behaviors (i.e., how much they move in the moment)—but not necessarily their locomotor status as a "crawler" or "walker"—shapes their proximity to adults. Locomotor development is characterized by considerable inter- and intra-individual variability (e.g., Rachwani et al., 2020). When infants spend a great deal of time in a stationary position, regardless of whether they can crawl or walk, they may experience prolonged periods of proximity to adults. But when infants spend more time moving, they may experience shorter intervals of proximity. It is important to note, however, that infant locomotion need not always change their proximity to adults. Estimates suggest that 30–60% of infants' locomotor bouts include fewer than four steps (Cole et al., 2016; Hoch et al., 2020; Lee et al., 2018) and frequently include steps in-place (Cole et al., 2016; Hoch et al., 2020). Short locomotor bouts are unlikely to displace infants significantly, and therefore are unlikely to affect patterns of proximity. Thus, the connection between infants' moment-to-moment locomotion and their proximity to adults remains an open question.

Current study

Prior work presents several alternative hypotheses as to whether learning to walk influences patterns of infant-adult proximity during daily life, when infants and caregivers can move freely through their homes and choose to spend time in close proximity or at a distance from one another. To test among these alternatives, we documented infants' locomotion and proximity to adults longitudinally across the transition from crawling to walking. First, we examined whether infant-adult proximity changed across developmental time by comparing data from two at-home, naturalistic observations: the first when infants were crawlers, and the second a month later, when all infants could walk independently. Second, we investigated whether the frequency of infants' in-the-moment locomotion—regardless of their locomotor status—mapped onto patterns of proximity to adults. Finally, we documented whether infants or adults primarily initiated changes in interpersonal distance, either bringing the dyad together or moving apart.

Method

Participants

Data for the current report were drawn from two longitudinal studies that investigated motor and language development in infancy. All infants were born at term and from uncomplicated pregnancies. Data were collected between 2002 and 2014 in two Midwestern cities. The present study was conducted according to guidelines laid down in the Declaration of Helsinki, with written informed consent obtained from a parent for each infant before any assessment or data collection. All procedures involving human subjects in this study were approved by the Institutional Review Board at the University of Pittsburgh. The sample included 75 infants with an elevated likelihood for developing autism spectrum disorder (ASD), defined by the presence of an older sibling already diagnosed with ASD. Twenty-four infants had no first- or second-degree relatives with ASD. A preliminary goal of this project was to examine whether measures of infant-adult proximity varied among infants based on these sampling characteristics. However, there were no significant differences between groups on any measure.

Ten infants received an ASD diagnosis at the conclusion of the original study (see Leezenbaum & Iverson, 2019 for additional information on diagnostic criteria). We excluded infants with an ASD diagnosis from the current analyses given the potential host of additional factors that may influence these infants' patterns of proximity-seeking behavior. Thus, the final sample included data from 89 infants (47 girls, 42 boys) collapsed into a single group. Caregivers reported their infant's race and ethnicity: 87 infants were White (five were Hispanic or Latino) and two were Multiracial. Mothers and fathers were similar in age (*M* mothers = 33.84 years, *SD* = 4.45; *M* fathers = 36.17 years, *SD* = 5.31) and education (85.4% of mothers and 83.1% of fathers held a college degree or higher).

Procedure

As part of the larger longitudinal studies, researchers visited infants and their caregivers at home following either a biweekly (from 2–19 months) or monthly (from 5–14 months) observation schedule. Home visits typically occurred on weekdays and during times when infants were awake and ready to play. At each visit, infants were videorecorded during everyday activities (e.g., playing with toys, interacting with adults, locomoting around the house) for approximately 45 minutes. Prior to filming, infants and caregivers were given time to acclimate to the researchers' presence, and researchers who visited each family were consistent across sessions. After warm-up, a researcher followed the infant with a single camera and ensured the infant's entire body was in view at all times while also keeping adults and the surrounding environment in frame as much as possible. Infants and caregivers spent the majority of their time in a few main rooms (e.g., the living room, kitchen), but frequently changed locations. In addition to the cameraperson, two researchers were typically present. All researchers remained at a distance during filming and took care to not interact with infants. However, infants were free to approach any adult as we did not constrain their activities.

To examine how infant-adult proximity changed across the transition from crawling to walking, we focused on two observations. We first identified each infant's age at *walk onset*, defined as the first day when infants were able to take five continuous, independent steps without stopping or falling. We confirmed walk onset ages by cross-referencing caregivers' prospective reports of their infants' motor skills with experimenters' notes from each visit. On average, infants began to walk at 12.15 months (*SD* = 1.47, range = 8–15).

After establishing walk onset, we then selected the first monthly session (to balance differences in observation schedules) that followed each infant's walk onset age and considered it to be the initial *walking session* (e.g., if an infant began to walk at 11.5 months, the 12-month session was identified as the walking session; *M* walking experience = 0.16 months, *SD* = 0.33). The session one month prior was identified as the final *crawling session* (i.e., when infants could only move by crawling, cruising, etc.; *M* crawling experience = 2.92 months, *SD* = 1.37). Our milestone-based design reflected individual differences in the ages at walk onset for each infant, and thus infant ages at each session varied. As a result, we controlled for infant age in all analyses.

Data coding

We selected the first 10 minutes of each 45-minute observation in which infants were free to move and not constrained by furniture (e.g., a highchair) for coding. All behaviors were coding using the computerized coding tool Datavyu (datavyu.org). Coders were trained until overall percent agreement reached ≥ 90% on all coding categories for three consecutive videos. After establishing reliability, a primary coder scored 100% of each video, and a reliability coder independently scored a randomly selected 25% of each video to verify inter-observer reliability. Disagreements were resolved through discussion.

Infant locomotion.—Each video was first coded for locomotion. All times when infants engaged in crawling (moving on hands-and-knees), cruising (moving upright with support), and walking were identified. We coded locomotion in *bouts*, or a series of steps separated by a pause in which the infant came to a complete stop for at least 0.5 seconds (e.g., Adolph et al., 2012; Cole et al., 2016). To be included, bouts were required to contain at least two steps or crawl cycles. A bout of locomotion began at the first frame of video when an infant's foot or knee began to move and ended at the first frame when the foot or knee came to rest (Adolph et al., 2012). We calculated the total duration of infants' locomotion time by summing the individual durations of all bouts (regardless of type) and dividing this value by the session duration to derive the *proportion of time spent in motion*. Inter-observer reliability was high for bout identification (percent agreement = 92%) and for specification of locomotion type (κ = .97).

Infant-adult proximity.—Given the complexity of capturing changes in interpersonal distance from video, we utilized an interval-based coding system (see Schneider et al., 2022 for a similar application). Each 10-minute observation was divided into sixty 10-second intervals. We established interval length using an iterative pilot coding process in which codes were tested using a variety of interval durations. Our goal was to select an interval that was long enough to provide an appropriate level of detail for capturing change in infant-adult proximity over time while also maintaining coder efficiency (see Bakeman & Gottman, 1997). Based on these initial observations, a 10-second interval was chosen as the best solution for balancing these parameters.

We coded infant-adult proximity in each interval using two mutually exclusive categories. As shown by the line drawings in Figure 1, we identified whether infants were *within reach* of an adult (the blue drawing) or *out of reach* of an adult (the yellow drawing) throughout the entire interval. We used adults' wingspans to determine whether infants were within or beyond reach. Specifically, if the adult could fully stretch out their arms and touch the infant without needing to locomote or change their posture, infants were considered to be within reach.

We only coded one of the two proximity categories if the infant remained in the same proximity state across the full 10-second interval (i.e., the infant stayed within arm's reach of an adult for the entire 10 seconds). If a transition between proximity states occurred during the interval, we assigned it to a separate *proximity transitions* category (the grey drawing) and noted who (infant or adult) initiated the transition. Infants and adults could initiate proximity transitions by locomoting to be within or out of reach of the other. Given that infants could approach and interact with the researchers who were present at the session, we did not limit the coding of infant-adult proximity to just the primary caregiver. Thus, our measures of proximity reflect the time that infants spent near vs. far away from any adults. Inter-observer reliability was high for categorizing infant-adult proximity (coders agreed on 91.6% of intervals, κ = 0.83) and identifying the initiator of proximity transitions (agreement on 94.6% of intervals, κ = 0.76).

Results

We documented whether infants' *locomotor status* ("crawler" or "walker") or *locomotor behavior* (how much time infants spent in motion) was related to patterns of infant-adult proximity. Specifically, our primary measures included: (1) the total number of intervals in which infants were within reach of an adult; (2) the frequency of proximity transitions (instances when the infant or adult moved in or out of reach); and (3) the relative frequency with which infants vs. adults initiated proximity transitions (i.e., whether the infant or adult was primarily responsible for shaping proximity). We used generalized estimating equations (GEEs) for all analyses, which accounted for the non-independence of repeated sessions at the crawling and walking time points (Hardin & Hilbe, 2002). A Wald X^2 statistic is reported for each GEE. Partial correlations, controlling for infant age, were calculated to follow-up on significant main effects and interactions. Infant age and sex were included as covariates in all models. Preliminary analyses revealed no differences on any variable based on the number of additional researchers present at home visits ($M = 1$, range = 0–3; all ps > .05).

Infants' time spent within versus beyond adult reach

We first analyzed how much time infants spent locomoting at each session. Overall, infants spent similar proportions of their observation time in motion at both the crawling ($M = 0.11$, $SD = 0.09$) and walking ($M = 0.14$, $SD = 0.12$) observations. A GEE confirmed that the proportion of time spent in motion did not significantly change between sessions, $X^2 = 1.06$, $p = .303$.

To assess patterns of infant-adult proximity, we examined the distributions of time that infants spent within vs. beyond arm's reach of an adult. Figure 1 presents raster plots depicting individual timelines for each infant—color-coded to show when infants were near or far from adults and when there were transitions between proximity states. The figure displays both the real-time fluctuations in proximity between each 10-second interval within a session and change in patterns of proximity across the crawling and walking sessions.

As shown by the blue vs. yellow bars in Figure 1, infants spent far more intervals within reach of adults ($M = 38.89$ intervals, $SD = 16.47$) than they spent out of adult reach ($M = 13.65$ intervals, $SD = 13.93$). However, there was substantial individual variability in patterns of infant-adult proximity. At both the crawling and walking sessions, infants ranged from 0–60 intervals near adults. That is, some infants were consistently within reach of an adult during the observation (see the full-length blue bars running across each raster plot), while other infants were never within reach of an adult (the full-length yellow bars).

Infants' locomotor status *and* real-time locomotor behavior were related to patterns of infant-adult proximity. Indeed, the GEE revealed main effects of both Locomotor Status, $X^2 = 4.76$, $p = .029$, and Time in Motion, $X^2 = 34.63$, $p < .001$. Specifically, infants showed a modest decrease in intervals spent near adults from the crawling ($M = 40.44$ intervals, $SD = 14.32$) to the walking session ($M = 37.35$ intervals, $SD = 16.94$). Within sessions, when infants spent more time locomoting, they tended to spend fewer intervals near adults. Figure 2 presents scatterplots of the relations between infants' time in motion and our proximity measures. As shown in Figure 2a, there was a significant association between locomotion time and proximity, such that an increase in the proportion of time that infants spent in motion was associated with a decrease in the number of intervals within reach of adults. Finally, the GEE also revealed a Locomotor Status × Time in Motion interaction, $X^2 = 7.29$, $p = .007$. Follow-up tests showed that the negative relation between locomotion time and proximity to adults was stronger at the crawling session compared to the walking session (rs = −.542 vs. −.386, ps < .001, respectively; see Figure 2a).

Transitions between proximity states

We next analyzed how often intervals contained transitions between proximity states (e.g., when an infant locomoted out of adult reach). As shown by the grey bars in Figure 1, infants and adults engaged in transitions frequently, accumulating an average of 7.46 transition intervals (*SD* = 5.56) per 10 minutes. Again, we observed substantial variability in how often proximity transitions occurred (range = 0–28), suggesting that some infants remained near or far from adults for prolonged stretches of time, while other infants exhibited multiple, shorter episodes of social proximity throughout the session.

The GEE revealed only a main effect of Time in Motion, $X^2 = 25.24$, $p < .001$. Specifically, at both the crawling and walking sessions, infants who spent more time locomoting also exhibited a larger number of transition intervals (*r*s = .591 and .691, *p*s < .001, respectively; see Figure 2b). Infants who moved the least during their 10-minute observation spent prolonged stretches of intervals either near or far from adults (see the prevalence of long, uninterrupted bars in the top halves of each raster plot in Figure 1). By contrast, infants who spent more time locomoting demonstrated a back-and-forth pattern of proximity, in which stretches of time near adults were frequently interspersed with transitions. There was no main effect of Locomotor Status, $X^2 = 2.52$, $p = .112$, and no Locomotor Status × Time in Motion interaction, $X^2 = 0.61$, $p = .436$.

Initiator of proximity transitions

Our final analyses examined whether infants or adults were primarily responsible for initiating proximity transitions (e.g., by moving closer or farther away from one another). To do so, we calculated a change score for each infant by subtracting the total number of adult-initiated transitions from the total number of infant-initiated transitions. Thus, positive values denote that the infant was responsible for changes in proximity more often than adults, negative values denote the reverse, and the magnitude of the value reflects the magnitude of the difference between the infant- and adult-initiated transitions. These data are presented in Figure 3.

Overall, infants and adults generated similar numbers of proximity transitions (*M* infants = 4.35, *SD* = 4.06; *M* adults = 3.38, *SD* = 3.19). However, as shown in Figure 3, the difference in each partner's propensity to initiate transitions was highly related to the time that infants spent in motion, regardless of locomotor status. Infants who spent more time locomoting drove the ebb and flow of proximity to adults and more often initiated transitions between proximity states (see the blue regions in Figures 3a–b). Conversely, when infants moved less, adults largely determined when the pair was near vs. far (the green regions). The GEE confirmed these patterns with a main effect of Time in Motion, $X^2 = 16.78$, $p < .001$, but no effect of Locomotor Status, $X^2 = 0.01$, $p = .931$, and no Locomotor Status × Time in Motion interaction, $X^2 = 1.18$, $p = .278$.

Discussion

We investigated the connection between infants' locomotion and proximity to adults on two timescales: over developmental time as infants transitioned from crawling to walking, and in real time as infants moved about their homes during everyday play. Overall, the transition to walking corresponded to a decrease in infant-adult proximity, regardless of infant age. In addition, infants' moment-to-moment locomotion (for crawlers and walkers alike) was strongly related to patterns of interpersonal distance. When infants were highly mobile, they instigated bouts of proximity by approaching or departing from adults' reach, and their bouts were shorter and dispersed across the entire observation. When infants were less mobile, adults instigated most bouts of proximity and bouts were less frequent, but prolonged in duration compared to those of more mobile infants.

Infant locomotion organizes infant-adult proximity

The onset of walking corresponded to a significant (albeit modest) reduction in infants' time spent near adults. There are at least two potential explanations for the decrease in social proximity. First, walking infants have a better view of their surroundings while moving than crawlers do, which may guide their movements differently (e.g., Kretch et al., 2014). Because walkers' upright posture enables them to see far-off locations, distant toys and spaces may entice them to venture away from caregivers for long periods of time as they engage in solo exploration. Indeed, distal toys prompt infants to travel farther and play at a distance from their mothers (Rheingold & Eckerman, 1970). Moreover, infants walk to their caregivers less often in a playroom filled with toys relative to an empty room (Hoch et al., 2019). In everyday life, infants' homes are brimming with toys and household objects (Herzberg et al., 2022), and walking infants may forgo proximal social interactions to explore other exciting destinations.

Second, walking is a more efficient means for locomotion than crawling (e.g., Adolph et al., 2012). Even newly walking infants travel at faster speeds, covering greater distances, than infants with many months of crawling experience (e.g., Adolph & Tamis-LeMonda, 2014). As a result, walkers may be more likely to spend time "foraging" in their everyday environments; that is, moving for movement's sake without a specific destination in mind. Instead, locomotion is costly for crawling infants—it requires more time and energy—and accordingly, crawlers may use locomotion more sparingly and strategically to reach specific destinations, like objects and people, than do walkers (e.g., Cole et al., 2016; Hoch et al., 2020). Distinct movement patterns among crawlers and walkers may explain why moment-to-moment locomotion was more strongly related to infant-adult proximity at the crawling session than the walking session, as crawlers may use a greater proportion of their movements to approach adults compared to walkers. Nevertheless, for all infants, the amount of time spent moving shaped the organization of infant-adult proximity, suggesting that movement itself (rather than *how* infants move) may be a more critical factor in determining the physical arrangement of social interaction.

Here, we focused on the transition from experienced crawling to novice walking, but motor development may shape patterns of interpersonal distance well before and after this skill is acquired. For example, pre-locomotor infants rely almost entirely on adults to determine the spatial arrangement of social interaction. Indeed, dyadic interactions are predominantly shaped by caregivers early in the first year. Caregivers often place their infants in supine and supported sitting postures during object play and position themselves to face their infants from above or directly opposite (Schneider et al., 2022). As infants get older and acquire new motor skills (e.g., sitting, crawling), however, they autonomously move in and out of body positions and actively shape the physical configuration of their social interactions (e.g., choosing to position themselves close or far, towards or opposite their caregivers). In addition, the transition from novice to experienced walker may prompt other changes in infant-adult proximity. With each passing month of walking experience, infants become faster, more skilled movers (Adolph et al., 2012). The decrease in infants' time near adults observed here may be amplified with additional walking experience, as infants move back and forth between dyadic and independent play with greater ease.

It is important to note that the *setting* of existing studies on infant-adult proximity (either in infants' homes or in novel laboratory spaces) may account for prior mixed results on the connection between walking and interpersonal distance. Infants may behave differently in curated laboratory spaces compared to natural environments (e.g., Tamis-LeMonda et al., 2017). For example, our findings align with Biringen et al. (1995), who found that infants spend less time near adults after they begin to walk—both studies took place in infants' homes during everyday play. In contrast, laboratory-based observations revealed that increased walking was associated with more time near caregivers (e.g., Clearfield, 2011; Gustafson, 1984). It is likely that infants' proximity-seeking behaviors are shaped, in part, by the familiarity of their location. Familiar settings like the living rooms, bedrooms, and kitchens may guide walking infants towards independent play, and caregivers may allow infants to explore at a distance in the safety of their homes. But in novel settings, infants may approach caregivers to share new toys or experiences more often, and in turn, caregivers may accompany their infants as they move about and explore the new location.

Developmental cascades arise from real-time behavioral cascades

Psychologists often propose that new motor skills—like learning to reach, sit, or walk—have cascading effects on other domains of infant learning and development (e.g., Iverson, 2021). Such studies typically identify associations between the timing of new motor skills and strides in social-communicative development. For example, the onset of walking is accompanied by vocabulary growth (e.g., He et al., 2015; Walle & Campos, 2014; West et al., 2019) and alterations in caregiver communication (e.g., Karasik et al., 2014; Schneider & Iverson, 2022; West & Iverson, 2021). But importantly, such associations documented over months or years likely arise from *real-time behavioral cascades*. That is, infants' in-the-moment motor actions may play a causal role in shaping their opportunities for social communication and interaction. Our data shed light on the importance of examining real-time behavioral cascades that connect infant locomotion—not just their locomotor status—to aspects of interaction; in our case, the time that infants spent near adults.

The real-time spatial arrangement of everyday activities may play an important role in structuring the content of dyadic interaction, and in turn, the acquisition of skills across other domains. For example, during proximal activities, close face-to-face interactions allow infants to establish mutual gaze (e.g., Northrup & Iverson, 2020), learn about social contingencies (e.g., Beebe et al., 2016; Kaye & Fogel, 1980), and jointly engage with objects and caregivers, promoting early vocabulary development (e.g., de Barbaro et al., 2016; Suarez-Rivera et al., 2022; Yu & Smith, 2012). Similarly, side-by-side book reading allows infants to acquire pre-literacy skills (e.g., page-turning) and exposes them to rich linguistic input benefiting language (e.g., Demir-Lira et al., 2019; Luo & Tamis-LeMonda, 2017; Muhinyi & Rowe, 2019).

Activities at a distance from adults, such as rolling a ball back and forth, climbing on playground equipment, or riding tricycles may offer infants practice refining their whole-body movements and spatial exploration, benefiting skills like spatial cognition (e.g., Garcia et al., 2021; Oudgenoeg-Paz et al., 2015) and the acquisition of motion verbs (e.g., West et al., 2022). Thus, different types of play (enabled by their physical organization) may give rise to different opportunities for interaction and infant learning. And in fact, studies have found that more frequent locomotion (and relatedly, the back-and-forth pattern of social interaction that follows when infants are more mobile) is associated with a larger receptive vocabulary among crawling and walking infants (Walle & Campos, 2014).

Limitations and future directions

There are several important limitations to note when interpreting our results. First, our sample included families from predominantly White and highly educated sociocultural backgrounds from a Western culture. Therefore, it is unclear whether our findings generalize beyond this limited demographic sample. Infants reared in other cultural communities across the globe vary tremendously in the timing of motor skill expression. For example, infants from cultures that engage in daily exercise and massage routines (e.g., parts of India, Africa, and the Caribbean) begin to walk weeks or even months earlier than Western infants do (see Karasik et al., 2010 for a relevant review). Other infants skip certain skills altogether (e.g., crawling; Karasik & Robinson, 2022). Even within the United States, sociodemographic factors appear to influence characteristics of infants' home environments—like how crowded living spaces are—which may in turn account for later attainment of walking (Hospodar et al., 2021). Differences in these sociocultural factors likely influence motor development, which in turn may shape the association between walking and infant-adult proximity documented here. Future work is necessary to identify how culture and context shape the connection between locomotion and proximity.

Second, measuring interpersonal distance in the home environment poses unique challenges. Documenting infant-adult proximity with detailed precision is difficult from video alone because infants' homes vary substantially in their dimensions, and thus lack a common parameter of distance. Here we focused on times when infants were within adult reach. However, when infants were out of adults' reach, their precise distance from an adult could vary dramatically. For instance, the adult could be just out of infants' reach in a small playroom or in an entirely different room altogether. Future research should leverage wearable technologies (e.g., TotTag; Salo et al., 2021) to precisely quantify interpersonal distance. Further, aspects of infants' home environments—like the number and dimensions of rooms, or the availability and location of objects—may influence infants' movements and proximity to caregivers. Additional research should document how the physical characteristics of infants' homes shape their behaviors and proximity to adults.

Finally, although we asked caregivers to engage in their typical everyday activities, dyads generally chose to play together during the 10-minute observation. Patterns of interpersonal distance shift over the course of daily routines as infant-caregiver dyads transition between play, mealtimes, grooming activities, and stretches of time when caregivers are occupied by chores and infants play independently. Interpersonal distance likely fluctuates throughout the day, and the role of infant locomotion may be more or less influential depending on the activity context. Moreover, infants' time spent outside the home (e.g., in childcare settings) may offer unique opportunities for social proximity with peers and other adults (see van Liempd et al., 2020 for a review). Future work should measure infant-adult proximity spanning longer durations of time and across activity contexts.

Conclusions

Our findings have important theoretical and methodological implications. First, our data shed new light on how infants' motor achievements reverberate across domains and potentially shape the physical context of their social interactions. Infants' in-the-moment motor actions have *immediate consequences* for their proximity to social partners, and potentially their access to social information and ways to play and interact with their adult caregivers. As a result of real-time connections, the acquisition of new motor skills—like learning to walk—may give rise to corresponding changes in infant-adult social interaction. Thus, infants' social development should be considered as an embodied process that unfolds within the context of a rapidly changing repertoire for motor action.

Second, infancy researchers often study infant-adult interactions in laboratory spaces, with infant-caregiver dyads placed in close proximity in a small observation room or seated at tables with limited opportunities to move. However, infants are often "on the go" at home, and proximal social interactions are often broken up into episodes of back-and-forth exploration as infants shift between dyadic play and solo ventures. This temporal pattern of social proximity may meaningfully impact how infants produce other behaviors of researchers' interest. Finally, the connection between infants' locomotor development and social proximity may have implications for infants with gross motor delays, who walk later in development than their peers, and for whom the temporal and spatial organization of social interactions with caregivers may differ in important ways.

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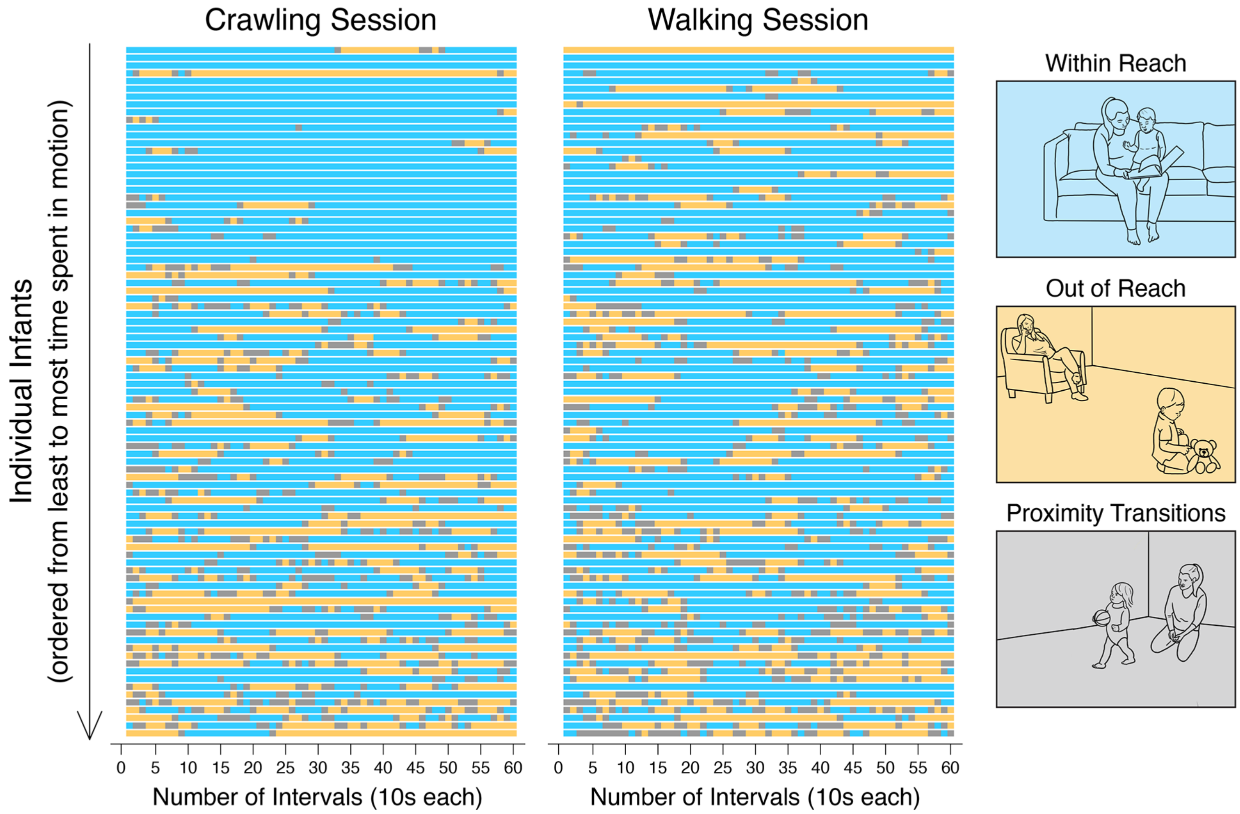

Figure 1.

Data on infant-adult proximity across the transition to walking. The raster plot presents individual timelines for each infants' patterns of proximity to adults across sixty, 10-second intervals spanning a total of ten minutes of play. The data represent both the real-time distributions of proximity states during each 10-second interval within a session and change in patterns of proximity between sessions. Each row displays data from a single infant. Rows are ordered from least to most time in motion within each session. Proximity states for each interval are color-coded, and the line drawings serve as a legend. Each color represents a proximity state: blue = within reach; yellow = out of reach; and grey = proximity transitions.

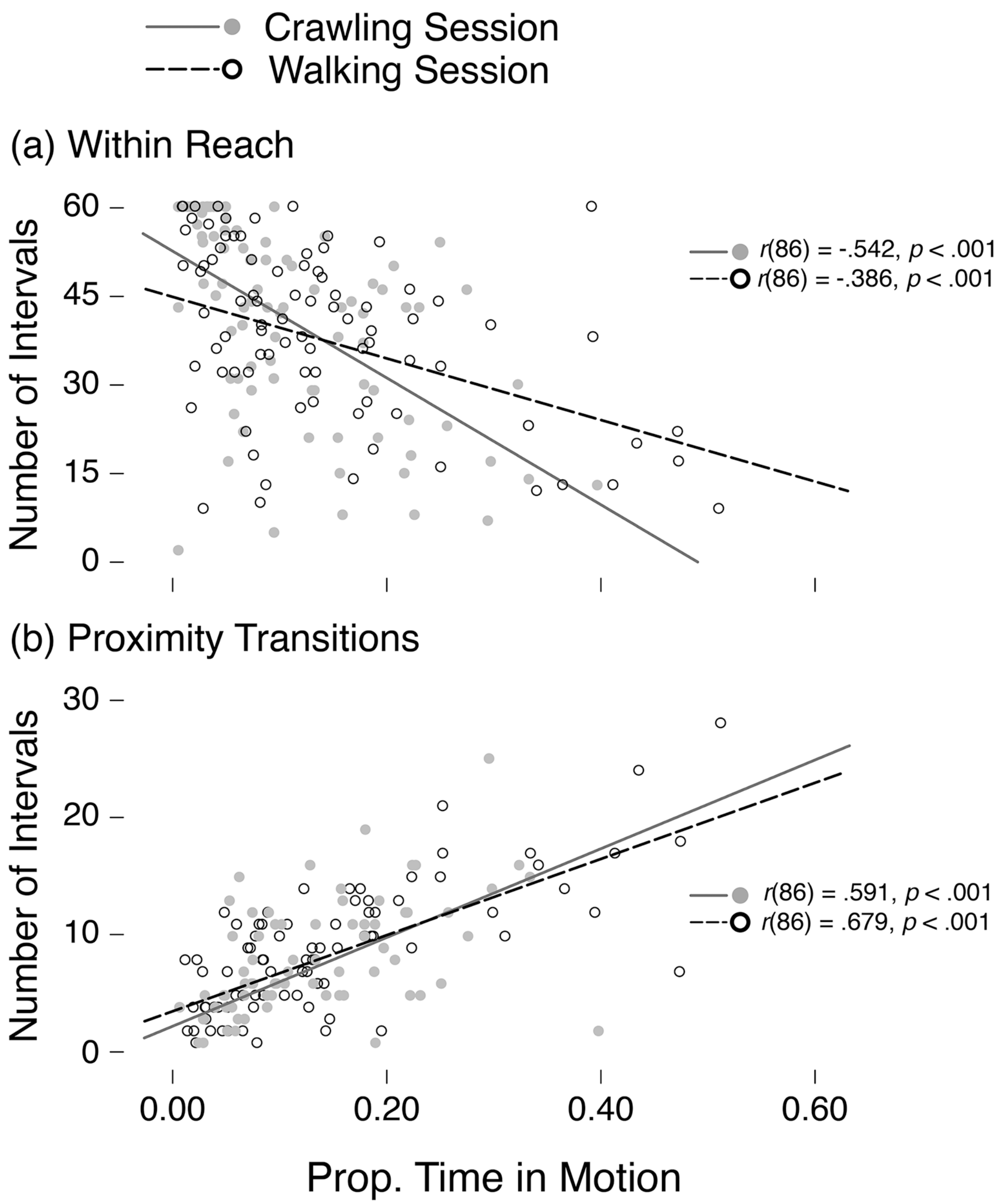

Figure 2.

Scatter plots showing partial correlations (controlling for infant age) between the proportion of time that infants spent in motion and: (a) the number of intervals within reach of an adult and (b) the number of intervals engaging in proximity transitions. Solids grey lines represent data from the crawling session; dashed black lines are data from the walking session.

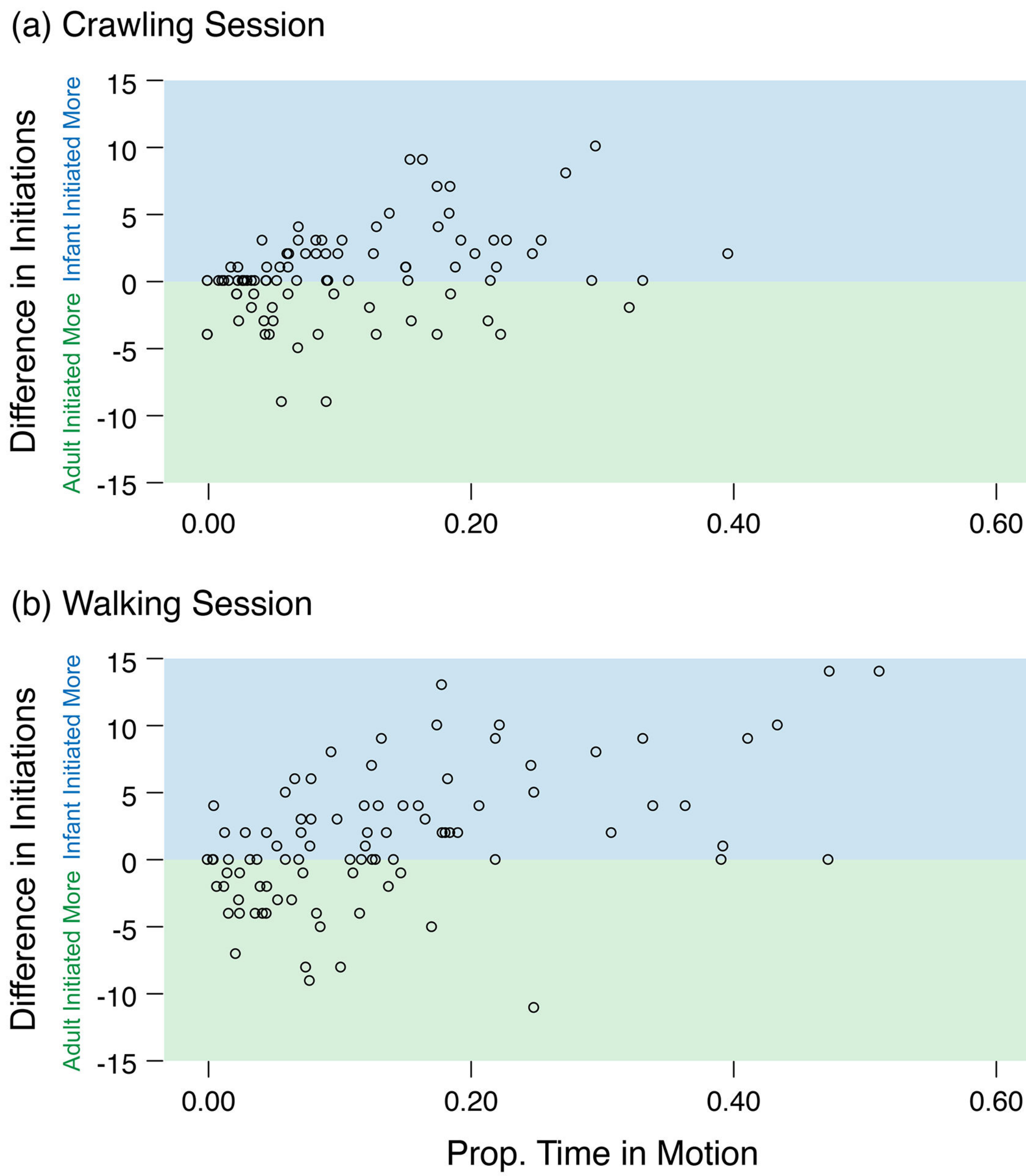

Figure 3.

Difference scores showing whether infants (blue regions) vs. adults (green regions) initiated proximity transitions. Panel (a) displays data for the crawling session and panel (b) shows data for the walking session.