Published in final edited form as:
Dev Sci. 2015 March ; 18(2): 206–218. doi:10.1111/desc.12205.

A new twist on old ideas: How sitting reorients crawlers

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Abstract

Traditionally, crawling and sitting are considered distinct motor behaviors with different postures and functions. Ten- to 12-month-old infants were observed in the laboratory or in their homes while being coaxed to crawl continuously over long, straight walkways (Study 1; *N* = 20) and during spontaneous crawling during free play (Study 2; *N* = 20). In every context, infants stopped crawling to sit 3-6 times per minute. Transitions from crawling to sitting frequently turned infants' bodies away from the direction of heading; subsequent transitions back to crawling were offset by as much as 180° from the original direction of heading. Apparently, body reorientations result from the biomechanics of transitioning between crawling and sitting. Findings indicate that sustained, linear crawling is likely an epiphenomenon of how gait is studied in standard paradigms. Postural transitions between crawling and sitting are ubiquitous and can represent a functional unit of action. These transitions and the accompanying body reorientations likely have cascading effects for infants' exploration, visual perception, and spatial cognition.

Keywords

sitting; crawling; spatial exploration; infant locomotion; motor development

Motor milestones such as sitting, crawling, and walking are important markers of developmental progress (Gesell, 1946; Gesell & Ames, 1940; McGraw, 1941; Piper & Darrah, 1994). But motor achievements can be more than benchmarks of development; they can also facilitate progress. New motor abilities can instigate a cascade of new experiences that change infants' opportunities for learning and thereby affect development of perception, cognition, affect, and social interaction (Campos et al., 2000; Gibson, 1988; Karasik, Tamis-LeMonda, & Adolph, 2011; Oakes, 2009; Rakison & Woodward, 2008).

Sitting is an important motor milestone because it is the first instantiation of upright posture. Keeping balance in a sitting posture requires infants to coordinate the trunk and pelvis from head to hips, using their legs and buttocks as the base of support (Harbourne, Lobo, Karst, & Galloway, 2013). Most infants sit independently at about six months of age (Bayley, 2006; Bly, 1994). Sitting is an important facilitator of development because it opens up new opportunities for exploration and learning. The upright posture affords new views of the

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world and the people who inhabit it (Cashon, Ha, Allen, & Barna, 2013; Frank, Simmons, Yurovsky, & Pusiol, 2013; Kretch, Franchak, & Adolph, in press). The hands are freed from a supporting role, providing new opportunities for reaching, exploring objects, and learning about object properties (Gibson, 1988; Harbourne et al., 2013; Lobo & Galloway, 2008; Soska & Adolph, 2014). For example, the sitting posture facilitates more sophisticated types of object exploration—concurrent looking and touching—which in turn leads to 3D object form perception (Soska, Adolph, & Johnson, 2010).

Crawling also is an important motor milestone because it typically marks the first instance of independent mobility. Crawling on hands and knees requires infants to coordinate limbs and trunk to keep balance and control forward propulsion (Adolph, Vereijken, & Denny, 1998; Freedland & Bertenthal, 1994; Gesell, 1946; McGraw, 1941). Most infants begin crawling at about eight months of age, and crawling remains the predominant form of locomotion until it is replaced by upright walking at about 12 months (Bayley, 2006; Bly, 1994). Crawling is also an important impetus for psychological development because it allows infants to move their bodies through the environment. Now they can explore the spatial layout by themselves, visit distal objects and people, and see what is around the corner without dependence on caregivers (Campos et al., 2000; Gibson, 1988; Karasik et al., 2011). Thus, crawling provides infants with opportunities for spatial learning, experience with optic flow and changing visual scenes, selection and exploration of environmental features and objects, and the wherewithal to approach or move away from caregivers. For example, crawling infants show greater success in object search tasks compared with pre-crawlers and they become more sensitive to optic flow (Anderson et al., 2001; Clearfield, 2004; Dahl et al., 2013; Uchiyama et al., 2008).

Traditionally, researchers have considered sitting and crawling as distinct behavioral milestones (Gabbard, 2004; McGraw, 1945). This is a reasonable assumption: The two skills appear at different ages, and sitting is a stationary posture whereas crawling is a form of locomotion. Indeed, the way these behaviors are studied and measured highlights their separateness. Motor development researchers typically study sitting in infants planted on a force platform or kept in one place for normative assessment or monitoring of postural sway or muscle activity (Harbourne & Stergiou, 2003; Hedberg, Carlberg, Forssberg, & Hadders-Algra, 2005; Piper & Darrah, 1994; Rachwani et al., 2013). If infants fall over or try to escape, the trial is stopped. In contrast, researchers study crawling by encouraging infants to move continuously over a long walkway or on a treadmill while their movements are recorded on video or with motion tracking sensors (Adolph et al., 1998; Freedland & Bertenthal, 1994; Patrick, Noah, & Yang, 2009). If infants trip, fall, or stop crawling, the trial ends.

Despite the traditional approach to sitting and crawling, researchers have always recognized that the distinction between stationary postures and active locomotion is somewhat artificial. Sitting needn't be stationary. Infants can locomote in a sitting posture by bum shuffling over flat ground, sliding down slopes, and scooting down steps and drop-offs (Adolph, 1997; Fox, Palmer, & Davies, 2002; Kretch & Adolph, 2013; Patrick, Noah, & Yang, 2012). Similarly, the hands-and-knees posture is not limited to active locomotion. Just as infants can stand upright without walking, they can stand on all fours in one place or rock back and forth (Gesell & Ames, 1940; Goldfield, 1989). Moreover, infants can smoothly transition from crawling to sitting and from sitting to crawling, and they do so at about 7 to 8 months (Adolph et al., 1998). An accurate characterization of infants' exploratory behavior is imperative to understand the functional relations between infants' spatial exploration and cognitive, affective, and social learning (e. g., Campos et al., 2000; Horobin & Acredolo, 1986; Kermoian & Campos, 1988; Schwarzer, Freitag, Buckel, & Lofruthe, 2012). Nonetheless, motor development researchers have largely ignored functional synergies between sitting and crawling in favor of the distinct milestone approach.

Current Studies

The present research aimed to characterize transitions between crawling, sitting, and quadrupedal stance. Study 1 employed a traditional approach to studying infant locomotion: Infants were encouraged to crawl continuously down a long straight walkway. In Study 2, we observed infants during spontaneous free play to document crawl-to-sit transitions in natural, unconstrained exploration. In both studies, infants were tested in the lab and in their homes to ensure that observations were not affected by infants' drive to explore a novel environment or, conversely, their reticence to locomote in an unfamiliar place.

We anticipated that infants' crawling exploration would be segregated into short bursts of locomotion and longer bouts of quiescence, similar to upright walking a few months later (Adolph et al., 2012). However, pilot testing revealed that unlike walking infants, who stop locomotion by standing still, crawlers stopped locomotion by frequently transitioning to a sitting posture. Moreover, when they sat up, they often reoriented their bodies so that they were facing 90° away from their original direction of heading. Also, unlike walking, every infant displayed a variety of crawling and sitting configurations. Thus, we examined the frequency and form of crawling, sitting, and stance, sequential relations among these behaviors, and changes in body orientation that occur during these postural transitions.

Study 1. Crawling Along a Straight Path

In Study 1, we observed infants crawling over a straight, flat walkway. Parents and experimenters endeavored to keep infants crawling continuously over the walkway using encouragement, toys, and food. Half of the infants were tested in the laboratory and half in their homes.

Method

Participants—We tested 20 infants (14 boys, 6 girls) between 9.89 and 11.90 months of age (*M* = 10.87 months), 10 infants in the lab and 10 in their homes. Families were recruited through mailing lists, referrals, and hospitals from the greater NYC metropolitan area. Most infants were white and of middle-class socioeconomic status. All were healthy and born at term. Following a strict protocol (Adolph, 2002), a highly trained experimenter interviewed parents about the first day they saw their infant sit independently (on the floor with legs outstretched for 30 s without using the hands for support) and the first day they witnessed their infant crawling (on all fours with the belly off the floor for a distance of 3 m without stopping or falling). Parents augmented their memories by referring to family "baby books," calendars, and electronic records. We verified in the laboratory that all infants could crawl 3 m without stopping and could sit independently. Sitting experience ranged from 1.61 to 6.31 months (M = 4.81 months) and crawling experience ranged from 0.49 to 5.52 months (M = 2.50 months); experience was similar for infants tested in the lab and at home, ts (18) < 1.2 ps > .2. Test age was correlated with sitting and crawling experience, rs (18) > .44, ps < .05, but sitting and crawling experience were not correlated, r (18) = .26, p > .1. Families received small souvenirs for their participation.

Procedure—In both lab and home settings, infants crawled down a straight, flat path. In the lab, infants were tested on a raised wooden walkway (5.0 m long × 1.0 m wide × 0.64 m high) to constrain them from crawling around the room. The walkway was padded with high-density foam to protect infants' knees and covered with a vinyl runner for ease of cleaning. In the home, infants crawled over a 5.0 × 1.2 m length of denim fabric on the carpeted floor of a long hallway, which served the same purpose as the raised walkway.

In the lab, an experimenter placed infants in a crawling position at one end of the walkway. Caregivers stood at the other end and encouraged their infants to crawl using toys and dry cereal. An assistant, walking a few steps ahead of the infants, provided additional incentive to crawl by enticing them with pull toys. The experimenter followed alongside infants to ensure their safety on the walkway. Each infant crawled 3-7 times (M = 4.50) from one end to the other end of the walkway, although they sometimes paused midway before resuming crawling. Trials were video recorded from two camera views: one provided a lateral view perpendicular to the walkway and a second provided a head-on view from the end of the walkway. The two camera views were mixed into a single video frame for later coding.

In the home setting, caregivers placed infants in a crawling position at the start of the walkway and then raced to the far end of the walkway and coaxed infants to crawl using toys and food as enticements. The experimenter followed infants and helped to encourage them. Each infant crawled over the walkway 1-4 times (M = 2.90). Using a hand-held video camera, the experimenter recorded infants' movements.

Data Coding—A primary coder scored behaviors using computerized video coding software, DataVyu (www.datavyu.org). This software allows coders to identify the duration and frequency of behaviors. A second coder independently scored 25% of each infant's data as a check for reliability. Coders agreed on ≥ 94.1% of behavioral segments ($\kappa \geq .90$) for each code. Disagreements were resolved through discussion.

The coder scored the occurrence of three behaviors: crawling, sitting, and quadrupedal stance (Figure 1). *Crawling* included two forms: moving on hands and knees (both knees) or moving on hands and feet (both feet or one knee and one foot). Each instance of crawling began with the video frame when the leg producing forward movement contacted the floor and ended when infants stopped for at least 1.5 s or switched from one type of crawl to the other. *Sitting* also included two forms: legs-out sitting when one or both of infants' legs were in front of the body and kneel-sitting when both of infants' legs were tucked under or behind the body (with the knees pointing out and the toes pointing backward). Both legs-out sitting and kneel-sitting required infants' buttocks to be in contact with the floor. Each instance of sitting began on the first video frame when the buttocks touched the floor and ended when infants began moving again or shifted to stance. Quadrupedal *stance* was coded when infants were in a crawling position but stopped moving forward for at least 1.5 s. Each instance of stance began on the video frame when the last leg to produce forward movement contacted the floor. Thus, coders identified a new behavioral *segment* every time infants switched among the 5 coded behaviors—hands-knees crawling, hands-feet crawling, legs-out sitting, kneel-sitting, and quadrupedal stance.

The coder also scored infants' *body orientation* in 30° increments during each crawling and sitting segment. To quantify changes in orientation, we superimposed a virtual clock face over the infant (Figure 2), with 12 o'clock aligned to the direction of infants' heading (as indicated by the alignment of their hips).

Results and Discussion

There were no differences between infants tested in the home and in the lab on measures of sitting, stance, and crawling, ts (18) < 1.42 ps > .2, Cohen's d = .14-.67, and infants' body orientation during sitting and crawling χ^2s (4) < 5.60, ps > .2, Cramer's V = .17-.21; so we collapsed across settings. We also found no differences based on infants' sex, ts (18) < 1.57 ps > .13; χ^2s (4) < 3.5, ps > .5, or the number of trips down the walkway, rs (18) < .1, ps > .6.

Crawling, Stance, and Sitting—Despite continuous encouragement, most infants (90%) paused while crawling. Table 1 shows the frequency and duration of crawling, sitting, and stance in the walkway task. Infants mostly crawled on hands and knees (70.1% of crawling segments) and otherwise crawled on hands and feet—often switching between methods several times during a single trip down the walkway. On most occasions when infants paused in crawling, they remained in quadrupedal stance; but in a substantial number of instances, they stopped crawling to sit (31.9% of stops). Pauses in stance were briefer than stops in sitting, t (114) = 2.89, p = .005. The rate of pausing in stance, per minute of crawling, was marginally higher than the rate of stopping to sit, paired t (19) = 2.07, p = .053. Crawling was usually brief, punctuated by changes to a sitting posture that often lasted longer than bouts of locomotion.

Why did infants stop crawling? Crawling experience did not predict whether infants stopped crawling in stance or to sit, ps > .1. Similarly, crawling proficiency (time to crawl the entire length of the walkway without stopping) was not correlated with the rate of stopping in stance or sitting, ps > .1. Rates of stopping also did not increase or decrease across trials, ps > .1. Possibly, natural crawling—at all levels of experience and proficiency—is segmented into brief episodes.

Sequential Patterns—To examine the common sequences of transitions among hands-knees crawling, hands-feet crawling, legs-out sitting, kneel-sitting, and quadrupedal stance, we summarized the sequential relations between behaviors in a transition matrix of 20 possible combinations (Table 2). The definitions of these events precluded self-recursion (i.e., no event category could immediately follow itself). Thus, expected frequencies and degrees of freedom were adjusted to exclude these cells from the models (Bakeman &

Gottman, 1997). Although the sample size was small, a Chi-Square test of quasi-independence confirmed that the overall sequential pattern differed significantly from a random ordering of events, χ^2 (11) = 53.2, N = 281, $p < .001$.

Next, we calculated binomial test z-scores from frequency counts of transitions between each consecutive behavior. Hands-knees and hands-feet crawling differed in their functional relations to sitting and stance. Most notably, transitions from hands-knees crawling directly to legs-out sitting were less common than expected (z = -2.65), whereas hands-knees crawling followed by stance occurred as often as expected by chance ($p > .1$). The sequential transitions between hands-feet crawling and sitting did not differ from chance (ps > .05), but hands-feet crawling preceded stance less often than expected (z = -2.41). Similarly, the two crawling patterns differed in their initiation following stops. Transitions from legs-out sitting and from stance into hands-knees crawling occurred more commonly than expected (zs > 3.20), but transitions from stance to hands-feet crawling were less frequent than expected (z = -4.58). These analyses suggest that hands-feet and hands-knees crawling are not functionally equivalent and may serve different roles during infant activity.

Body Orientation—When infants stopped crawling to sit, the transition to sitting usually caused them to face away from their original heading direction (Figure 3A). An initial comparison of all turn angles to the left versus right revealed no bias in turn direction (Binomial test, p = .6), so we collapsed turns of the same magnitude to left and right in subsequent analyses, creating a seven-point scale in 30° increments. The frequency of the seven turn angles across all crawl-to-sit transitions differed significantly from a uniform distribution (expected values were doubled in left-right collapsed cells from 30-150° in these tests), χ^2 (6) = 47.7, N = 36, $p < .001$.

Body orientation after transitions from crawling to sitting differed for legs-out sitting and kneel-sitting. Legs-out sitting turned infants sharply away from the original direction of heading: over 90% of transitions turned infants' bodies 60° to 120°, χ^2 (6) = 55.9, N = 32, $p < .001$ (Figure 3A, left). But kneel-sitting never turned infants more than 30° from the original heading direction. Transitions from a sitting posture back to crawling also resulted in changes in body orientation (Figure 3B). Transitions from legs-out sitting back to crawling again involved nearly right-angle turns: 70% of transitions were turns of 60° to 120°, χ^2 (6) = 26.1, N = 27, $p < .001$ (Figure 3B, left). Thus, infants typically faced the caregiver at the end of the walkway before and after stopping to sit (but not during); over 75% of transitions from crawling to sitting and from sitting back to crawling involved net changes of orientation of 30° or less, χ^2 (6) = 50.7, N = 13, $p < .001$.

Why would infants turn away from the direction of heading (see Ieft side of Figure 3A) so that they could no longer easily see the goal? It is unlikely that they turned to explore the rest of the room or to interact with the experimenter. They never turned away from the goal in kneel-sitting or stance, and they turned away from the experimenter as frequently as they turned toward him. A likely possibility is that the transition from crawling to legs-out sitting imposes biomechanical constraints that are most easily overcome by turning. Turning away from the direction of heading would have profound effects on infant exploration, especially in spontaneous locomotion where infants select their own goals.

Study 2. Spontaneous Crawling

The standard crawling task used in Study 1 is designed to provide measures of crawling proficiency and gait patterns. However, the standard crawling task—coaxing infants to crawl continuously along a straight path—is not representative of spontaneous infant crawling under natural conditions (Adolph et al., 2012). During free play, infants can (and do) move in every direction and there is no walkway that constrains their direction of travel.

Would infants show a similar tendency to interrupt spontaneous crawling in the same way as they did in the standard crawling task? If so, would there be further evidence of sequential relations among crawling and stopping behaviors? Moreover, if transitions from crawling to sitting turn infants away from their original direction of heading, would the transition from sitting to crawling return them to the original path or would they set off in a new direction? In Study 2, we addressed these questions by observing sequences of spontaneous crawling during free exploration in a large laboratory playroom and in the family home. Again, observing infants in the lab and home would allow us to assess whether the rates of crawling and stopping and the patterns of body orientations were affected by the novelty of the laboratory environment or endemic to spontaneous exploration across context.

Method

Participants—We observed 20 infants (9 boys and 11 girls) during spontaneous, free play: 10 in the laboratory and 10 in their homes. Infants were between 10.39 and 12.23 months of age (M = 11.41 months). All could sit independently and crawl 3 m without stopping, as defined in Study 1. Sitting experience ranged from 1.61 to 5.92 months (M = 4.57 months) and crawling experienced ranged from 0.85 to 6.15 months (M = 2.77 months); experience was similar for infants tested in the lab and at home, ts (18) < 1.95, ps > .05. Sitting and crawling experience were correlated with testing age, rs (18) > .45, ps < .05, but were not intercorrelated, r (18) = .24, p > .1.

Procedure and Data Coding—Infants tested in the lab could move freely through the lab playroom; infants tested at home could freely enter any room of the house but were not permitted on stairs. The lab playroom (8.66 × 6.96 m) had a varied layout (steps, slides, large unobstructed areas). Infants' homes differed in layout and size. In both laboratory and home settings, caregivers were allowed to interact with infants as they would normally. Caregivers were told that we were interested in infant exploration and play. In most cases, caregivers in the laboratory sat on a couch and monitored infants' activity; caregivers in the home did chores or watched television while monitoring infants' activity and interacting intermittently. The experimenter video recorded infants with a hand-held camera as they crawled around the room. Coders scored at least 20 minutes of video from each infant in each setting using the same criteria as in Study 1. Coders agreed on ≥ 91.1% of segments (κ ≥ .88).

Results and Discussion

We again collapsed across settings, since we found no differences between infants tested in the lab and those tested at home for measures of sits, stances, and crawls, ts (18) < 1.67 ps

> .1, Cohen's d = .01-.79, and infants' body orientation, χ^2s (4) < 9.0, ps > .1, Cramer's V = .05-.08. As in Study 1, we found no sex differences, ts (18) < 1.4, ps > .15; χ^2s (4) < 9.0, ps > .1.

Crawling, Stance, and Sitting—Table 3 shows the frequency and duration of crawling, sitting, and stance during free play. As in Study 1, infants typically crawled on hands and knees (66.7% of segments), rather than hands and feet, and the average hands-knees segment was longer in duration than the average hands-feet segment, t (530) = 10.03, p < .001. Without concerted encouragement to crawl continuously, in Study 2 crawling segments were shorter in duration, t (781) = 4.05, p < .001, and stopping was longer in duration, t (444) = -2.40, p = .017. In about half of the stops, infants transitioned to sitting (44.5% of stops), and in about half they remained in quadrupedal stance. Pauses in stance were briefer than stops in sitting, t (328) = 5.22, p < .001. The rate of pausing in stance per minute of crawling was similar to the rate of stopping to sit, paired t (19) = 1.64, p = .12. Crawling experience was unrelated to the rate of stopping in stance or sitting, ps > .1.

Sequential Patterns—Sequences of crawling, sitting, and stance were analyzed as in Study 1 (see Table 4). A Chi-Square test of quasi-independence revealed that the overall sequential pattern differed significantly from a random ordering of events, χ^2 (11)= 141.8, N = 671, p < .001. Figure 4 summarizes patterns of sequential transition among hands-knees crawling, hands-feet crawling, legs-out sitting, kneel-sitting, and stance.

The larger number of observed event transitions in Study 2 allowed us to refine our characterization of the functional asymmetry found between hands-knees and hands-feet crawling in Study 1. Hands-knees crawling most commonly transitioned to either stance (z = 3.33) or hands-feet crawling (z = 2.57) but seldom transitioned to legs-out sitting (z = -6.42). In contrast, kneel-sitting, albeit rare, predominantly followed hands-knees crawling directly (81.8% of transitions to kneel-sit). The overall sequential pattern suggested that infants relied on hands-knees crawling as the predominant form of forward progression, occasionally pausing in stance. To transition into sitting, infants either paused briefly in stance or shifted from hands-knees crawling to hands-feet crawling. Thus, stance and hands-feet crawling appear to serve similar roles: as intermediary patterns between hands-knees crawling and legs-out sitting.

Unlike transitions into sitting, transitions from sitting back to crawling did not involve intermediary patterns. Legs-out sitting was followed directly by hands-knees crawling more often than expected (z = 6.58) and by hands-feet crawling (z = -3.66) or stance (z = -2.89) less often than expected. Kneel-sitting exclusively transitioned directly to hands-knees crawling.

Body Orientation—Using the same procedure as in Study 1, we quantified changes in body orientation before and after transitions from crawling to sitting. Figure 5A shows the overall distribution of body orientations after transitions from crawling to sitting. The frequency of the seven turn angles differed significantly from a uniform distribution, χ^2 (6) = 175.9, N = 148, p < .001. As in Study 1, nearly 90% of transitions from crawling to legs-out sitting resulted in turns of 60° to 120°, χ^2 (6) = 203.1, N = 137, p < .001 (Figure 5A, left), and kneel-sitting resulted in no change in body orientation greater than 30° (Figure 5A, right).

Transitions from a sitting posture back to crawling also resulted in turning from the sitting orientation (Figure 5B). However, transitions back to crawling were distributed more widely than the modal 90° turns of Study 1, which re-oriented infants to their original path of progression on the walkway. In the unconstrained settings of Study 2, almost half of transitions from legs-out sitting to crawling resulted in turns of less than 60° or more than 120°—causing further deviations in their body orientation, χ^2 (6) = 27.1, $N = 112$, $p < .001$ (Figure 5B, left). Even kneel-sitting resulted in variable changes in body orientation in the transition back to crawling, with the 9 observed transitions distributed evenly between 0° and 90° (Figure 5B, right).

The interruption of crawling by sitting resulted in a net change of 0° to 180° in infants' heading direction in subsequent crawling (Figure 6). Overall, these changes in orientation were distributed broadly, with less than half of the crawl-sit-crawl sequences involving net changes of 30° or less (thereby restoring the original heading direction), and 34% involving reversals of direction of 150° or more, χ^2 (6) = 32.0, $N = 73$, $p < .001$. Thus, during spontaneous crawling, infants often altered their crawling direction radically, sometimes doubling back on their original heading after sitting.

General Discussion

Some of the findings from this study may seem obvious: Every parent knows that during spontaneous activity infants sometimes stop crawling to sit, and they often transition from sitting to crawling. The fact that infants stop crawling in the walkway situation where they are encouraged to crawl continuously toward a goal is also not surprising; every researcher would agree that infants are often recalcitrant. But *why* infants stop crawling to sit up is not so obvious; why not simply stand there on all fours? Moreover, other findings from this study were a surprise to us: When infants transition from crawling to sitting, the process turns their body sharply away from the initial direction of heading—potentially affecting how they access visual information. And the finding that transitions from sitting back to crawling set infants off in a completely new direction during spontaneous activity is also remarkable and may have important implications for understanding the development of exploratory behavior.

Why Do Infants Interrupt Crawling to Sit?

Both studies showed that infants frequently stop crawling. They do so during spontaneous activity (Study 2), and they do so even when coaxed to crawl continuously (Study 1). We doubt that the stopping behavior reflects changes in proficiency (we found no relation between stopping rates and crawling experience) or that infants were becoming fatigued or learning the task (we found no differences in stopping rates between the beginning and end of the sessions). On the walkway, there were no toys or other interesting diversions in their immediate vicinity, and they were as likely to turn away from the experimenter as toward him. We also found no differences between lab and home environments, paralleling similar results from home and lab observations of infant walking (Adolph et al., 2012). The novelty of the laboratory or familiarity of the home likely did not contribute to infants' frequent stops.

What remains as an explanation is simply that infant crawling, much like infant walking several months later, is typically segmented into brief episodes. In fact, most bouts of infant walking consist of only 1-3 steps (Adolph et al., 2012), and in the current study we found crawling segments to be short (1-3 s in duration). Moreover, these observations of human infant locomotion mirror those found throughout the animal kingdom (Kramer & McLaughlin, 2001), where exploration occurs in fits and starts to allow time for processing of perceptual information and to improve endurance. Thus, frequent pausing is endemic to spontaneous and elicited locomotion across environments, locomotor postures, and species.

But why should infants who briefly stop crawling bother to sit? Although infant walkers stop a lot, they rarely stop walking to sit (K. E. Adolph, unpublished data). And we could find no mention of postural reversions in intermittent locomotion in non-human animals. The time and effort to enact the crawl-to-sit transition may not seem great, but the rates observed in Study 2 during spontaneous crawling—7 crawl-to-sit transitions per minute of crawling—suggests that the accumulated time and effort are substantial. Previous research has shown that infants devote about 20% of each hour to crawling (Adolph et al., 2012). Thus, infants may transition from crawling to sitting more than 80 times per hour, amounting to hundreds of times each day.

What might sitting buy infants that they can't get from remaining in quadrupedal stance? Recent work with infants wearing head-mounted eye trackers suggests that sitting up offers infants an expanded view of the room (Kretch et al., in press). While crawling, infants primarily see the floor in front of their hands, since they do not consistently crane their necks upward to compensate for their angled-down heads. But while sitting and standing, the whole room comes into view. Therefore, infants may stop crawling to sit so that they can actually see where they are going. Ironically, changes in body orientation during the crawl-to-sit transition may obscure infants' view of where they had been heading.

Why Does Sitting Position Affect Body Orientation?

In 95% of cases across Studies 1 and 2 when infants transitioned from quadruped to legs-out sitting, the transition turned their bodies at least 60° away from the original direction of heading. Most frequently, the transition caused a 90° shift in body orientation. The transition from quadruped to kneel-sitting never caused a shift larger than 30° away from the original direction of heading. Why should transitions into these two forms of sitting, both achieved by the age of 9 months (Bly, 1994) have such different consequences for body orientation?

We believe that the answer has to do with the biomechanics of infants' movements. Qualitative observations of our video records suggested that infants pushed perpendicular to gravity to achieve kneel-sitting but moved with the assistance of gravity when transitioning into legs-out sitting. The sequential relations among hands-knees crawling, hands-feet crawling, and sitting supports this interpretation. During hands-feet crawling, infants briefly placed one foot forward, breaking the symmetrical posture of hands-knees crawling and allowing them to shift their body weight over the hips into a sitting posture. The outcome is

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an asymmetric maneuver that results in a sharp change in body orientation relative to the original direction of heading.

Why would infants prefer to roll over one hip rather than pushing directly back into a kneel-sit? (Note that kneel-sitting comprised only 8% of sits.) Rolling the body over one leg may be easier than other ways of transitioning into the legs-out sitting posture: pushing the hips backward into a straddle split and then pulling the legs toward the front of the body or sitting to the side and then releasing one leg (Bly, 1994). Only infants displaying hip joint hypotonicity and low muscle tone—for instance, those with achondroplastic dwarfism or Down syndrome— routinely transition from crawl-to-sit by pushing directly over the hips (Åkerström & Sanner, 1993; Fowler, Glinski, Reiser, Horton, & Pauli, 1997). Furthermore, this asymmetric movement may have antecedents in earlier-emerging postural transitions. An important milestone in motor development is the ability to roll from a supine to a prone posture (McGraw, 1945). A recognizable posture in this developmental sequence is the 5-month-old recumbent lateral flexion posture (Bly, 1994), known among pediatric physical therapists as the “Burt Reynolds” posture, in which infants roll to one side with the contralateral leg shifted over the body and the foot placed on the ground in front of the groin. This body position, with one leg flexed and the foot firmly planted to provide traction and leverage is precisely the position of the leg and foot contralateral to the direction of turning during the crawl-to-sit transition.

These studies are the first that we know of to present frequencies and descriptors of these full body reorientations accompanying natural crawling. Although motor development texts and standardized infant assessments describe transitions between crawling and sitting postures (Bayley, 2006; Bly, 1994; Mullen, 1995; Piper & Darrah, 1994), they are agnostic about the orientation of infants’ bodies before, during, and after these transitions. In fact, many of the depictions of the crawl-to-sit transition entail an infant being coaxing forward directly over their outstretched legs (e. g., Mullen, 1995). We found the ubiquity of these reorientations to be surprising, because although they may make sense biomechanically, they are counter-intuitive for perceptual exploration. The infant is now facing away from the previous direction of heading.

Body Orientation and Opportunities for Learning

This radical shift in body orientation may have important implications for infant exploration. Common sense intuition, endorsed by Piaget (1954), Gibson (1988), and Campos (2000), is that independent mobility allows infants to identify distal goal objects and employ crawling as a means to attain those goals. However, common sense intuition is not supported by recent observations (Adolph et al., 2012; Karasik et al., 2011; Kretch et al., in press) or the current studies. Natural infant locomotion—crawling or walking—does not consist of long paths terminating in arrival at a pre-specified goal. For crawlers, visual exploration of the world is segmented into brief periods of staring at the floor while in motion, interspersed with more encompassing views of the world while sitting (Kretch et al., in press). The goals identified at the beginning of a crawling sequence are likely to be revised after shifts in body orientation as infants transition to sitting and revised again as infants transition back to crawling and head off in different directions. Only in Study 1, where infants had a clearly defined goal—the caregiver— and physical constraints on their paths—the walkway—did they regularly return to their original heading orientation. Thus, in free play, the biomechanical constraints imposed on the crawl-tosit-to-crawl transitions expand infant exploration into a larger space, but also may interfere with goal-directed locomotion by thwarting infants' initial intentions.

Future research may, however, reveal potential benefits for spatial learning that stem from infants' punctuated visual exploration and jagged crawling routes. Crawl-to-sit transitions may naturally segment infants' visual experiences into temporally and spatially distributed chunks. Distributed learning is the most effective way to promote retention for spatial learning (Commins, Cunningham, Harvey, & Walsh, 2003; Goodrick, 1973). A second potential benefit may be that infants are not crawling over long stretches of time and space; they are making sharply angled turns in numerous short bursts. These angled routes could affect how infants encode spatial layout (see Newcombe, Huttenlocher, Drummey, & Wiley, 1998). At 9 months of age, infants fail to locate hidden objects after being moved in a combined linear-rotation path (Landau & Spelke, 1988). We found this type of spatial reorientation to be common following crawl-to-sit transitions. Indeed, it is possible that crawling infants' frequent body reorientations may explain why 12-month-infants can successfully search for hidden objects even after complex geometric reorientations, especially if they are allowed to self-locomote (Acredolo, Adams, & Goodwyn, 1984; Clearfield, 2004). Because researchers have historically viewed crawling and sitting as dissociated milestones, they presumed that crawling infants only experience linear translations and not rotations of their bodies: “Translations with rotations are not likely to be experienced very often by [crawling] infants” (Campos et al., 2000, p. 204). As a consequence, the traditional segregation of crawling and sitting may have limited the scope of research examining the cascading effects of motor behavior on spatial cognition and other psychological domains.

Many of these purported benefits, however, are not relegated to crawling, which shares intermittent locomotion with upright walking (Adolph et al., 2012) at a later age. Moreover, walking infants see more of the environment (Kretch et al., in press), share objects with caregivers in more varied ways (Karasik et al., 2011), and cover more ground (Adolph et al., 2012). For infants at risk for motor delays, encouraging independent mobility as early as possible whether through upright walking, crawling, or assistive devices (e. g., Huang, Ragonesi, Stoner, Peffley, & Galloway, 2014) is likely the best course of action. Future research should investigate whether crawling, sitting, and transitions between them create unique perceptual experiences that impact early learning. The current results do suggest that for clinicians interested in promoting crawling, focusing on the transitions to and from sitting— especially lateral transitions—might be helpful in facilitating typical patterns of crawling exploration. Yet, the ubiquity of our findings should be considered within the wider scope of cultural and socioeconomic variation in motor skill acquisition (see Adolph, Tamis-LeMonda, & Karasik, 2010). With only 20 infants in each group, selected for displaying “typical” crawling patterns, and coming from mostly White, middle-class backgrounds, we cannot be certain that our results broadly represent early spatial exploration across crawling styles and experiences.

Conclusions: Distinct Milestones or Functional Synergy?

Traditionally, crawling and sitting are studied as distinct action systems that serve different functions during infancy: Sitting is a static posture and functions as a stable base for exploring proximal objects and viewing the larger layout; crawling is a form of locomotion and functions as a means for retrieving distal objects and exploring the larger layout. Our findings suggest to the contrary that crawling and sitting are intimately interrelated and may best be viewed as a functional synergy for gaining visual access to the world and for locomotor exploration. The postural transitions between sitting and crawling may be just as important for facilitating new opportunities for infant learning as the attainment of sitting and crawling milestones. As such, understanding the real-time transitions between behavioral forms may provide insights into how new motor skills propagate a cascade of developmental change.

Acknowledgments

This research was supported by Grant R37-HD33486 from the Eunice Kennedy Shriver National Institute of Health and Human Development to Karen E. Adolph. The content is solely the responsibility of the authors and does not necessarily represent the official views of the Eunice Kennedy Shriver National Institute of Health and Human Development or the National Institutes of Health. Portions of this work were presented at the 2010 meeting of the International Society for Developmental Psychobiology, San Diego, CA and the 2011 meeting of the Society for Research in Child Development, Montreal, Canada.

We gratefully acknowledge Adam Lurie for coding assistance and the members of the NYU Infant Action Lab for their help collecting data and for providing comments on the manuscript. We thank Gladys Chan for her beautiful illustrations.

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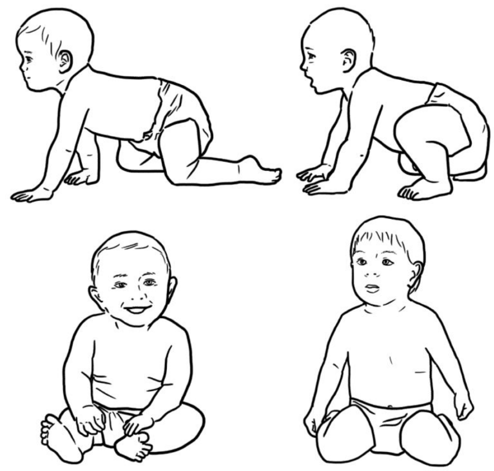

Figure 1. Different patterns of crawling and sitting distinguished in Studies 1 and 2. Panels depict typical hands-knees crawling (top left), hands-feet crawling (top right), legs-out sitting (bottom left), and kneel-sitting (bottom right). The fifth behavioral category—quadrupedal stance—is a stationary posture resembling hands-knees crawling with all four limbs in contact with the ground.

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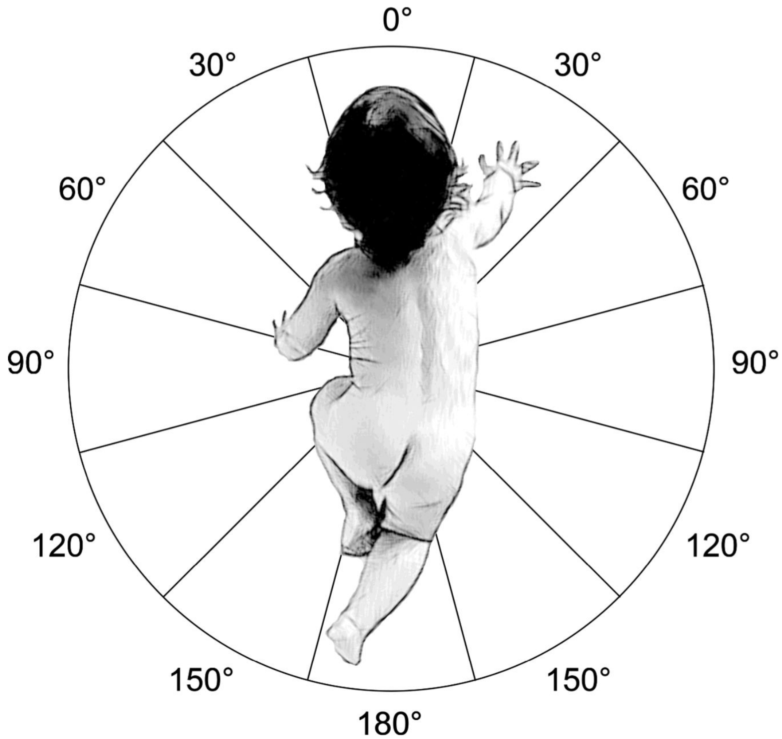

Figure 2.
Virtual clock face illustrating the method used to score changes in body orientation, in 30° increments, during transitions between crawling and sitting. 12 o'clock on the clock face (0°) represents the facing direction of the body (as indicated by the hips) immediately before the transition. For analysis, the clock face was collapsed left-right (as there were no laterality effects), resulting in seven turning magnitudes from 0° to 180°.

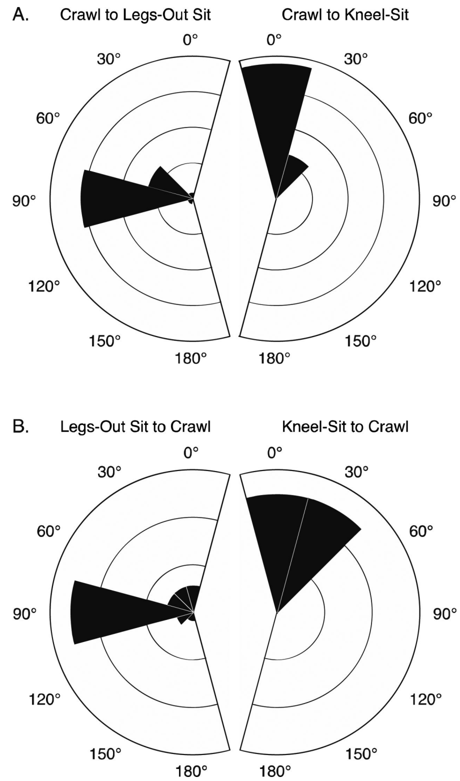

Figure 3.

Polar frequency histograms of changes in body orientation during transitions from (A) crawling to legs-out sitting and kneel-sitting and (B) legs-out sitting and kneel-sitting to crawling by infants tested on walkways (Study 1). Concentric circles mark 20% increments in relative frequency.

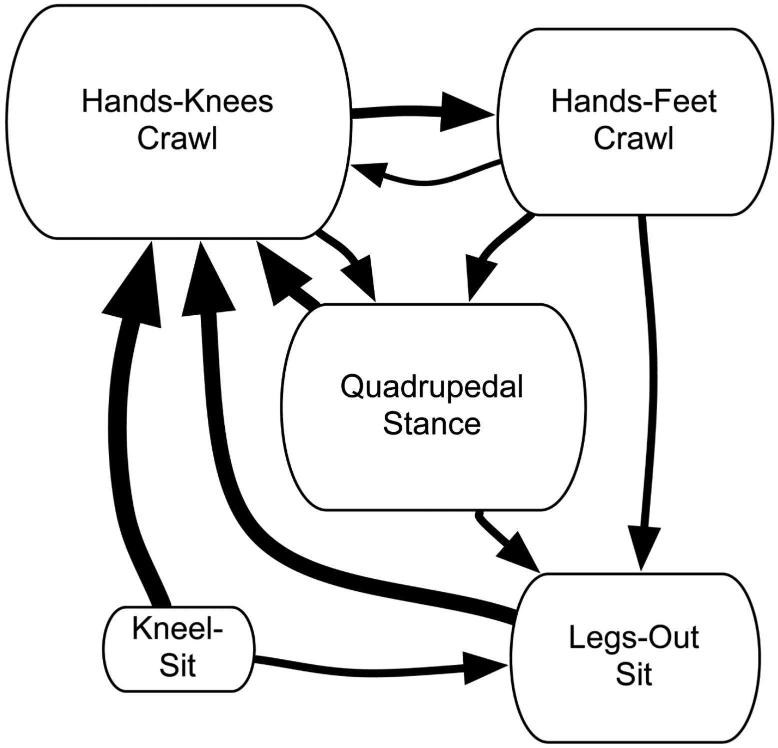

Figure 4.
Patterns of sequential transition during free exploration in Study 2. Arrows depict conditional probabilities of the next behavior in the sequence; arrow width is proportional to the magnitude of the probability. Only probabilities > .20 are depicted. Box size reflects the relative frequency of each behavior.

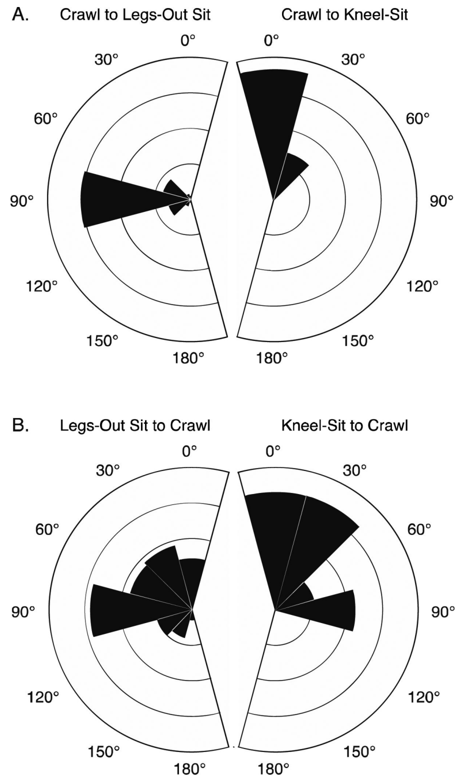

Figure 5.

Polar frequency histograms of changes in body orientation during transitions from (A) crawling to legs-out sitting and kneel-sitting and (B) legs-out and kneel-sitting to crawling by infants tested during free exploration (Study 2). Concentric circles in (A) mark 20% and in (B) mark 10% increments in relative frequency.

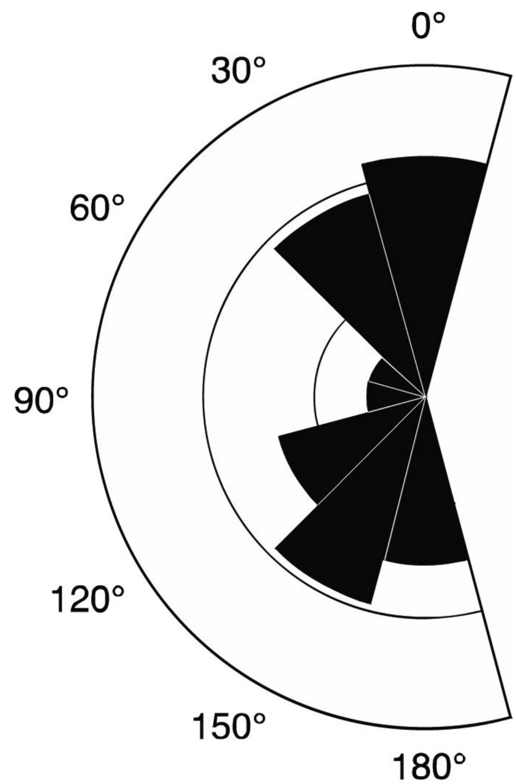

Figure 6.
Polar frequency histogram of changes in body orientation during transitions from crawling to sitting and back to crawling by infants tested during free exploration (Study 2). Concentric circles mark 10% increments in relative frequency.

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Table 1

Frequencies and Durations of Crawling, Sitting, and Stance in Study 1

		Behavioral Segments			Infants			
			Duration		Total Duration		Rate Per min Crawling	
Behavior	**% Infants**	***N***	***M***	***SD***	***M***	***SD***	***M***	***SD***
Crawling (any)	100%	251	3.50	3.41	43.90	23.24	16.69	5.59
Hands-Knees	100%	176	4.43	3.62	38.95	17.53	12.55	3.69
Hands-Feet	70%	75	1.32	1.20	7.08	9.65	5.92	4.33
Sitting (any)	75%	37	6.67	7.81	16.45	15.87	3.07	3.06
Legs-Out	60%	33	7.28	8.06	20.01	15.71	4.45	2.74
Kneel-Sit	20%	4	1.67	0.78	1.67	0.99	1.99	0.47
Stance	85%	79	3.83	2.75	17.79	12.96	5.63	4.47

Note. Statistics calculated for behavioral segments were pooled across infants such that individual infants could contribute different numbers of segments. Statistics calculated for infants were first summed across each infant's segments and then averaged across infants.

Table 2

Frequencies of Sequential Transitions Between Consecutive Actions in Study 1

	Following Action				
Preceding Action	**Hands-Knees**	**Hands-Feet**	**Legs-Out Sit**	**Kneel-Sit**	**Stance**
Hands-Knees	–	56	9††	3	62
Hands-Feet	35	–	10	0	11†
Legs-Out Sit	20**	5	–	0	2†
Kneel-Sit	3	0	0	–	1
Stance	53**	3††	7	1	–

Note.

** Observed > Expected, $p < .01$

† O < E, $p < .05$

†† O < E, $p < .01$

Table 3

Frequencies and Durations of Crawling, Sitting, and Stance in Study 2

		Behavioral Segments			Infants			
			Duration		Total Duration		Rate Per min Crawling	
Behavior	% Infants	*N*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Crawling (any)	100%	532	2.59	2.67	68.91	36.95	25.78	10.60
Hands-Knees	100%	355	3.34	2.92	62.48	55.40	16.11	5.78
Hands-Feet	95%	177	1.08	1.00	10.06	7.51	9.67	8.23
Sitting (any)	100%	150	7.83	6.80	58.70	42.67	6.92	3.54
Legs-Out	100%	139	8.02	6.94	55.77	41.64	6.44	3.77
Kneel-Sit	35%	11	5.32	4.21	8.36	7.38	0.48	0.76
Stance	100%	180	4.74	3.71	42.69	28.42	8.65	6.18

Note. Statistics calculated for behavioral segments were pooled across infants such that individual infants could contribute different numbers of segments. Statistics calculated for infants were first summed across each infant's segments and then averaged across infants.

Table 4

Frequencies of Sequential Transitions Between Consecutive Actions in Study 2

	Following Action				
Preceding Action	**Hands-Knees**	**Hands-Feet**	**Legs-Out Sit**	**Kneel-Sit**	**Stance**
Hands-Knees	–	116**	26††	9	96
Hands-Feet	38†	–	46**	1	44
Legs-Out Sit	88**	††	–	0	25††
Kneel-Sit	7**	0	3	–	0
Stance	77	17††	59**	1	–

Note.

** Observed > Expected, $p < .01$

† O < E, $p < .05$

†† O < E, $p < .01$