

Where Infants Go: Real-Time Dynamics of Locomotor Exploration in Crawling and Walking Infants

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Where do infants go? A longstanding assumption is that infants primarily crawl or walk to reach destinations viewed while stationary. However, many bouts of spontaneous locomotion do not end at new people, places, or things. Study 1 showed that half of 10- and 13-month-old crawlers' ($N = 29$) bouts end at destinations—more than previously found with walkers. Study 2 confirmed that, although infants do not commonly go to destinations, 12-month-old crawlers go to proportionally more destinations than age-matched walkers ($N = 16$). Head-mounted eye tracking revealed that crawlers and walkers mostly take steps in place while fixating something within reach. When infants do go to a destination, they take straight, short paths to a target fixated while stationary.

Why Go?

Why do infants crawl or walk? For more than a century, researchers addressed this question in terms of the developmental onset of locomotion. Dozens of studies investigated the role of balance control, strength, processing speed, and other factors in facilitating infants' first crawling and walking steps (Hallemans, De Clercq, & Aerts, 2006; McGraw, 1945; Zelazo, Weiss, & Leonard, 1989). However, few studies examined the real-time impetus for infant locomotion: What motivates a stationary infant who can already crawl or walk to get up and go?

The predominant, commonsense view is that locomotion is directed toward destinations (Campos et al., 2000; Gibson & Schmuckler, 1989; Piaget, 1954). That is, infants see an alluring person, place, or thing, and then crawl or walk to that destination. In the words of E.J. Gibson (1978),

Exploratory skills in a human infant begin with looking around the world; everything within the baby's field of view provides an incentive. When

mobility is achieved, the baby first reaches for, then creeps toward and finally walks (or runs) for the attractive goal he or she spies (p. 610).

Indeed, mobility in blind infants is delayed relative to sighted infants, and the prevailing explanation is that blind infants cannot see distant destinations that instigate locomotion (Fraiberg, 1977; Gibson & Schmuckler, 1989).

Locomotor Exploration

Although decades of researchers assumed that infants crawl or walk to explore people, places, or things in the visible world, most studies of locomotor exploration were not designed to test this assumption. Instead, most studies focus on *exploration in the service of locomotion* (Adolph, Eppler, Marin, Weise, & Clearfield, 2000; Kretch & Adolph, 2017). In these studies, infants are encouraged to navigate an obstacle between themselves and a goal—typically a caregiver with toys who beckons from the far side of a cliff, slope, drop-off, bridge, or other obstacle (for review, see Adolph & Robinson, 2015). On small drop-offs, shallow slopes, and wide bridges, infants rarely stop to explore—instead, they go straight to the goal. Under more challenging conditions, infants stop and explore at the brink of the precipice by looking, touching, and testing various locomotor options before deciding whether

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and how to cross (Adolph, 1997; Gibson & Schmuckler, 1989; Kretch & Adolph, 2013, 2017; Witherington, Campos, Anderson, Lejeune, & Seah, 2005).

Here we focused on *locomotion in the service of exploration*. We asked how frequently infants go to destinations when allowed to choose their own paths during free play. Of course, infants interact with people and objects, and they do so increasingly over the course of locomotor development (Campos et al., 2000; Karasik, Adolph, Tamis-LeMonda, & Zuckerman, 2012; Karasik, Tamis-LeMonda, & Adolph, 2011; Thurman & Corbetta, 2017). But the focus on reaching new destinations may misrepresent the nature of locomotor exploration. Each individual bout of locomotion need not have a short-term motivation. Instead, bouts of locomotion with seemingly no destination may serve long-term functions by generating information about the body, the environment, and the relations between them.

Indeed, a growing field of research suggests that locomotor exploration may be more of a means unto itself than a means unto an end. Many of infants' spontaneous walking bouts—each instance when infants initiate and terminate a step or sequence of steps—are likely too short (1-3 steps) to carry them to new destinations (Lee, Cole, Golenia, & Adolph, 2018), and many bouts (60%–70%) do not end near discernable destinations such as toys, caregivers, or climbable surfaces (Cole, Robinson, & Adolph, 2016; Hoch, O'Grady, & Adolph, 2018). Infants walk just as much in an empty room as in a room full of toys (Hoch et al., 2018), and they are just as likely to stop walking after five steps as after fifty steps, suggesting that they start and stop stochastically (Cole et al., 2016). Moreover, the prevalence of short bouts and the rarity of destinations persists across the development of walking—at least until 19 months of age (Cole et al., 2016; Lee et al., 2018).

Study 1: Locomotor Exploration in Novice and Experienced Crawling Infants

Compared to walkers, less is known about locomotor exploration in crawlers. Crawling and walking infants play both near and far from active caregivers (Adolph et al., 2012) and leave their seated caregivers to venture into the surrounds or into an adjoining room (Rheingold & Eckerman, 1970). Mobile infants attend more to far space than prelocomotor infants (Campos et al., 2000), and over

weeks of locomotor experience, infants move more (Adolph et al., 2012) and interact with more objects (Clearfield, 2011; Thurman & Corbetta, 2017). However, data about the destination of each crawling bout are limited. Only one study examined the subset of bouts where crawlers carried objects to new destinations (Karasik et al., 2012), and no studies examined the bout destinations of infants with a wide range of crawling experience.

Despite the lack of data, there are good reasons to suspect that locomotor exploration differs between crawlers and walkers. Compared to same-aged walkers, crawlers are less efficient—they take slower, shorter steps, spend less time in motion, and cover less ground (Adolph, 1997; Adolph & Tamis-LeMonda, 2014; Adolph et al., 2012). Moreover, due to their low vantage point, crawlers have limited visual access to faces and objects (Franchak, Kretch, & Adolph, 2018; Frank, Simmons, Yurovsky, & Pusiol, 2013; Kretch, Franchak, & Adolph, 2014). But differential physical and visual access does not lead to clear predictions about locomotor exploration in crawlers. One possibility is that crawlers locomote to destinations less frequently than walkers due to the postural constraints imposed by crawling. While moving on hands-and-knees, infants primarily see the ground, so the sight of a distant target is often lost at the start of the bout (Kretch et al., 2014). When crawlers sit up to regain their bearings, the transition from crawling to sitting causes them to turn 60°–180° away from the original direction of heading (Soska, Robinson, & Adolph, 2015). Thus, compared to walkers who are not subject to these constraints, crawlers may be less able to spot and make their way toward desired destinations.

Alternatively, crawlers might locomote to destinations more often than walkers because crawlers move less than walkers and crawling comes at a greater cost (Adolph & Tamis-LeMonda, 2014; Adolph et al., 2012). For instance, crawlers cope with the limitations of their posture by using different strategies to transport objects. Because their hands are occupied by locomotion, crawlers often resort to bum shuffling or scooting and sometimes carry objects in their mouths or under an arm. Nonetheless, crawlers carry objects to new destinations more often than walkers, who are more likely to stop in the middle of the floor (Karasik et al., 2012). Thus, crawlers may be less likely than walkers to take extraneous steps because crawling is a more effortful locomotor posture than walking.

Study 1 addresses gaps in previous work by examining whether locomotor exploration changes

across the development of crawling skill. We first quantified the spontaneous locomotion of 10- and 13-month-old crawlers. Because previous work showed that infants walk more with increased age and walking experience (Adolph et al., 2012), we expected that older, more experienced crawlers would crawl more than younger, less experienced crawlers. We then determined how frequently crawlers locomoted to new destinations by scoring whether bouts ended within arms' reach of a new person, specific place, or object. If crawlers primarily locomote to reach new destinations, then the majority of their bouts should end near new destinations. However, if like walkers, crawlers do not primarily locomote to new destinations, a high percentage of their bouts should end out of arms' reach of a new destination. Because prior work with walkers showed no effects of age or experience (Cole et al., 2016), we did not expect group differences in the percentage of bouts ending at destinations.

Finally, due to differences in locomotor posture, we expected that the percentage of crawling bouts ending near destinations would differ from the percentage previously reported in walkers (Cole et al., 2016; Hoch et al., 2018). Compared to walkers, a low percentage of crawling bouts ending at destinations would suggest that crawling limits locomotor exploration. A relatively high percentage would suggest that crawlers move more selectively than walkers.

Method

Participants

We tested fifteen 10-month-old ($M = 10.1$, $SD = .3$) and fourteen 13-month-old ($M = 13.0$, $SD = .2$) crawling infants (12 girls, 17 boys). Families were recruited from maternity wards in the New York City metropolitan area and received photographs as souvenirs of participation. Most families were white and middle class. Parents used calendars, baby books, and cell phone recordings to report their child's crawling experience (Adolph, Vereijken, & Shrout, 2003). Dating from the first day infants crawled 3 m on hands and knees, the 10-month-olds had $M = 1.9$ months of crawling experience (range = 0.3–3.3 months), and the 13-month-olds had $M = 4.6$ months of crawling experience (range = 3.3–6.5 months), $t(26) = 7.62$, $p < .001$; Figure 1A. Crawling experience for one 13-month-old crawler was not reported. All infants demonstrated they could crawl 3 m in a standard laboratory test (Adolph, Vereijken, & Denny, 1998).

Procedure and Playroom

Infants played freely with their caregivers in a large laboratory playroom. As shown in Figure 1B, the playroom was filled with elevations (couch, slide with stairs, two sets of 18-cm high risers, a pedestal, a small wooden cube, and a platform) and six toys (ball, "happy apple," toy saxophone, stuffed dog, xylophone, toy car). Infants were filmed from two camera views: a fixed overhead view captured infants' location in the playroom, and an experimenter operated a hand-held camera to obtain a close-up view of infants' arms and legs. We aimed to collect at least 20 min of free play data. Some infants had shorter sessions because they became fussy ($M = 21$ min, range = 15–30 min). Session lengths were comparable between novice and experienced crawlers, $t(27) = 0.11$, $p = .92$.

Data Coding and Processing

Camera views were synchronized with a light flash at the beginning and end of each session and combined using Adobe Premier to produce a composite video for coding. Coders scored videos frame-by-frame using Datavyu—a video-coding tool (datavyu.org). All videos are available on Databrary (databrary.org). To assess interobserver reliability, a second coder scored 25% of each infant's data. Coders agreed on 85% of bout destinations, Cohen's $\kappa = .69$, $p < .001$. The total number of bouts and their durations were highly correlated between coders $r_s \geq .84$, $p_s < .001$. Disagreements were resolved through discussion.

Identification of locomotor bouts. First, coders distinguished *bouts* of crawling (on belly or hands-knees), cruising (holding a support surface), "knee walking" (moving only on knees), and walking (taking a step or two) from periods when infants were stationary. Bouts began when infants moved a knee or foot, and ended when all four limbs/both feet were on the ground for at least 500 ms (Adolph et al., 2012; Cole et al., 2016). Coders also noted whether infants moved independently or with assistance from caregivers (holding infants' hands or torso).

To ensure that analyses focused on infants' decisions to start and stop moving, we excluded bouts when caregivers provided assistance because in those cases we could not determine whether infants or caregivers were guiding the route. Ten-month-old crawlers moved independently for $M = 83\%$ ($SD = 17\%$) of bouts, and 13-month-old crawlers

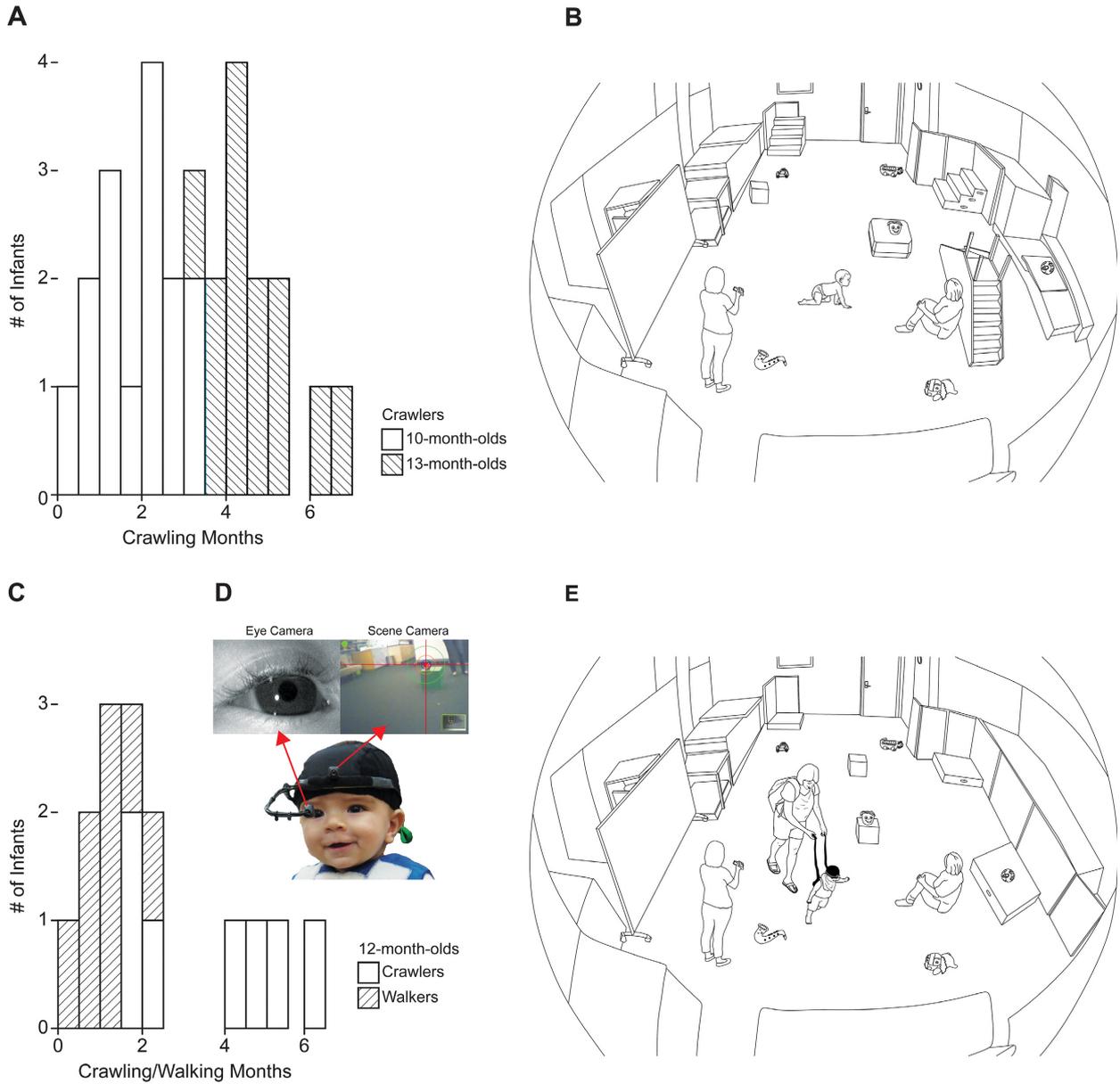


Figure 1. Participants and procedures. Study 1: (A) Crawling experience for 10- and 13-month-old crawlers. (B) Overhead view of playroom. Study 2: (C) Crawling and walking experience for 12-month-old crawlers and walkers. (D) Head-mounted eye tracker. Eye camera records infant's right eye. Scene camera shows infant's point of gaze. Red circle denotes 4° radius of spatial accuracy. (E) Playroom similar to Study 1. Experimenter with harness ensured infants' safety.

moved independently for $M = 88\%$ ($SD = 10\%$) of bouts. To ensure comparable analyses across Studies 1 and 2, bouts of belly crawling, knee walking, and cruising (33% of bouts) were excluded, and although rare ($< 1\%$), bouts of independent walking were included.

Bout terminations. Coders scored where each bout ended using a coding scheme similar to Cole et al. (2016) and Hoch et al. (2018). Some bouts ended at a new, specific destination and some did

not. New destinations were previously out of reach objects (e.g., toys), the caregiver, elevations (e.g., climbing up/down a step), or features of the environment (e.g., edge of the carpet, divot in the floor). Bouts ending at no destination were steps in place (e.g., in the middle of the room, or in front of a destination in reach for the entirety of the bout), or bouts that covered ground but ended when infants stopped locomoting out of arms' reach of a recognizable destination (e.g., in the middle of the

room or an elevation). Finally, some bouts ended because infants *fell* (lost balance and dropped to the floor) or were picked up and *held* by a caregiver.

Results and Discussion

Amounts of locomotion were computed as rates or percentages to account for differences among individual infants and because sessions differed in length. For bout level analyses (e.g., comparisons of bout terminations), we used generalized estimating equations (GEEs) because infants moved freely and thus contributed different numbers of nested observations (bouts). For continuous variables, we used an identity link function with an independent covariance structure. For dichotomous outcomes (destination, no destination), we used binary logistic GEEs with a logistic link function and an independent covariance structure. Preliminary analyses showed no effects of gender, so it was collapsed in subsequent analyses.

Amount of Locomotion

In contrast to previous work with walkers (Adolph et al., 2012), crawlers' age and experience did not predict more locomotion. In total, 10-month-olds contributed 902 bouts and 13-month-olds contributed 1017 (range = 30–125 bouts per infant). One 10-month-old and five 13-month-olds produced short bouts of walking (range = 1–9 bouts), but none walked 3 m without falling or stopping. Ten- and 13-month-olds spent equal time in motion, fell just as frequently, and produced the same number of bouts per hour (Table 1). Bouts were generally short in duration (range = 0.1–24.9 s) and did not differ between 10- and 13-month-olds (Table 1). Across age groups, time in motion, bouts per hour, falls per hour, and bout duration were not correlated with parent reports of crawling experience, $r_s(26) \leq .30$, $p_s \geq .14$. Likely, we failed to find correlations between crawling experience and amount of activity because the data set included few truly novice crawlers (only three infants with < 1 month of experience and only six with < 2 months). In previous work with walkers, the strongest improvements occurred over the first 2 months of walking (Adolph et al., 2012).

We found no evidence that infants became either bored or more adventurous over the 20-min play period. The percentage of time spent in motion and number of bouts per hour did not differ between the first and second halves of the session, $t_s \leq 0.90$, $p_s \geq .38$.

Table 1
Comparisons Between 10- and 13-Month-Old Crawling Infants

	10-month-olds		13-month-olds		<i>t</i> (27)	<i>p</i>
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>		
% Time in motion	15.64	5.55	19.11	6.64	1.53	.137
Falls per hr	11.62	8.86	8.78	7.43	0.93	.359
Bouts per hr	192.28	82.05	225.27	56.96	1.25	.222
Bout duration (s)	3.04	0.58	3.09	0.98	0.170	.866

Destination Versus No-Destination Bouts

Our central question was whether the majority of crawling bouts ended at a destination. About half the time they did. Whereas in previous work (Cole et al., 2016), walkers were less likely to go to destinations than not, crawlers were equally likely to do both, suggesting that locomotor posture influences locomotor exploration. Overall, 53% of crawlers' bouts ended at a destination. A binary logistic GEE confirmed that crawlers locomoted to destinations just as often as no destination, and that 10- and 13-month-olds did not differ (Wald $\chi^2_s \leq 1.96$, $p_s \geq .16$; see Figure 2A). The percentage of bouts ending at destinations did not differ between the first and second halves of the session, $t_s \leq 0.90$, $p_s \geq .38$. Our findings corroborate previous work with walkers (Cole et al., 2016; Hoch et al., 2018) showing that age, locomotor experience, and exposure to a new environment (as estimated by the split-session analysis) did not affect the percentage of bouts ending at a destination.

As in previous work with walkers (Cole et al., 2016; Hoch et al., 2018), most of crawlers' bouts to destinations ended at objects or elevations, not caregivers. A GEE revealed a destination type (objects, elevations, features of the environment, caregiver) by age group interaction, Wald $\chi^2(3) = 20.99$, $p < .001$. Post hoc comparisons revealed that 10-month-olds had a larger percentage of bouts ending at objects and caregivers and a smaller percentage of bouts ending at elevations than 13-month-olds, $p_s \leq .03$ (see bottom panel of Figure 2B). Thus older, more experienced infants spent more time exploiting affordances for climbing.

When bouts ended at no destination, crawlers mostly took steps in place. A GEE revealed a main effect of no-destination type (steps in place, stopped, fall/held), Wald $\chi^2(2) = 307.36$, $p < .001$, but not age group, Wald $\chi^2(2) = 2.49$, $p = .115$. Post hoc comparisons revealed that for both 10-

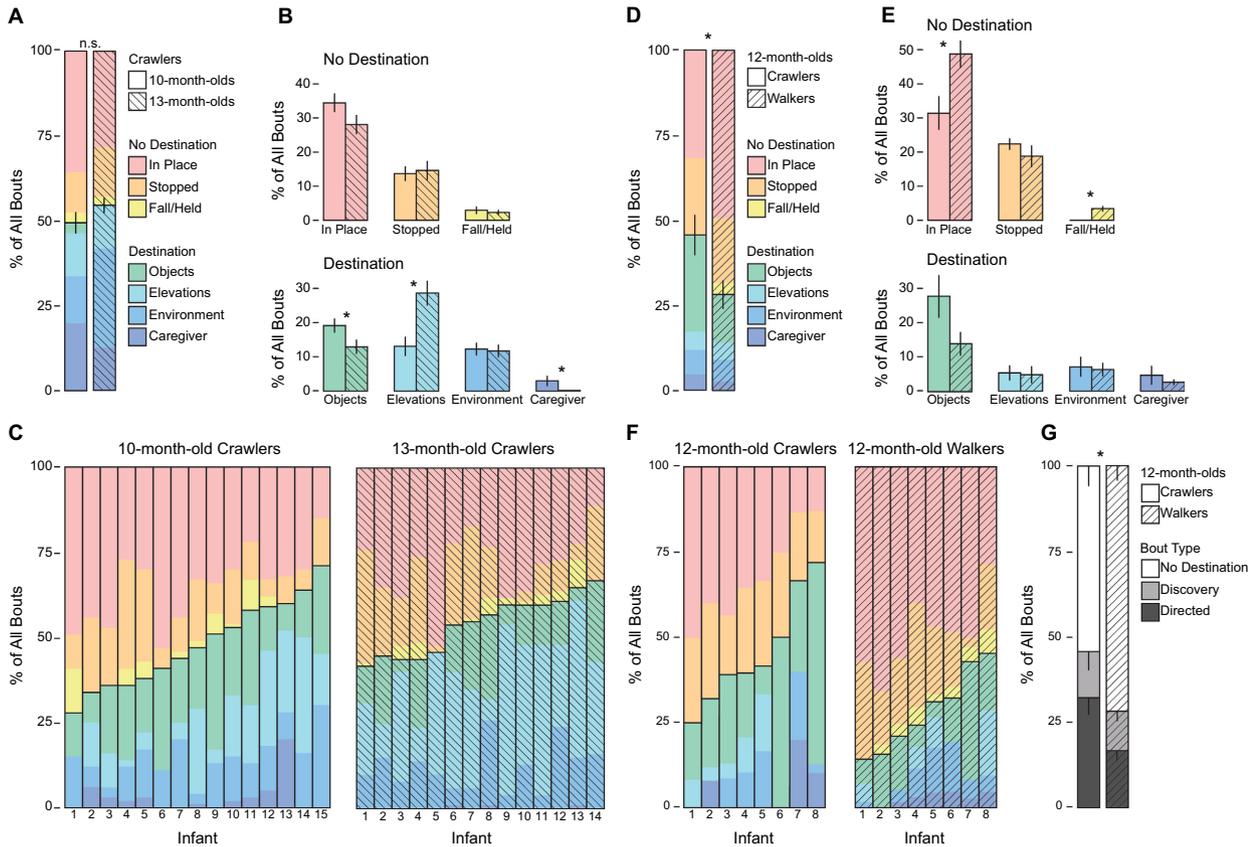


Figure 2. Bout terminations and bout types. Study 1: (A) Average percentage of bouts ending at a destination (cool colors) and no destination (warm colors) for 10- and 13-month-old crawlers. (B) Pairwise comparisons of bout terminations. (C) Bout terminations for each infant ordered by percentage of destinations. Study 2: (D) Average percentage of bouts ending at a destination and no destination for 12-month-old crawlers and walkers. (E) Pairwise comparisons of bout terminations. (F) Bout terminations for each infant ordered by percentage of destinations. (G) Average percentage of bout types: no-destination, discovery, and destination-directed bouts. (A–G) Error bars denote standard errors. (A and D) Error bars are reciprocal for destination and no-destination bouts; asterisks denote $p < .05$ in pairwise comparisons between groups. [Correction added on April 27, 2020 after first online publication: the sentence “(D) Bout terminations for each infant ordered by percentage of destinations” has been changed to “(F) Bout terminations for each infant ordered by percentage of destinations”.]

and 13-month-olds, steps in place were followed by bouts where infants stopped crawling in the middle of the room, and finally bouts where infants fell or were picked up and held by their caregiver, $ps \leq .005$ (see top panel of Figure 2B). Group patterns of locomotor exploration were reflected in data from individual infants (Figure 2C).

Summary of Study 1

As in previous research with walkers, a large percentage of crawlers’ spontaneous locomotion does not end at new destination. Although crawling is effortful, crawlers also take many steps in place or stop crawling before reaching something new. We found no difference in the percentage of bouts ending near destinations between 10- and 13-month-

olds, and no correlation with crawling experience. Thus, infrequent bouts to destinations were not due to younger infants’ poor crawling skill. However, the 10- and 13-month-old crawlers in Study 1 locomoted to destinations more often than 13-,15-, and 19-month old walkers in prior work (30%–40% of bouts in Cole et al., 2016, and Hoch et al., 2018). These findings suggest that, compared to walking, a higher percentage of crawling bouts end at destinations.

Study 2: Real-Time Dynamics of Crawling and Walking

In the context of previous work, Study 1 suggests that locomotor posture influences locomotor exploration. In Study 2, we tested this hypothesis directly by comparing same-aged crawlers and walkers. The

age-held-constant design controlled for age-related changes whereas the factor of interest—locomotor posture—varied. We focused on 12-month-olds because, at that age, about half of infants can walk and half only crawl. Based on previous work, we expected that 12-month-old crawlers would move less than 12-month-old walkers (Adolph et al., 2012). Although we also expected that crawlers would have more crawling experience than walkers have walking experience, the results of Study 1 and findings from Cole et al. (2016) suggest that the propensity to travel to new destinations does not change over several months of locomotor experience within each posture.

Study 1 and previous work (Cole et al., 2016; Hoch et al., 2018) relied on analyses of what was in reach when infants *stopped* locomoting—whether they traveled to something new or not. But, the number of bouts ending at a destination does not reveal what *instigated* a bout of locomotion—whether infants crawl or walk toward an attractive goal spied while stationary, as Gibson (1978) proposed. Thus, infants in Study 2 wore a head-mounted eye tracker so we could record their point of gaze as they moved through the playroom. The eye tracker allowed us to describe occasions when infants fixated and then moved to a new destination and where infants looked when they did not go to a new destination. Moreover, the eye tracker allowed us to test whether destination-related fixation patterns differed between crawlers and walkers.

Previous work using head-mounted eye tracking shows that fixations guide upcoming actions. For example, when preparing a sandwich or a cup of tea, adults look at a target before their hands move to that target (for review, see Land & Hayhoe, 2001). Similarly, when infants are presented with a prescribed task such as navigating an obstacle to reach a caregiver at the end of a raised walkway, infants fixate their destination and then move to its location. Infants only make brief glances to the obstacle; mostly, they look at the destination (Kretch & Adolph, 2017).

Less is known about where infants direct visual attention during free play, but new data from head-mounted eye tracking reveal some surprising findings. Locomotor posture affects the objects and people in view, and walkers have greater visual access than crawlers (Kretch et al., 2014). Contrary to researchers' assumptions, crawlers and walkers rarely fixate their caregivers' face during free play (< 5% of the time), but infants are more likely to do so while sitting or upright than prone (Franchak et al., 2018). Prior work also shows that infants use

fixations to guide locomotion. While playing in a cluttered room, infants fixate obstacles in their path more frequently than older children and adults (Franchak & Adolph, 2010; Franchak, Kretch, Soska, & Adolph, 2011). However, previous work did not examine relations between where infants look and where they go or how looking and locomotion are affected by infants' posture.

The primary aim of Study 2 was to directly compare effects of locomotor posture on locomotor exploration. We scored crawling and walking infants' locomotor bouts and their destinations using the same methods described in Study 1. Based on Study 1, we predicted that crawlers would locomote to a higher percentage of destinations than walkers.

In Study 1 and in previous work, the impetus for travel to a destination was unknown. Thus a second aim of Study 2 was to identify the real-time impetus for each bout of locomotion to a destination. We used head-mounted eye tracking to record where infants looked while stationary and moving. The timing of fixations to destinations relative to the onset of locomotion allowed us to distinguish *destination-directed* from *discovery* bouts. Destination-directed bouts were *instigated* by the sight of a distant destination—infants fixated a destination while stationary and then moved to its location. Discovery bouts were *not instigated* by the sight of a destination—infants started moving before fixating their destination. We predicted that crawlers would have more destination-directed bouts, whereas walkers would discover more destinations en route because walkers' upright posture enables them to see new destinations while in motion. We also used head-mounted eye tracking to investigate where infants looked during bouts that did not end at a new destination—while they took steps in place and when they stopped walking beyond arms' reach of any discernable destination. For in-place and stopped bouts, we expected that walking infants would fixate objects beyond arms' reach and scan the room more often than crawling infants due to walkers' higher vantage point.

To characterize patterns of exploration, we assessed whether infants' paths differed depending on the destination. We expected in-place bouts to be short because infants did not travel to a new location; destination-directed bouts to be longer because infants had to cover ground to reach a new destination; and discovery bouts or bouts that stopped in the middle of the room to be longest because infants did not move with a destination in

mind. Moreover, we expected more destination-directed bouts to be straight than curved because infants would move directly to their fixated target.

Finally, we tested whether infants' locomotor posture influenced the destinations in view. We predicted that crawling infants would travel to more destinations on the floor due to their limited vantage point whereas walking infants would be better able to spot destinations at higher heights. We also predicted that both crawling and walking infants would engage in more destination-directed locomotion when starting locomotion from sitting and upright postures that allowed infants to view all of the potential destinations in the room.

Method

Participants

Sample size was small ($N = 16$) because eye tracking yields rich time-series data and manually coding fixations and targets are labor intensive. We tested eight crawlers (3 girls, 5 boys) and eight walkers (5 girls, 3 boys) within 1 week of their 12-month birthday. Families were recruited and compensated as in Study 1. Most families were White and middle class. Parents reported children's crawling and walking experience as in Study 1. Dating from the first day infants crawled or walked 3 m, the crawlers were relatively experienced ($M = 3.7$ months of crawling experience, range = 1.5–6.1 months), and the walkers were relative novices ($M = 1.3$ months of walking experience, range = 0.8–2.3 months); Figure 1C. Experience for one crawler and one walker were not reported. Data from eight infants were excluded: three became fussy, three contributed < 5 min of data before disturbing the eye-tracking calibration, one had poor eye-tracking calibrations so fixations could not be analyzed, and one novice walker contributed < 10 bouts of independent walking.

Head-Mounted Eye Tracker

We recorded infants' eye movements with a Positive Science head-mounted eye tracker (Franchak et al., 2011). The tracker consists of a small camera that records the visual scene, and another that records the infant's right eye (Figure 1D). Both cameras were mounted on a headband attached to a fitted cap. Due to the potential danger of falling face down while wearing the eye tracker, a second

experimenter walked behind infants holding tethers attached to a harness (shown in Figure 1E) that supported infants' weight if they fell (Franchak et al., 2011). Video from the eye tracker was routed through a cable to a recording computer in the backpack of the experimenter. Experimenters did not interact with infants or caregivers.

During calibration, infants sat 1.5 m from a display board. An assistant inserted noisy, salient toys into windows spanning the visual space to attract infants' attention. A video demonstration of the procedure is shared on Databrary (<https://doi.org/10.17910/b7.124>). After the session, we imported the two videos into Positive Science Yabus software to calculate the point of gaze for each video frame using estimates of the center of pupil and corneal reflection. The software exported a new video with point of gaze indicated on each frame of the scene video with a spatial accuracy of approximately 2° (Franchak et al., 2011). The point of gaze indicator was a circle with a 4° radius to allow for spatial error (Figure 1D).

Procedure and Playroom

After calibration, caregivers played freely with infants. As shown in Figure 1E, the playroom was filled with elevations (couch, three 18-cm high platforms, two wooden cubes) and six toys, (ball, "happy apple," toy saxophone, stuffed dog, xylophone, toy car). Camera views were identical to Study 1. We aimed to collect at least 10 min of useable data. However, some infants had shorter sessions because they became fussy or pulled off the eye tracker ($M = 10.8$, range = 5.0–17.4 min, four infants had sessions < 10 min). Session lengths were comparable between crawlers and walkers, $t(14) = 1.63$, $p = .14$.

Data Coding and Processing

The scene video superimposed with infants' point of gaze was synced with views from the hand-held and overhead cameras to produce a composite video for coding. Videos were synced in Adobe Premiere using a light flash visible in all camera views. Videos were scored with Datavyu. To assess interobserver reliability, a second coder scored 25% of each infant's data. For categorical variables, coders agreed on $\geq 86\%$ of bouts, Cohen's kappa coefficients $\geq .81$, $ps < .001$. Bout durations and fixation durations were correlated between coders, $rs \geq .93$, $ps < .001$. Disagreements were resolved through discussion.

Identification of locomotor bouts and bout terminations. Coders distinguished *bouts* of crawling and walking and infants' *destinations* as in Study 1. Coders also scored the number of *steps* per bout based on the number of knee or foot movements. Steps could be forward, backward, sidewise, or in place. We excluded bouts when infants moved with assistance from caregivers (dashed paths in Figure 3). Crawlers moved independently for $M = 74\%$ ($SD = 23\%$) of bouts, and walkers moved independently for $M = 89\%$ ($SD = 15\%$) of bouts. In Figure 3, walking infant #6 (who had < 1 month of walking experience) had a large number of supported walking bouts in which his mother held his hands and walked him around the room. Bouts of cruising, belly crawling, and knee walking were rare, so these were excluded (11% of bouts).

To determine distance traveled and new area visited, coders manually digitized each step on the floor by marking the center of infants' feet on the overhead camera view (Figure 1E). We used the xy coordinates of each step to map infants' paths (adjusting for lens and perspective distortion) as in Hoch et al. (2018). Figure 3 shows each infant's path. Locomotion on elevations was not included in the paths due to perspective distortion, but these bouts were scored from video and included in all other analyses. The digitizing method returned $< 5\%$ error per bout. *Total distance* traveled was the summed distance of each step on the floor. We estimated exploration of new area by amassing the area covered by a 15-cm radius circle centered on the left foot. If infants took steps in place or revisited a location, they did not get credit for traveling to a new area. We divided the cumulative area explored by the total area of the room (29 m^2) to calculate the *percentage of the room explored*.

As in Lee et al., 2018, coders scored *path shape* for bouts of ≥ 4 steps. Paths were straight if infants moved directly to their destination. Paths were curved if infants turned their bodies for ≥ 2 continuous steps, took serpentine, hooked, or circular paths, or walked forward and then retraced their steps backward along the same trajectory. The destination-directed bout in the legend of Figure 3 shows an example of a straight path, and the discovery bout shows an example of a curved path (drawn from actual data). Coders also scored infants' *posture* at bout onset as upright (standing independently or supported by furniture, kneeling), prone (on belly or in a crawling position), or sitting (buttocks in contact with the ground as in Soska et al., 2015).

Fixations to destinations. For bouts ending at destinations, coders scored fixations to the destination prior to and during each bout. Fixations were counted if the destination was within the 4° gaze indicator for three consecutive frames (~ 90 ms). Bouts ending at destinations were *destination directed* if infants fixated the destination during the period between the last destination and the current bout initiation. Typically infants fixated destinations while stationary, but if infants fixated the destination while taking steps in place or during a bout that stopped in the middle of the room, the subsequent bout to the fixated destination was coded as destination directed. *Discovery* bouts occurred when infants traveled to a new destination that was fixated after infants were already in motion, or if infants stopped moving near a destination that was never fixated. Figures 4A–4D shows examples of fixations in destination-directed and discovery bouts. Video exemplars of each bout type are on Databrary (<https://doi.org/10.17910/b7.458>). Coders also scored the *height* of each destination as high (\geq infants' standing chest height), mid-height ($<$ infants' chest height, but above the floor), or on the floor.

Fixations for bouts ending at no destination. For *in-place* bouts, coders scored whether infants fixated objects in hand, objects within or beyond arms' reach, or made no fixations. For *stopped* bouts, coders scored whether infants fixated something that they moved closer to or farther from, something in hand, or made no fixations while in motion.

Results and Discussion

Statistical analyses were similar to Study 1. To compare the percentage of bouts that were destination directed, involved a discovery, or had no destination, we used a multinomial logistic GEE. This method is used to estimate parameter coefficients and standard errors for a dependent variable with more than two response categories and to account for observations clustered within subjects (Fitzmaurice, Laird, & Ware, 2011; Rodríguez, 2007). Walkers and no-destination bouts were the reference category. We examined real-time relations between fixations and destinations by distinguishing bouts that ended at destinations fixated while stationary from bouts that ended at destinations fixated while already in motion. We also examined the time lag between target fixation and bout initiation, the timing of fixations to the destination while in motion,

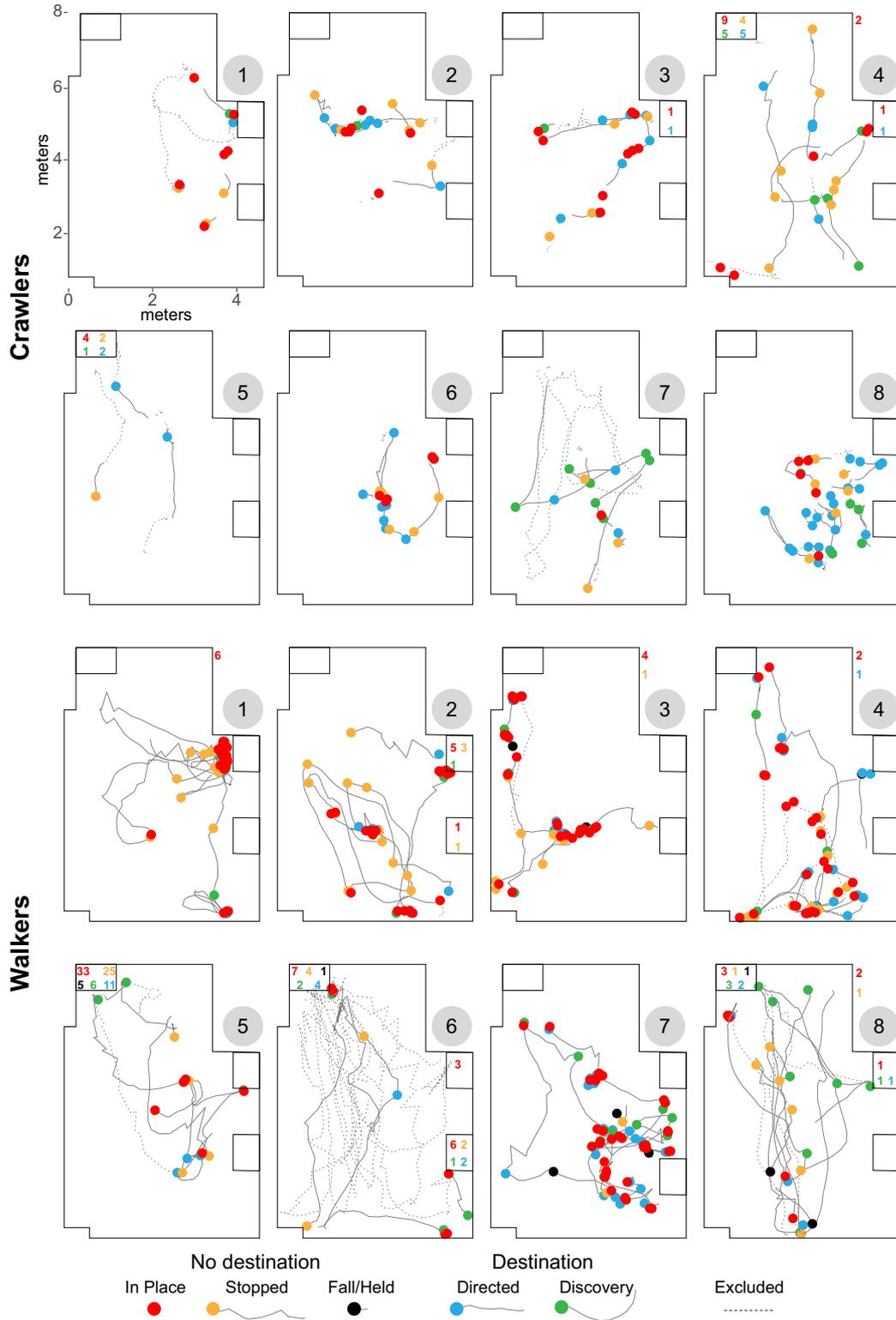


Figure 3. Study 2: Paths and bout types for each infant. Numbers in gray circles map to infants in Figure 2F. Black lines outline playroom and elevations (boxes). Solid gray paths were included for analyses. Dashed gray paths were excluded. Colored circles denote bout termination for no-destination bouts (in place, stopped, fall/held). Bout terminations at destinations are collapsed by bout type (directed, discovery). Numbers on elevations and outside of the playroom denote bouts that were included for analyses but were not digitized due to perspective distortion or because infants were not in view of the overhead camera. [Correction added on April 27, 2020 after first online publication: the sentence “Numbers in gray circles map to infants in Figure 2D” has been changed to “Numbers in gray circles map to infants in Figure 2F”.]

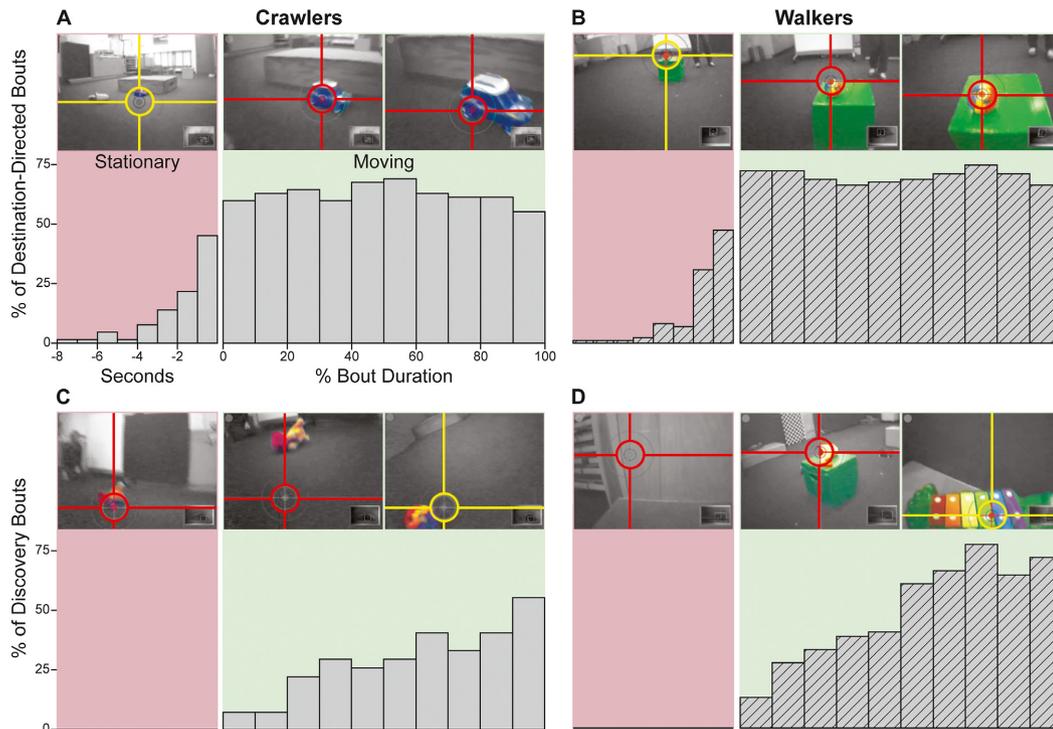


Figure 4. Study 2: Timing of visual fixations to destinations. Exemplar video frames of fixations for an infant in a single bout. Red circles denote infants' point of gaze. Yellow circles denote infants' first fixation to the destination. Y-axis shows the percentage of all bouts where infants fixated their destination. X-axis shows time. Before bout onset infants are stationary, and fixations are plotted in seconds (red panels). After bout onset infants are in motion, and fixations are plotted as a percentage of the bout's duration because bouts differed in length (green panels). (A and B) Destination-directed bouts. Infants fixated the destination just prior to bout onset and continually fixated the destination during approach. (C and D) Discovery bouts. Infants did not fixate the destination prior to bout onset, and fixations to the destination increased during approach.

and infants' moment-to-moment location in the playroom.

Amount of Locomotion

As in previous work (Adolph et al., 2012), experienced crawlers moved less than novice walkers. In total, crawlers contributed 194 bouts and walkers contributed 499 (range = 12–95 bouts per infant). In contrast to Study 1, crawlers never walked independently. Walkers mostly walked ($M = 91\%$ of bouts, $SD = 9\%$). Walkers spent more time in motion, fell more frequently, and accumulated more bouts and more steps per hour than crawlers. As shown by the individual paths in Figure 3, walkers also traveled greater distances and explored more of the playroom (Table 2). However, the average bout duration and average number of steps per bout did not differ between crawlers and walkers (Table 2). Although $\sim 60\%$ of bouts were only 1–3 steps in length, all crawlers produced at least one bout of ≥ 9 steps, and all walkers produced at least one bout with ≥ 22 steps. The percentage of 1–3 step

bouts did not differ between crawlers and walkers (Table 2). These findings support prior work showing that 1–3 step bouts are pervasive in infant walking (Lee et al., 2018). Locomotor measures were not correlated with crawling or walking experience, $r_s \leq .68$, $p_s \geq .09$.

As in Study 1, crawling and walking did not differ between the first and second halves of the session, $p_s \geq .22$. Crawlers and walkers in Study 2 took a comparable number of steps per hour ($M_s = 622$ and $2,456$, respectively) to same-aged crawlers and walkers who played with their caregiver but did not wear an eye tracker ($M_s = 636$ steps/hr, $1,456$ steps/hr, respectively; Adolph et al., 2012). Walkers in Study 2 also took a similar number of 1–3 step bouts to 13-month-olds in prior work ($M = 50\%$ of bouts; Cole et al., 2016). However, compared to the crawlers in Study 1, the crawlers in Study 2 moved less (see Table 2), suggesting that the eye tracker and/or harness may have depressed rates of crawling. Moreover, the crawlers in Study 2 spent less time in motion ($M = 10\%$) compared to same-aged crawlers in

Table 2
 Comparisons Between Crawling and Walking 12-Month-Old Infants

	Crawlers		Walkers		<i>t</i> (14)	<i>p</i>
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>		
% Time in motion	10.18	6.77	28.95	9.68	4.49	.001
Falls per hr	1.15	3.24	24.56	19.34	3.38	.005
Bouts per hr	129.90	48.20	438.90	155.91	5.36	< .001
Bout duration (s)	2.72	1.10	2.51	0.98	0.40	.694
Steps per hr	621.65	336.56	2,455.99	845.32	5.74	< .001
Meters per hr	55.27	31.99	248.32	74.85	6.71	< .001
% Room explored	16.55	8.76	36.01	15.12	3.15	.007
Steps per bout	4.71	2.10	5.85	1.82	1.16	.226
% 1–3 step bouts	59.98	15.72	58.86	7.27	0.184	.857

prior work ($M = 20\%$; Adolph et al., 2012). Crawlers and walkers in our sample also fell less frequently ($M_s = 1$ fall/hr, 25 falls/hr, respectively) compared to crawlers and walkers in previous work ($M_s = 17$ falls/hr, 32 falls/hr, respectively; Adolph et al., 2012) due to the safety harness.

Destination Versus No-Destination Bouts

Overall, most bouts (63%) did not end near a destination (Figures 2D and 3). However, Study 2 confirmed that crawlers travel to a higher percentage of destinations than walkers. A binary logistic GEE corroborated a main effect of locomotor status on the percentage of bouts ending at a destination, Wald $\chi^2(1) = 7.53$, $p = .006$. Thus, as suggested by Study 1 and previous work, locomotor posture influenced infants' travel to destinations. Moreover, as in Study 1, crawlers went to destinations and no destination equally, Wald $\chi^2(1) = 0.34$, $p = .55$. In contrast, walkers went to destinations less often than no destination, Wald $\chi^2(1) = 24.89$, $p < .001$. The percentage of bouts ending at a destination did not differ between the first and second halves of the session, $t_s \leq 1.16$, $p_s \geq .28$.

Locomotor exploration in Study 2 was similar to infants without eye trackers. Crawlers in Study 2 locomoted to destinations just as often as the novice and experienced crawlers in Study 1. Walkers in Study 2 locomoted to destinations as frequently as 13-, 15-, and 19-month old walkers in previous laboratory studies (Cole et al., 2016; Hoch et al., 2018), and both crawlers and walkers in Study 2 locomoted to destinations at rates similar to 13-month-old crawlers and walkers who carried objects to destinations in the home (Karasik et al., 2012).

For both crawlers and walkers, the most attractive destinations were objects—typically toys (see

bottom panel of Figure 2E). A GEE revealed a main effect of locomotor status, and a main effect of destination type (objects, elevations, features of the environment, caregiver), Wald $\chi^2_s \geq 6.88$, $p \leq .01$. Crawlers visited more destinations than walkers, and post hoc comparisons revealed that both crawlers and walkers visited objects most often ($p_s \leq .001$), followed by features of the environment and elevations (which did not differ, $p = .39$), and caregivers (which differed from environment $p = .05$, but not from elevations, $p = .51$).

Steps in place constituted the largest percentage of infants' crawling and walking bouts (top panel of Figure 2E). Infants could take steps in place in front of a destination or in the middle of the room, but these steps did not take infants to anything new. A second sizeable percentage of bouts did not reach a new destination because infants stopped in the middle of the room. A GEE revealed a no-destination type (steps in place, stopped, fall/held) by locomotor status interaction, Wald $\chi^2(2) = 12.10$, $p = .002$. Post hoc comparisons revealed that steps in place were most common followed by stopping bouts, and falls, but walkers took more steps in place and had more bouts ending in falls than crawlers ($p_s \leq .003$). Group patterns of locomotor exploration were reflected in data from individual infants (Figures 2F and 3). Figure 3 also shows that bouts of all types occurred in varied locations around the playroom.

Real-Time Looking and Locomotion

Where infants stop does not reveal the whether or not a bout was instigated by a destination. Infants could stop near a new destination because they directed a bout of locomotion to that destination as Gibson (1978) proposed, or they could start

moving and then discover a destination incidentally. Thus, in a separate analysis, we used head-mounted eye tracking to compare destination-directed, discovery, and no-destination bouts.

All infants had at least one destination-directed bout, and all but one crawler had at least one discovery bout. Figure 3 shows each bout for each infant and whether the bout was destination directed, resulted in a discovery, or ended at no destination. Destination-directed bouts were more common than discovery bouts, and crawlers had more destination-directed bouts than walkers (Figures 2G and 3). A multinomial logistic GEE confirmed that for both crawlers and walkers, destination-directed and no-destination bouts were more common than discovery bouts ($\beta_s \geq 0.44$, $p_s \leq .05$). For crawlers, destination-directed and no-destination bouts did not differ ($\beta = -0.45$, $p = .10$), but for walkers, destination-directed bouts were less prevalent than no-destination bouts ($\beta = -1.46$, $p < .001$). Crawlers had more destination-directed bouts than walkers ($\beta = 1.01$, $p = .003$), but discovery and no-destination bouts did not differ between groups ($\beta_s \leq 0.57$, $p \geq .15$). Thus, the difference between crawlers and walkers in the percentage of bouts ending at a destination was driven by destination-directed bouts.

When infants engaged in destination-directed locomotion, they started moving almost immediately after spotting their target and continually fixated that target while in motion. Although infants could have fixated the target at any point prior to initiating locomotion, for most destination-directed bouts, crawlers and walkers fixated their destination just prior to bout onset, crawlers: $M = 1.4$ s before bout onset, $SD = .9$; walkers: $M = 1.4$ s, $SD = .6$; $t(12) = 0.16$, $p = .87$; see Figures 4A and 4B. Fixations to the destination did not change as infants approached, $r_s \leq .05$, $p_s \geq .88$ (Figures 4A and 4B). Thus, sight of an attractive target appeared to instigate locomotion to that target.

When infants discovered a destination, they first fixated it mid bout, crawlers: $M = 34\%$ of bout, $SD = 24\%$; walkers: $M = 42\%$ of bout, $SD = 16\%$; $t(10) = 0.80$, $p = .44$; Figures 4C and 4D. After infants fixated a discovered destination, looking to that destination increased as infants approached, $r_s \geq .92$, $p_s < .001$ (Figures 4C and 4D). Rarely (18 bouts), infants arrived at a target that they never fixated prior to bout onset or while in motion; for these bouts, infants discovered something to explore after they had stopped moving. Finally, as shown in Figures 4A–4D, infants spent more of

each bout fixating a destination for destination-directed bouts ($M = 60\%$ of bout, $SE = 5\%$) compared to discovery bouts ($M = 40\%$ of bout, $SE = 6\%$). A GEE confirmed a main effect of bout type (destination-directed, discovery), Wald $\chi^2(1) = 7.22$, $p = .007$, but not locomotor status, Wald $\chi^2(1) = 0.36$, $p = .55$.

We also examined where infants looked during no-destination bouts. When infants took steps in place, they mostly fixated objects already within reach (Figure 5A). Perhaps infants took steps because they were aroused or to get a better vantage point, but these steps were not necessary to contact the fixated destination. A GEE confirmed a fixation pattern (something within/beyond arms' reach, a held object, or scanned the room) by locomotor status interaction, Wald $\chi^2(3) = 8.89$, $p = .03$. Post hoc comparisons revealed that while taking steps in place, crawlers most often fixated targets within arms' reach ($p_s \leq .004$), and they fixated targets beyond arms' reach and scanned the room more often than held objects ($p_s \leq .01$). Similarly, walking infants most often fixated targets within arms' reach, followed by fixations to targets beyond reach, scanning the room, and finally held objects ($p_s \leq .02$). Crawling infants fixated fewer destinations beyond arms' reach than walkers ($p = .04$), likely because those destinations were not in view (Figure 5A). Thus, the difference between crawlers and walkers in the percentage of in-place bouts was driven by a difference in bouts where infants fixated targets beyond arms' reach.

When infants stopped in the middle of the floor, they mostly scanned the room or moved closer to a fixated target (Figure 5B). A GEE revealed a main effect of fixation pattern (whether infants fixated something and moved closer or farther away, fixated a held object, or scanned the room), Wald $\chi^2(3) = 208.15$, $p < .001$, but no effect of locomotor status, Wald $\chi^2(3) = 7.46$, $p = .06$. Post hoc comparisons revealed that infants scanned the room or moved closer to a fixated destination equally ($p = .14$), and did so more often than they fixated something they were holding or fixated something while moving farther away ($p_s \leq .02$). Fixations to something in hand or while moving farther away did not differ ($p = .06$). Thus, head-mounted eye tracking suggests that sometimes infants stopped locomoting before reaching a destination because they became distracted or because they were moving to get a better view, but just as frequently, infants stopped and looked at nothing in particular.

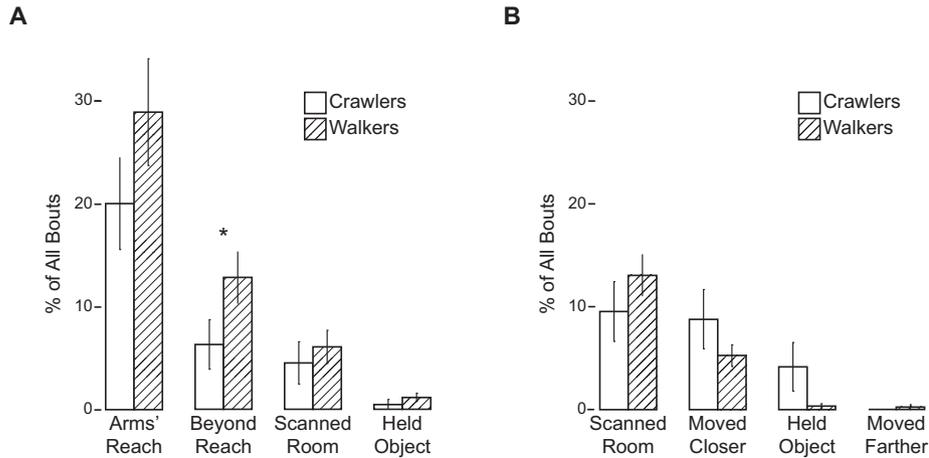


Figure 5. Study 2: Fixations for no-destination bouts. (A) In-place bouts. (B) Stopped bouts. Error bars denote standard errors; asterisks denote $p < .05$ in pairwise comparisons between crawlers and walkers.

Locomotor Paths

Patterns of exploration differed depending on where infants were going (Figure 3). Bouts ranged from 1 to 29 steps in crawlers and from 1 to 57 steps in walkers, and bouts of different lengths and shapes reflected different functions. Most in-place bouts were too short to reach a new destination. Destination-directed bouts were slightly longer, and discovery bouts and bouts where infants stopped walking in the middle of the room were the longest (Figure 6A). A GEE revealed a bout type (in-place, destination-directed, discovery, stopping) by locomotor status interaction, Wald $\chi^2(3) = 13.70$, $p = .003$. Post hoc comparisons revealed that walking bouts were longer than crawling bouts for each bout type, and in-place bouts were the shortest for both crawlers and walkers ($ps < .001$). Discovery bouts and stops in the middle of the room were the longest for walkers ($ps < .001$) and did not differ from each other ($p = .06$). For crawlers, discovery bouts did not differ from stopping bouts ($p = .20$) and destination-directed bouts did not differ from discovery bouts ($p = .07$). We found the same pattern when comparing the distance and unique area covered by each bout type, Wald $\chi^2s \geq 16.09$, $ps \leq .001$.

Our work extends previous findings by demonstrating that the abundant short bouts observed in spontaneous infant locomotion (Adolph et al., 2012; Cole et al., 2016) do not carry infants to something new. In principle, short bouts could (and sometimes did) bring infants within arms' reach of a target, but usually bouts of 1–3 steps occurred in the middle of the floor or while interacting with and

fixating something already within reach. Why take so many steps if not to get to something new? In principle, short bouts in novice walkers could reflect poor skill, resulting from attempts to maintain balance or failed bout initiation. This explanation would predict that experienced walkers don't display short bouts. But they do: Short bouts persist from walkers' first week of walking until 10 months later (Cole et al., 2016; Lee et al., 2018). Moreover, in Study 2, experienced crawlers displayed the same percentage of 1–3 step bouts as novice walkers. When infants traveled longer distances (7+ steps), they often passed several potential targets before stopping or discovering a destination. Our laboratory playroom measures 5×8 m or about 20×30 infant walking steps (assuming a 30 cm walking step length, Lee et al., 2018). At any given position in our playroom, and in most real-world environments, infants need not travel far to reach a new destination of interest. Thus, when infants traveled very short or very long distances, their locomotion was not typically destination directed.

Infants' path shape also differed depending on their destination. As in previous work with walkers (Lee et al., 2018), many bouts with 4+ steps were curved (crawlers: $M = 50\%$ $SD = 24\%$, walkers: $M = 69\%$ $SD = 13\%$), and the percentage of curved bouts did not differ between groups, $t(14) = 1.96$, $p = .07$. However, more straight than curved bouts were destination directed (Figure 6B). A binary logistic GEE revealed a main effect of path shape (curved, straight), Wald $\chi^2(1) = 5.69$, $p = .02$, but not of locomotor status, Wald $\chi^2(1) = 1.32$, $p = .25$,

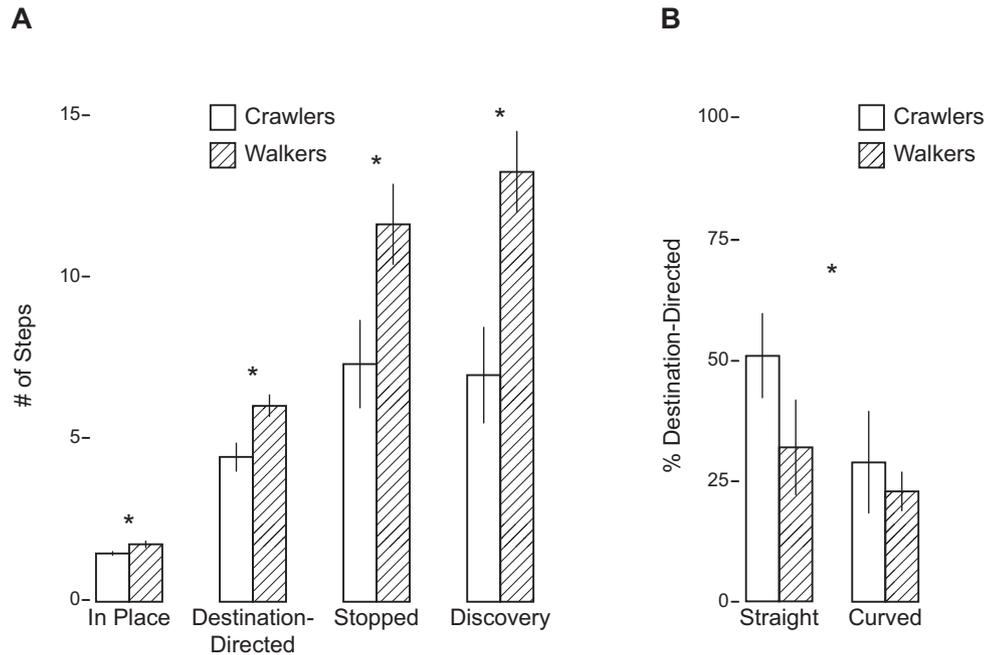


Figure 6. Study 2: Patterns of locomotor exploration. (A) Average number of steps per bout termination and bout type. (B) Average percentage of straight and curved bouts that were destination directed. Error bars denote standard errors; asterisks denote $p < .05$ in comparisons between (A) crawlers and walkers and (B) straight and curved.

on the percentage of destination directed bouts. Thus, both crawlers and walkers tended to move along a straight path to a previously fixated destination.

Target Height and Starting Posture

Infants' locomotor posture affected the visual availability of destinations (Figure 7A). A GEE confirmed a destination height (high, medium, floor) by locomotor status interaction, Wald $\chi^2(2) = 23.33$, $p < .001$. Post hoc comparisons revealed that crawling infants locomoted to destinations on the floor and at medium heights equally ($p = .61$) and never went to destinations at higher heights ($ps < .001$). Walking infants mostly locomoted to destinations at medium heights ($ps \leq .001$), and less often to destinations on the floor and high heights (which did not differ $p = .73$). Crawlers locomoted to more destinations on the floor, and fewer high destinations than walkers ($ps \leq .004$), presumably because of their posture and field of view.

Infants' posture at bout onset also influenced destination-directed locomotion. Crawlers' bouts started in prone or sitting postures ($M = 45\%$ of bouts, $SD = 16\%$, $M = 34\%$, $SD = 20\%$, respectively) more often than walkers' bouts started from prone

or sitting ($M = 5\%$, $SD = 6\%$, $M = 5\%$, $SD = 8\%$, respectively; $ts \geq 3.75$, $ps \leq .002$). In contrast, walkers' bouts started in upright postures ($M = 40\%$ of bouts, $SD = 11\%$) more often than crawlers' bouts ($M = 22\%$, $SD = 15\%$; $t(14) = 10.36$, $p < .001$). But crawling infants benefitted by starting from sitting and upright postures that allowed them access to the visual scene (Figure 7B). A binary logistic GEE revealed an interaction between starting posture (upright, sitting, prone) and locomotor status, Wald $\chi^2(2) = 7.82$, $p = .02$. Post hoc comparisons revealed that for crawlers, more destination-directed bouts started from upright or sitting postures compared to prone ($ps \leq .03$). Upright and sitting postures did not differ ($p = .55$). For walkers, bouts that started in upright, sitting, or prone postures were equally likely to be destination directed ($ps \geq .22$). Crawlers had more destination directed bouts from sitting and upright postures than walkers ($ps \leq .04$).

Summary of Study 2

As in Study 1 and previous work (Cole et al., 2016; Hoch et al., 2018), Study 2 showed that most bouts of infant locomotion do not end at a new destination. Moreover, Study 2 confirmed that crawlers direct more bouts to destinations than same-aged walkers. Crawlers moved less than walkers and

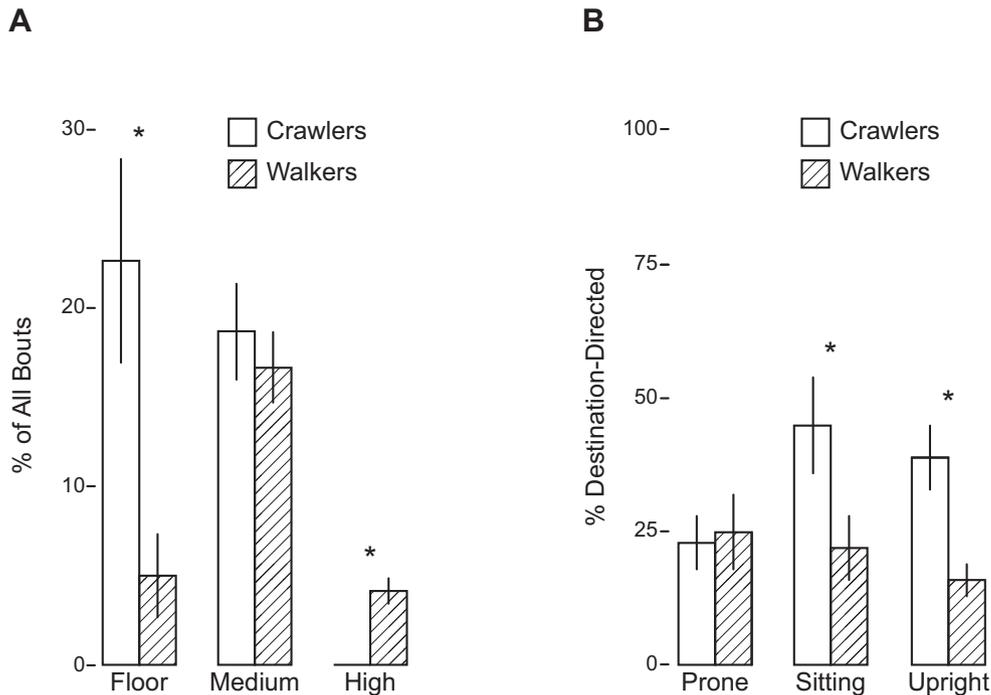


Figure 7. Effects of posture on fixations to destinations. (A) Height of fixated destination. (B) Percentage of prone, sitting, and upright bouts that were destination directed. Error bars denote standard errors; asterisks denote $p < .05$ in pairwise comparisons between crawlers and walkers.

visited less of the playroom, suggesting that crawling is less efficient and more effortful than walking (Adolph & Tamis-LeMonda, 2014; Adolph et al., 2012). Thus, compared to walkers, crawlers may take fewer extraneous steps and, as a result, a higher percentage of crawlers' bouts end at destinations.

Study 2 also provides the first evidence that—albeit relatively infrequent—seeing a distant destination can provide the real-time impetus for bouts of crawling or walking. Eye tracking shows that when infants moved to a new destination, there were more destination directed than discovery bouts. When infants fixated a destination while stationary, they fixated the target just prior to initiating locomotion and continually looked at it while in motion. When infants discovered a destination while already in motion, they fixated their target mid bout and continued to fixate it as they approached. When infants took steps in place, they mostly fixated targets within reach. When infants stopped moving out of arms' reach of a new destination, they mostly scanned the room or moved closer to a fixated target.

Infants' paths revealed distinct patterns of exploration. When infants went to a destination, they tended to go straight to the target. But when infants discovered a destination or stopped moving in the

middle of the room, their paths were long and winding. Finally, locomotor posture affected the available destinations in view. Crawlers went to fewer destinations high off the ground than walking infants, and crawlers engaged in more destination-directed locomotion when initiating locomotion from postures that enabled full range of vision (sitting and upright).

General Discussion

Where Infants Go

Historically, researchers assumed that infants move in order to go somewhere (Gibson & Schmuckler, 1989). That is, the sight of an alluring destination motivates infants to crawl or walk to that destination. But real-time analyses of infants' exploration showed that this commonsense assumption does not describe most bouts of locomotion. Two studies, along with recent work (Cole et al., 2016; Hoch et al., 2018), indicate that a large percentage of infants' locomotor bouts do not go anywhere at all. Half the time, both younger and older crawlers went to destinations, but half the time they did not. Walkers traveled to destinations even less—about 30% of bouts.

Albeit counterintuitive, a large percentage of infants' spontaneous locomotor bouts involve steps in place in front of a person, specific place, or thing that was already within sight and within reach. These bouts were seemingly extraneous and did not bring infants into contact with anything new. Walkers took more steps in place than crawlers in Studies 1 and 2, and as a consequence, walkers visited proportionally fewer destinations. Although in-place bouts tended to be short, experienced crawlers and novice walkers took the same percentage of 1–3 step bouts, and short bouts remain prevalent after 10 months of walking experience (Lee et al., 2018). Thus, differences in in-place bouts are likely due to locomotor posture, not novice walkers' poor walking skill. In particular, differences in prone and upright postures lead to changes in infants' field of view (Kretch et al., 2014). Accordingly, we found that the walkers in Study 2 took more steps in place while fixating distant destinations than crawlers. Thus, walkers, who are better able to spot distant targets than crawlers, may take more steps in place because they are aroused by the things they see or because they move to get a better view. Finally, walkers may take more steps in place because crawling is a more costly locomotor posture (Adolph & Tamis-LeMonda, 2014). Because crawlers move less than walkers, crawlers may be more likely to move with a mission in mind. Future work could test this hypothesis by increasing the cost of walking.

When infants went to something new, objects—primarily toys—were generally the most attractive destinations. We also found evidence that infants' preferences change with locomotor experience. In Study 1, more experienced crawlers were more likely to exploit affordances for climbing and went to more elevations than novice crawlers. In both studies, caregivers played with infants, so caregivers may not have been an alluring destination. As previously reported (Hoch et al., 2018; Rheingold & Eckerman, 1970), infants also found things in the environment to explore that were not intended for play—small divots in the floor to prod and door handles to jiggle. It seems that, for infants, almost anything can be a destination.

What Infants See

An important contribution of Study 2 was to describe, for the first time, the real-time relations between where infants look and where they go during free play. Infants were more likely to fixate destinations while stationary than to discover

destinations while in motion. But regardless of whether infants were stationary or mobile, their visual world was rich with targets. After several minutes in the playroom, the array of toys and elevations were likely familiar. We do not know why some targets became destinations and some did not, but once selected, the allure of a distant destination was almost immediate. During destination-directed bouts, infants initiated locomotion toward a fixated target within 1–2 s and kept the target in view while in motion. If infants discovered something while traveling, looking to that target continued until they arrived. As Gibson and others argued, infants guide locomotion to targets by keeping the target and surrounding layout in view (Gibson & Schmuckler, 1989; Kretch & Adolph, 2017).

Our findings also highlight the importance of infants' posture for visually motivated exploration. If infants can't see it, they are unlikely to go to it. Accordingly, compared to walkers, crawlers fixated more targets on the floor and fewer above chest height. Moreover, compared with prone, when crawlers began in a sitting or standing posture that enabled full view of the room, they were more likely to crawl to fixated destinations. Previous work suggests that the transition from sitting to prone poses a sort of double jeopardy: Infants cannot see far-off destinations while prone but when they sit up, the whole room swoops into view (Kretch et al., 2014). However, this transition from crawling to sitting (and from sitting to crawling) often turns infants' bodies 60°–180° away from their original direction of heading and away from any potential target (Soska et al., 2015). Despite these shifts in position, eye tracking and video in this study show that a relatively large percentage of crawling bouts that started in sitting postures were destination directed. Apparently, going to a seen destination is sufficiently compelling to get crawlers back on track.

Why Locomote?

Why does a stationary infant who can crawl or walk get up and go? We found that infants do not primarily initiate and terminate locomotion to reach new destinations. But if not to destinations, why go at all? Regardless of their destination, all bouts generate new information. Moreover, the length and shape of infants' locomotor paths may reflect different forms of exploration. While foraging, many organisms, including slime molds (Latty & Beekman, 2009), ferrets (Haskell, 1997), and human

adults (Hills, Klaff, & Wiener, 2013) exhibit composite strategies of directed and nondirected exploration. While searching for resources, foragers make short movements and reorient frequently (Nolting, Hinkelman, Brassil, & Tenhumberg, 2015). When a resource is detected, foragers make long, straight movements toward its location (Nolting et al., 2015). Likewise, while “foraging” in our playroom, many of infants’ bouts were short and curved. Even when they took steps in place or stopped walking in the middle of the room, infants still gathered information—they looked at objects beyond reach, moved closer to fixated targets, and scanned the room. When infants spotted something to investigate, they switched to more directed forms of exploration and moved to the target without extraneous steps.

But infants do not just forage, they play! Sometimes infants looped around the playroom with no destination in sight or in reach. Why? Locomotion in the absence of a destination or goal may simply be pleasurable—a means unto itself (Mears, 1978; Mears & Harlow, 1975). The premise is reasonable because if locomotion were not intrinsically rewarding, it might literally never get going. Developmental roboticists who design autonomous robots that—like infants—must independently learn about their body and the environment build in a reward for movement (Gottlieb, Oudeyer, Lopes, & Baranes, 2013). At first, the robot moves randomly and is rewarded for every movement. Over time, the robot learns associations between the parts of its body and how they interact. This process is termed “motor babbling” (Caligiore et al., 2008). Through this process of rewarded movement, the robot learns to perform an action, often of its own design (Gottlieb et al., 2013). Indeed, to discover anything—first you must do something. Fortunately, infants seem motivated to move. They take thousands of steps and travel hundreds of meters per hour (Adolph et al., 2012), and they move just as much in an empty room as in a room filled with toys (Hoch et al., 2018).

Limitations and Future Directions

Does locomotion ever become primarily directed toward destinations? Although it may intuitively feel like adults engage in more destination-directed locomotion than infants, the true rates remain unknown. Because we only collected eye-tracking data from 12-month-old crawling and walking infants, we do not yet know how the relations between looking and locomotion change over

the development of crawling and walking skill. Locomotion in the absence of immediate destinations may persist through the preschool years where children run, jump, and tumble when space is available (McLaren, Ruddick, Edwards, Zabjek, & McKeever, 2012; van Liempd, Oudgenoeg-Paz, Fukink, & Leseman, 2018). Longitudinal data are needed to track the development of locomotor exploration from early independent mobility through childhood. Furthermore, little is known about locomotor exploration in different environments (e.g., home, school, playground) or in children with disabilities that may affect the dynamics of crawling and walking. Future work examining a wide range of ages, contexts, and populations is needed to determine how locomotor exploration changes over the development of locomotion, and in different bodies and environments.

Conclusions

Locomotion in the service of exploration is not primarily destination directed. Although freely playing infants can engage in directed locomotor exploration, a large proportion of spontaneous bouts of locomotion do not take infants anywhere new. Many bouts are short and in place. Even when infants take several steps, their paths often curve in varied directions and end with no new destination in reach. Although the short-term motivations for such bouts of locomotion remain unknown, locomotor exploration likely serves a long-term function. While moving, infants gain information about their bodies, their skills, the environment, and the relations among them.

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