The role of crawling and walking experience in infant spatial memory

M.W. Clearfield*

Department of Psychology, Whitman College, Walla Walla, WA 99362, USA

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Abstract

This research explored infants' use of place learning and cue learning in a locomotor task across the transition from crawling to walking. Novice and expert crawling and walking infants were observed in a novel locomotor task—finding a hidden goal location in a large space. In Experiment 1, infants were tested with distal landmarks. Infants with fewer than 6 weeks of experience, either crawling or walking, could not find the goal location. All infants with more locomotor experience were more successful. Learning did not transfer across the transition to walking. In Experiment 2, novice and expert crawlers and walkers were tested with a direct landmark. Again, novice crawlers and walkers with fewer than 6 weeks of experience could not find the goal, whereas those with more experience could. Taken together, these findings suggest that infants' spatial learning is inextricably linked to mode of locomotion.
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Introduction

For decades, psychologists, biologists, ethologists, and others have sought to understand how humans and other animals learn about space and remember spatial

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* Fax: +1 509 527 5026.
   E-mail address: clearfmw@whitman.edu.

information. For most species, knowing where one has previously traveled is critical for survival. Spatial memory allows animals to remember the locations of things such as predators, home, and food. Navigational memory also allows animals to track their own movements through the environment. This enables animals to remember and revisit desirable locations (e.g., a large food cache) and to avoid undesirable locations (e.g., a predator's lair).

There is no single way of coding space; it all depends on what information is available to the user. There are two general categories of available cues: those with respect to the self and those with respect to external landmarks (e.g., Gallistel, 1990; Woodin & Allport, 1998). Within those categories, there are two different types of cues: those involving simple association and those involving distance and direction.

Self-referenced spatial coding involves encoding the position of the self while moving. A simple associative self-reference coding system is response learning, where what is remembered is a particular motor sequence. An example of response learning is a rat in a maze remembering to turn left twice and then right. This system is limited in that it is accurate only when the position of the coder and the spatial situation has not changed. A more complex self-reference system, one that requires distance calculations, is known as dead reckoning. Here, distance and direction of one's own movements are coded to continually update position. This method is also limited in that it is extremely difficult to gauge distance based only on one's own movements. Moreover, errors in one's calculations are difficult to detect and are magnified over great distances. Both response learning and dead reckoning are known as egocentric responding in the human infant spatial literature.

Externally referenced spatial coding involves noting spatial relations among objects and locations, such as landmarks, which are long-term stable reference systems for specific areas. Again, there are two kinds of spatial coding systems within this category. The simpler one is cue learning, where an association is established between a location and a visible landmark, typically one that is close by. The more complex type of externally referenced coding is place learning (also called allocentric responses). Place learning involves specifying the distance and relations between distal landmarks to find a location. In general, two landmarks are required to locate a third position.

Much early research has focused on self-referenced coding in infants (for a review, see Newcombe & Huttenlocher, 2000). However, response learning and dead reckoning are more limited and less useful than the external reference coding systems because they rely on (a) the environment remaining unchanged and (b) knowledge of distance traveled. In addition, most infants learn about space in an environment that contains cues, either direct or indirect. Thus, the current studies focused on the development of the two externally referenced coding systems: place learning and cue learning.

Development of place learning and cue learning in infants

One of the most robust findings on infants' spatial knowledge is that very young infants tend to use self-referenced cues (e.g., Acredolo, 1978; Bremner, 1978a,

1978b). In general, infants under 8 months of age tend to code space egocentrically, whereas infants over 8 months of age tend to use external or allocentric cues. Given this, the central question has been what factors cause infants to make the switch from self-referenced coding to externally referenced coding.

Researchers have addressed this question with two different methods. The first method is an object retrieval task, where infants are seated at a table with two hiding locations next to each other. An attractive toy is repeatedly hidden in one location, and the infants are allowed to reach for it. Then, the experimenter introduces a spatial transformation such as rotating the table 180 degrees or rotating the infants around to the other side of the table. If infants reach to the same body-centered location, they will not find the toy (i.e., self-referenced position coding or response learning). If infants are able to find the toy after the transformation, they are thought to use external cues (allocentric coding) (e.g., Bremner, 1978a, 1978b). The second method, the head-turning task, is similar but does not require infants to reach. Infants are seated in the middle of one wall of a square room with two identical windows, one to the left and one to the right. Infants are trained to look to one of the windows after a buzzer is sounded, where they see a smiling experimenter. After several training trials, infants are rotated to the opposite wall and the buzzer is sounded again, but the experimenter does not appear. If infants turn their heads in the same direction as they did during training, they are coding egocentrically. If infants look back to the original window, thereby changing the direction of their head turns, they are coding allocentrically (e.g., Acredolo, 1978; Acredolo & Evans, 1980; Acredolo, Adams, & Goodwyn, 1984).

Although several studies suggest that place learning emerges quite late in development, a few studies have tried to find some components of place learning in young children. For example, Acredolo (1978) tested 8-, 11-, and 16-month-olds in the head-turning task where the room contained no landmarks, only the two windows on either side of the room. Neither the 8-month-olds nor the 11-month-olds looked to the correct window after being rotated around the room, whereas the 16-month-olds did. Using a similar task, Bremner and colleagues found that infants as young as $8\frac{1}{2}$ months of age could use relational cues (Lew, Bremner, & Lefkovitch, 2000). They tested infants in a version of the looking task described previously, where the shape of the room was round and there were three different landmarks, none marking the goal window. The $8\frac{1}{2}$-month-olds looked to the correct window when the window was located between two landmarks, but they looked to the incorrect window when there were no landmarks at all. Thus, given the right combination of landmarks, $8\frac{1}{2}$-month-olds can use relations between cues to keep track of a location in space.

In another study, 12-month-olds also demonstrated the use of distal cues with distance coding (Bushnell, McKenzie, Lawrence, & Connel, 1995). In this study, infants were seated in a large pool filled with 58 identical pillows and were required to crawl through the pillows to retrieve a toy hidden a few feet away. Over several conditions, the toys were hidden either under a distinctive pillow or under a standard one near a distinctive pillow. Although 12-month-olds had some difficulty in recovering the toy when it was near a distinctive pillow, they were quite accurate when the toy was hidden under a distinctive pillow. Moreover, even when the infants' accuracy was low,

their search patterns were always in the right vicinity. So, even when they were unable to recover the actual toy, they always searched at pillows just next to the target one, indicating that they had remembered something about the distance and direction of the location of the toy. Thus, it appears that infants are unable to use distal cues before 12 months of age and that their use of place learning is not really stable until 16 months of age.

In contrast, numerous studies have found that infants perform much better when the task requires only relating a location to a single proximal landmark (i.e., cue learning). For example, one robust finding is that target distinctiveness (a distinct target serves as a landmark) helps infants to differentiate locations in the object retrieval task. When experimenters used distinctive covers to help disambiguate the hiding locations, 9-month-olds were more likely to correctly uncover the hidden toy (e.g., Bremner, 1978a, 1978b; Butterworth, Jarrett, & Hicks, 1982; Wellman, Cross, & Bartsch, 1987). In a variation of this task in which infants had to reach for one of two visible targets, when the targets were similar or identical in color, infants perseverated. However, when the targets were very different, infants reached correctly (Diedrich, Highland, Thelen, & Smith, 2001).

Landmarks also improve performance in the head-turning task. For example, in Acredolo's (1978) study on 6-, 11-, and 16-month-olds, the infants were tested in the head-turning task both with and without landmarks (the landmark consisted of a bright yellow star directly above one window). The 6-month-olds responded egocentrically in both conditions, the 11-month-olds responded egocentrically without a landmark and at chance with it, and the 16-month-olds responded allocentrically in both conditions. Acredolo concluded that 11 months of age is a transitional period from an egocentric reference system to a continually updated spatial reference system. To expand these results, the same task was used with 6-, 9-, and 11-month-olds except that the landmark was made even more obvious (changed from a yellow star to flashing lights) (Acredolo & Evans, 1980). Here, the 6-month-olds responded egocentrically despite the presence of flashing lights at the correct window. The 9- and 11-month-olds responded egocentrically in the absence of landmarks but correctly in the presence of landmarks. McKenzie, Day, and Ihsen (1984) reported similar results.

Acredolo concluded that salient landmarks are an important spatial cue to infants during this transitional phase. The transitional phase to which she referred is between 9 and 11 months, which is a significant age because most normally developing infants begin crawling during this time. Indeed, movement—both passive and active—during spatial tasks has been found to have profound effects on spatial memory.

The role of movement in spatial memory tasks

Multiple studies, using several methods, have converged on the importance of movement and locomotion as critical factors in the development of spatial memory. Passively moving infants improves spatial memory when compared with rotating the environment around infants. Bremner (1978b) found that 9-month-olds correctly

found the toy significantly more often when they were rotated around the table than when the table was rotated around them. Moreover, infants who actively move on the object retrieval task are more likely to find the hidden toy than are infants who are passively moved. For example, in an adaptation of the object retrieval task, infants had to move across the floor to the table to obtain a toy, either by crawling independently or by being carried by their parents. Note that this task did not involve rotation of the infants but rather involved active or passive locomotion. Infants who successfully crawled to the table independently retrieved the toy more often than did infants who were carried by their parents (Acredolo et al., 1984; Benson & Uzgiris, 1985). These results lend some support to the idea that movement helps infants to code spatial locations.

Furthermore, the onset of independent locomotion improves infants' performance, even on spatial tasks that do not require crawling. In particular, infants who crawl on their hands and knees could reach to the correct spatial location for a hidden toy even after they were rotated (Bai & Bertenthal, 1992; Horobin & Acredolo, 1986). In contrast, infants matched in age but not yet crawling reached egocentrically after the rotation. That is, they repeated the same movement and failed to get the toy. Infants who were belly crawling, again matched in age, were intermediate; some reached correctly and some did not.

Even experience with a walker improves spatial memory. In a series of studies, Bertenthal, Campos, and Barrett (1984) tested precrawling infants both with and without walker experience and crawling infants to compare the effects of movement in a walker. In the head-turning task, crawling infants and precrawlers with walker experience looked to the correct window even after they were rotated, whereas age-matched precrawlers without walker experience did not. Precrawling infants without walker experience could not even find a hidden target, whereas precrawlers with walker experience and crawling infants could uncover a toy and remember where it was hidden between two hiding locations.

There is also some evidence that the amount of locomotor experience improves performance on one aspect of spatial tasks. Kermoian and Campos (1988) tested crawling and precrawling infants (both with and without walker experience) on a sequence of object permanence tasks, including the spatial search task. The main finding was that locomotor experience was highly related to good performance. Infants with more than 9 weeks of experience, either with a walker or crawling, were most likely to pass more advanced tasks. No differences were found between the crawling infants and the precrawling infants with walker experience, suggesting that the effect is neither maturational nor specific to the type of locomotor experience (see also Bertenthal et al., 1984).

Taken together, these studies suggest that active movement by infants increases spatial ability such that infants perform spatial tasks more accurately after they have been moved and even more so after they have actively moved. Furthermore, the onset of independent locomotion seems to be a pivotal factor that aids infants in performing spatial tasks. Taken together, these findings raise an important question about the impact of learning to walk on spatial memory. It is possible that the onset of walking has no specific impact on spatial memory. This would be consistent with

the findings by Campos and colleagues that any kind of locomotor experience improves spatial memory (e.g., Bertenthal et al., 1984; Kermoian & Campos, 1988). In contrast, if improvements in spatial memory occur based on a novel locomotor experience such as learning to crawl, perhaps learning a different yet novel locomotor style might also affect spatial memory. Walking certainly has some critical differences from crawling that could affect spatial memory. As walkers, infants are higher up off the ground, so eye level is quite different. Walking infants can also see where they are going as they are moving, and this could dramatically affect spatial memory.

Indeed, ample evidence suggests that crawlers and walkers handle other aspects of their locomotor environments differently (Gibson et al., 1987). For example, Adolph, Eppler, and Gibson (1993) tested crawling ($8\frac{1}{2}$ months of age) and walking (14 months of age) infants on a walkway with various degrees of slope and measured both exploratory activity and their success at descending the slopes. Crawling and walking infants engaged in different exploratory behaviors, including looking at and touching the slope, and investigated alternative methods of descent.

Importantly, the knowledge gained across months of crawling experience did not transfer to walking infants. Using the same sloping walkway, Adolph (1997) tracked infants longitudinally from their first week of crawling through several months of walking experience. Infants' judgments increased in accuracy with more weeks of crawling experience. However, their accuracy judgments plummeted when the infants started walking. The same infants who accurately judged the steepness of the slopes as crawlers could not do so from an upright position 3 weeks later. Thus, whatever information the crawlers gained through their weeks of crawling experience did not transfer to walking. Taken together, these results suggest that for some aspects of exploration and perceptual learning, the transition from crawling to walking is a critical milestone that affects, if not disrupts, infants' behavior.

In sum, we know that crawling experience serves as a mediator of cognitive skills and that both the onset of crawling and crawling experience affect spatial memory. Furthermore, we know that infants shift to walking a few months after they learn to crawl and that this transition affects exploratory behaviors and perceptual learning. This raises the question of whether the onset of walking also affects developing spatial memory, especially in a task that requires infants to locomote to demonstrate that spatial memory. The purpose of the current studies was (a) to track the developmental course of place learning and cue learning in a locomotor task and (b) to explore the impact of locomotor experience, including the transition from crawling to walking, on spatial memory. Experiment 1 focused on the development of place learning, and Experiment 2 examined the development of cue learning.

Experiment 1

Experiment 1 tested the relation between place learning and locomotor experience in 8-, 11-, and 14-month-olds. These ages were chosen because they mirror the ages used by Acredolo (1978) and because, on average, 8-month-olds are new crawlers, 11-month-olds are experienced crawlers, and 14-month-olds are new walkers. To test

place learning in a task that required locomotion, the Morris water maze, a task used to study spatial memory in rats, was adapted for use with infants. Infants had to traverse a large octagonal arena to reach their mothers, who stood just outside the arena. An experimenter carried infants across the arena and put the infants down at different spots within the arena, facing the wall. Infants then turned around and crossed the floor to their mothers. After baseline trials with mothers visible, mothers hid behind the walls of the arena while the infants were carried across the arena. Thus, when the infants turned around, their task was to find their hidden mothers. The aim was to compare infants' success at finding their hidden mothers and strategies for doing so based on locomotor experience and the type of cues available.

Method

Participants

In this study, participants were 12 8-month-olds ($M = 8.43$ months, 8 boys and 4 girls), 12 11-month-olds ($M = 11.64$ months, 7 boys and 5 girls), and 12 14-month-olds ($M = 14.33$ months, 6 boys and 6 girls). Nearly all infants (there was 1 exception) were white and of middle-class socioeconomic status.

Children's names were identified from the birth announcements published in the local newspapers. Letters were then sent to the parents, followed by telephone calls to solicit participation. An additional five 11-month-olds and eight 14-month-olds were excluded due to failure to complete the pretest (see below) or due to fussiness. All infants received a small prize for their participation.

Parents provided motor milestone information for their infants, including the ages when the infants first began to crawl on their bellies, crawl on their hands and knees, cruise, stand, and walk independently, referring to calendars and baby diaries when available. The average number of weeks of locomotor experience was calculated for each age group (Table 1). The 8-month-olds were considered to be novice crawlers, the 11-month-olds were considered to be expert crawlers, and the 14-month-olds were considered to be walkers (but all were expert crawlers before starting to walk).

Apparatus

The Morris water maze was adapted for use with infants. Although there are numerous variations on procedures for the water maze, the procedure was modeled after Schenk's (1985) procedure because it is the most appropriate procedure for human infants.

Table 1
Weeks of locomotor experience for infants in Experiments 1 and 2

	Experiment 1		Experiment 2	
	Weeks crawling	Weeks walking	Weeks crawling	Weeks walking
8-month-olds	5.25		4.08	
11-month-olds	13.1		17.17	
14-month-olds	21.17	7.1	22.41	8.67

A large, enclosed octagonal arena was constructed by attaching eight 1 in. plastic pipes (each pipe was 42 in. long with 3 in. end joints) to each other, resulting in a space that was approximately 10 ft in diameter (Fig. 1). A blue curtain was then slid over the piping, and the piping with the curtain was hung from the ceiling with nylon ropes, so the curtain hung from 22 in. off the ground to the floor. The result was a 2 ft-high curtain barrier. The floor was covered in a soft blue carpet.

The arena was then surrounded by black curtains that hung from 4 in. below the ceiling to the floor so as to limit the distractions to the infants. The black curtains formed a square around the arena, leaving approximately 2 ft of space between the two curtains, with more in the corners.

There were several items within the black curtains but beyond the blue arena that the infants could use as cues. Specifically, there were two large beige cameras (3 × 1 ft) in opposite corners with a fluorescent orange flag hanging down from one of them. These were positioned near the ceiling, but the flags hung down at infants' eye level while they were being carried. There were also two video cameras in opposite corners of the room located 1 ft behind and 1 ft above the top of the blue arena. Finally, there were three shiny metal lights, approximately 1 ft in diameter, in a cluster along one wall of the black curtain, located approximately 3 ft above the edge of the arena (at infants' eye level while being carried within the arena). These were left in place so that there would be several available cues outside the arena but nothing inside marking the goal.
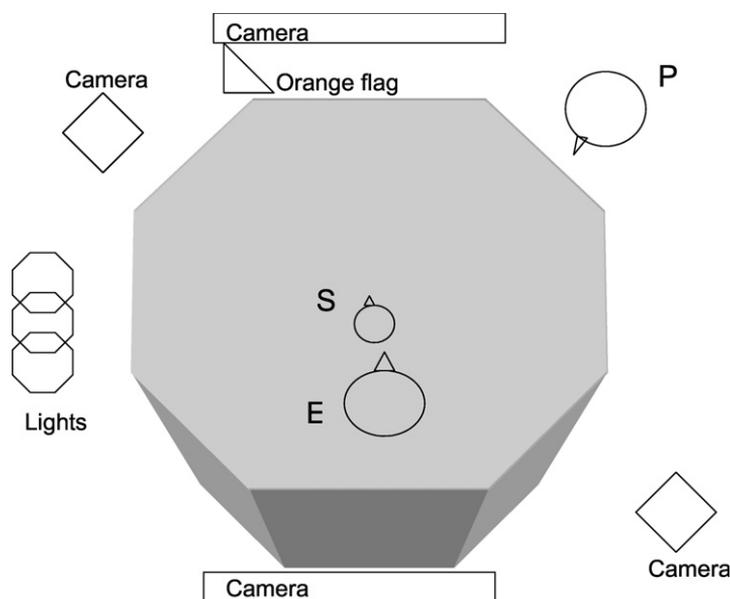

Fig. 1. Overhead view of the arena. The experimenter (E) and the infant (S) are inside the arena, whereas the parent (P) is outside the arena. The curtain enclosure is represented by the square border outside the octagonal arena. The three lights were shiny metal, and the flag hanging off of the one camera was fluorescent orange.

The infants' task was to move across the floor to their mothers, who were located outside the blue curtain. Given the height of the blue curtain, if the mothers kneeled outside the arena, they were visible to the infants from inside the arena. If the mothers sat down and ducked their heads, they were no longer visible from inside the arena. Thus, infants could be trained to move toward a visible or hidden goal (their mothers). An overhead camera with a fish-eye lens recorded the infants' behavior.

Procedure

The experimenter began the session by carrying infants inside the arena and allowing them to play with her or the infants' mothers. This gave the infants time to get acclimated to both the arena and the experimenter. After a few minutes, the experimenter picked up the infants, carried them across the arena, and put them down in either a crawling or a walking position facing their mothers (who were still sitting inside the arena). The mothers then coaxed the infants to move to them by calling their names and showing them interesting toys. This was the pretest, which was done to ensure that each infant was able to move across the floor.

The infants then participated in two baseline trials. For these trials, the mothers stepped outside the arena but within the black curtain enclosure, remaining fully visible. They remained in the same part of the room and behind the same octagonal wall as during the pretest, and all mothers in all conditions were placed in the same location. To begin the trial, the experimenter carried the infants to their mothers, so the starting point for all trials was the mothers. For the first baseline trial, the experimenter then turned the infants around, carried them directly across the arena, and placed them down in their normal locomotor position facing the wall. Infants were always carried facing forward. Note that there was no specific disorientation, but the experimenter did rock children from side to side to make the experience enjoyable for the infants. The infants' task was then to turn around and crawl or walk to their mothers, who were calling to the infants and showing them toys. The experimenter remained behind the infants inside the arena at all times. When the infants reached their mothers, they were lifted out of the arena to play with their mothers for a few seconds. If infants did not move to their mothers, more baseline trials were administered until infants successfully moved to their mothers twice. Two baseline trials were administered to ensure that infants were motorically capable of doing the task and that they had learned the game.

The starting position of the infants was randomized after the first baseline trial. Recall that the arena was octagonal and that the mothers always remained in the same location. Infants were never started at the side where their mothers were located or at the side directly to the mothers' left or right. Thus, infants' starting positions across trials was randomized within the five remaining sides. Infants were always placed directly in the center of a side, facing the wall. Because of the randomization, infants could not simply turn back toward the arena and walk in the same straight line back to their mothers trial after trial.

After two successful baseline trials, infants began the test phase. The same randomization procedure was used for all test trials. Here, the infants were brought to their mothers as in the baseline. However, while the experimenter turned the in-

fants around and carried them across the room, the mothers ducked down below the curtain and were instructed not to move or make any sounds (the videotapes confirm that mothers followed these instructions). When the infants were released from the experimenter's grip, their task was to cross the room to find their mothers. Infants were released from the experimenter's grip immediately on reaching the starting location (again, in the center of one of the five far sides of the arena). The experimenter occasionally talked to the infants during this time, encouraging them to find their mothers. Although the experimenter remained inside the arena, she moved around within it, always remaining behind the infants to ensure that she was not a cue. Infants were given 2 min to find their mothers. If an infant did not go to the correct location within that time or became extremely upset, the trial was stopped, the mother rose from behind the curtain, and the infant was carried to his or her mother.

After either two consecutive successful trials or two consecutive unsuccessful trials, where the infants either went to the wrong location or refused to search, the infants were given a posttest identical to the baseline (with mothers visible). The criteria of two successful or two unsuccessful trials, for both baseline and test trials, were modeled after the extensive manual search task literature (e.g., Wellman et al., 1987).

Data coding

Each trial was scored as a success (went to the correct location), a failure (moved across the floor but did not go to the correct location), or a refusal (did not move from the starting position). Success was coded as infants stopping within 6 in. of the edge of the curtain on the correct wall of the arena. The infants could stop anywhere along that side (recall that each side was 42 in. long) as long as they stopped within 6 in. of the edge. Trials in which infants went to the wrong location and stopped moving (as indicated by sitting down for the crawlers and by peering over the edge of the curtain for the walkers) were coded as failures. However, if infants went to the wrong location and only paused (as indicated by remaining in the crawling posture or turning around in a circle while looking around the room), they were given time to resume moving. If infants moved shortly after pausing and then stopped along the correct wall, this was coded as a success. If infants did not resume moving, this was coded as a failure. Note that no infants moved a small distance and then stopped in the center of the arena without resuming movement. To distinguish between direct successful and failed trials and those in which infants visited more than one location, the number of sides visited by each infant was also calculated for both successful and failed trials.

A trial was coded as a refusal if the infant did not move across the floor at all but was engaged with the task (i.e., looking around the room or looking at the experimenter). Infants who became upset during the test trials and stopped participating in the task (e.g., by crying) were excluded from the study. Thus, refusals represent an importantly different kind of failure. Of the total number of trials across all infants, five 8-month-olds, four 14-month-olds, and no 11-month-olds refused to move, and refusal trials generally occurred immediately following failed trials.

Infants who refused to move on the baseline trials were excluded from further analyses, so all infants included in the study were successful on the baseline trials.

The proportion of successful trials for each infant was then calculated for the test trials by dividing the total number of successful, failed, and refusal trials by the number of successful trials (identical to Adolph, 1997). A second coder who was blind to the experimental hypotheses coded 25% of the trials. Coders were in agreement on 100% of the trials.

Infants' behavior was also examined on each trial using the following measures:

1. *Latency.* The latency period began when infants were released from the experimenter's grip and ended when the infants began to locomote. Thus, this measure captures the amount of time that infants spent before starting to move—a measure of hesitation. A second coder who was blind to the hypotheses coded 20% of the videotapes for latency. Interrater reliability was high ($r = .92$).
2. *Duration.* The duration refers to how long infants spent crossing the floor. It began at the moment infants began moving (the end of the latency period) and ended when the infants either reached the goal location or stopped moving for more than 120 s. Again, interrater reliability based on 20% of the videotapes was quite high ($r = .92$).

For each infant, the latency and duration were compared between the last baseline trial and the first test trial.

Results

Success rates

Recall that all infants were successful on the baseline trials, implying that any differences in behavior on the test trials, where the mother was hidden, were not due to factors such as insufficient motor skills or motivation.

Average success ratios. A ratio of successful trials for each age group was calculated for the test trials (Fig. 2). An analysis of variance (ANOVA) on the proportion of successful trials confirmed that there was a main effect for age, $F(2, 33) = 5.328$, $p < .01$. Fisher's protected least significant difference (PLSD) tests revealed that the 8-month-olds were significantly less successful than both groups of older infants. Note that both the 11- and 14-month-olds were only moderately successful at finding their hidden mothers.

Success ratios and locomotor experience. To explore the effect of locomotor experience on infants' proportion of successes, each infant's success ratio on the test trials was plotted by his or her weeks of locomotor experience, keeping separate weeks of crawling versus walking experience (Fig. 3). Note that all of the walking infants were 14-month-olds and that all of the crawling infants were either 8- or 11-month-olds. The data reveal a distinct difference in success rates by locomotor experience. The infants with the least number of weeks moving, either crawling or walking, were those who were more likely to fail at least once. This is especially clear with the crawlers. Nearly all of the infants with fewer than 7 weeks of crawling experience
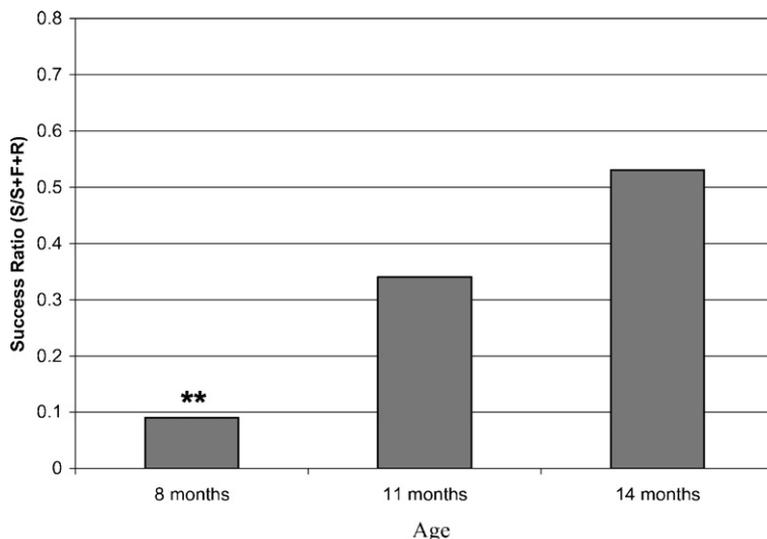
Fig. 2. Average success ratios with distal landmarks. Success ratios for each infant were calculated by the equation $S/S + F + R$, where S represents successful trials, F represents failed trials, and R represents refusal trials (identical to Adolph, 1997). $**p < .01$.
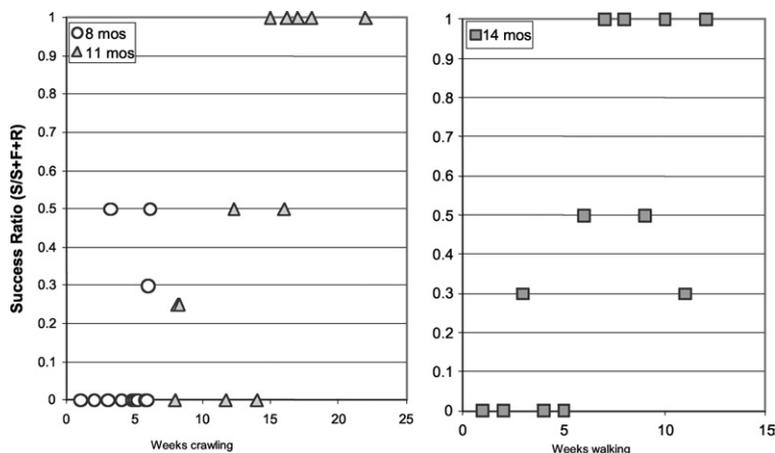

Fig. 3. Success ratio by weeks of locomotor experience. All 8-month-olds were novice crawlers, all 11-month-olds were expert crawlers, and all 14-month-olds were walking. Note that because weeks of locomotor experience were reported in whole numbers only, several of the data points overlapped. Thus, the weeks were altered slightly to show the overlapping points. This was done for visual clarity only, and the correct numbers were used in all analyses.

failed the task on every trial (or had some combination of failed and refusal trials). With a few more weeks of crawling experience, their behavior was more variable, with some successful trials and some failed trials (again, with some combination

of failed and refusal trials; there was no relation between locomotor experience and number of refusal trials). After many weeks of crawling experience, the infants were most likely to succeed on every trial. The data also indicate a step function in which even after many weeks of crawling experience, infants with fewer than 6 weeks of walking experience were more likely to fail than to succeed on the test trials. After 8 weeks of walking experience, infants were most likely to succeed on all test trials. A Pearson's correlation for the crawlers confirmed this pattern, $r = .74$, $p < .01$, but a separate correlation on the walkers did not reach statistical significance, $r = .35$, *ns*. Note that the small number of walking infants may have made it difficult to detect a significant relation between walking experience and spatial memory.

Latency

Infants' exploratory behaviors were examined during the baseline, test, and posttest trials. Note that I was unable to collect posttest data from the 8-month-olds, from five of the 11-month-olds, and from five of the 14-month-olds. In those cases, the infants did not move from the starting position. For the data that follow, the posttest data from the remaining infants are reported but not analyzed.

Infants' average latency to move (this measure captures hesitation) was calculated for the last baseline trial (a paired t test confirmed no difference in latency between the first and second baseline trials, $t < 1$) and the first test trial (Table 2). A 2 (Trial Type: baseline or test) × 3 (Age: 8, 11, or 14 months) repeated measures ANOVA re-

Table 2
Latency and duration means for Experiments 1 and 2

	Baseline	Test	Posttest
Experiment 1: Distal cues			
Latency			
8-month-olds	7.92 (1.98)	9.66 (3.42)	
11-month-olds	4.89 (1.78)	8.27 (3.34)	3.55
14-month-olds	0.94 (0.39)	1.41 (0.73)	1.98
Duration			
8-month-olds	7.93 (1.22)	25.34 (7.14)	
11-month-olds	5.83 (0.47)	26.74 (8.73)	7.79
14-month-olds	6.13 (1.41)	18.51 (4.76)	5.99
Experiment 2: Direct cue			
Latency			
8-month-olds	13.12 (4.28)	8.46 (3.99)	
11-month-olds	5.92 (2.72)	8.62 (4.13)	
14-month-olds	0.67 (0.31)	2.08 (1.15)	
Duration			
8-month-olds	15.24 (3.01)	29.12 (9.92)	
11-month-olds	7.86 (1.57)	24.57 (11.46)	
14-month-olds	3.03 (0.23)	5.09 (1.09)	

Note. Figures in table are in seconds. Standard errors are in parentheses.

vealed a significant main effect for age, $F(2, 33) = 4.33$, $p < .05$. Scheffe's S tests revealed that 14-month-olds spent significantly less time hesitating than did 8- and 11-month-olds.

What were the infants doing during the latency period? To address this question, infants' behaviors during the baseline and first test trial were divided into five categories: shifting position, looking around the room, looking at their mothers (this was possible only when mothers were visible), looking at the experimenter, and crying. The average percentage of time that each infant spent engaging in each of these behaviors was calculated for each age group.

Fig. 4 shows the breakdown of infants' behaviors across test trials. Each age group engaged in very different behaviors during the latency period. When their mothers were visible, the 8-month-old novice crawlers split their time between looking around the room and shifting position (which meant shifting from a crawl to a sit). However, when their mothers were hidden, they spent more than half of their latency looking at the experimenter. The 11-month-old experienced crawlers engaged in different behaviors. During the baseline, when their mothers were visible, they spent most of their latency looking at their mothers before starting to move. At the test trial, when their mothers were hiding, these infants spent more than 60% of their latency looking around the room. After they were placed in a crawling position, they shifted to a sitting position, looked around the room, and then shifted back to a crawl and began to move. In contrast, the 14-month-old walkers engaged in very little hesitation time, beginning to move within approximately 2 s of being released, on average, for both the baseline and test trials. These infants simply turned around and began to move, whether their mothers were visible or hidden.
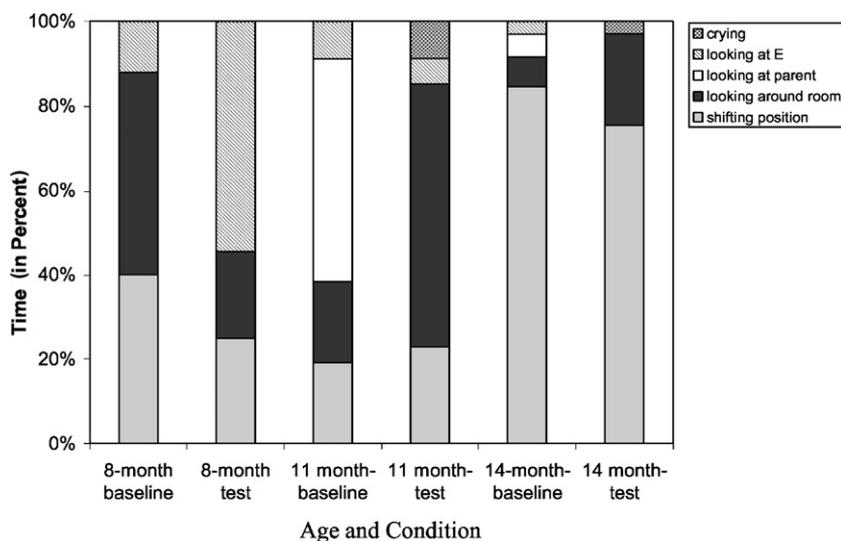

Fig. 4. Exploratory behavior across trials with distal landmarks.

Duration

Movement duration captures how long the infants took to cross the floor. A 3 (Age: 8, 11, or 14 months) $\times$ 2 (Trial Type: baseline or test trial) repeated measures ANOVA revealed a main effect for trial, $F(1,33) = 17.018$, $p < .001$, with all infants spending more time crossing the floor during the test trial compared with the baseline (Table 2).

It is possible that during the longer duration, infants were wandering around the arena, either exploring the arena and not searching for their mothers or performing an exhaustive search in which they stopped at every side until they found the right one. To address this, the numbers of sides that each infant visited on both successful and failed trials were compared. An ANOVA on the number of sides for successful and failed trials confirmed that there were no significant differences in age or type of trial (successful or failed), $F(2,9) < 1$. The mean numbers (and standard errors) of sides visited during successful trials were 1.25 (0.25) for the 8-month-olds, 1.33 (0.21) for the 11-month-olds, and 1.0 (0.0) for the 14-month-olds. Similarly, the mean numbers (and standard errors) of sides visited during failed trials were 1.25 (0.25) for the 8-month-olds, 1.38 (0.20) for the 11-month-olds, and 1.75 (0.75) for the 14-month-olds. Thus, infants were generally not searching at multiple locations.

Additional evidence for the lack of exhaustive search comes from the range of infants' duration times. For the baseline trials, the range was 1.0–36.2 s; for the test trials, the range was 1.0–74.9 s. (Note that the maximum was an outlier; the next highest was 43.1 s, and all remaining durations were less than 20 s.) To explore this possibility further, I correlated duration with success ratio and found no relation for all of the infants together ($r = -.28$, $p > .05$) or separated by locomotor style (crawlers: $r = -.29$, $p > .05$; walkers: $r = -.11$, $p > .05$). Similarly, I correlated duration and locomotor experience under the hypothesis that infants with more experience might be more likely to cover more ground searching. Again, there was no relation for all infants together ($r = -.25$, $p > .05$) or separated by locomotor style (crawlers: $r = -.35$, $p > .05$; walkers: $r = -.09$, $p > .05$).

Discussion

The key findings of this study were that 8-month-old novice crawlers could not find a hidden goal location while crawling, whereas both 11-month-old experienced crawlers and 14-month-old novice walkers were somewhat successful. The successful performance by the experienced crawlers indicates that infants as young as 11 months of age can use relations between landmarks to find a hidden goal. This is somewhat surprising in light of previous findings suggesting that children as old as 2 years of age are notoriously poor at spatial tasks that do not have a specific landmark to mark the goal (e.g., Acredolo, 1978; Hermer & Spelke, 1996; Newcombe, Huttenlocher, Drummey, & Wiley, 1998).

But in some ways, this finding is also not so surprising. First, recent findings that $8\frac{1}{2}$-month-olds could use distal landmarks to turn their heads to the correct location set the stage for early place learning (Lew et al., 2000). But more important, navigating through the environment to reach a goal is an everyday task that infants face in

real life the moment they begin locomoting. Thus, it does not seem so far-fetched that they would be successful at it.

This becomes even more clear when considering the task itself. The water maze adaptation is a good ecological task for studying navigational memory because it requires infants to move to attain the goal. This is important because in everyday life, people find their way around the world while moving through it. It is rare that people need to track a particular location while the environment is spun around them or while they are passively moved. Indeed, tracking environmental cues is something that is generally done during action. Thus, studying the development of the phenomenon during action captures the development of the behavior more accurately.

In addition, the goal location for the children is both typical in their everyday lives and motivating. Infants and young children often keep track of their mothers' location. Infants frequently crawl and walk toward their parents, so asking them to do so in this task is familiar and keeps the infants' interest throughout the experiment. Thus, the task asks infants to do something that they do every day—look at their mothers, keep track of their location, and move toward them.

It is important to note that this task likely did tap into place learning as opposed to dead reckoning. Dead reckoning is considered to be hierarchically related to place learning, where dead reckoning relies on self cues (locations are coded with respect to distance and/or direction from one's current position and then are updated as one moves) and place learning relies on external cues. Although it is certainly possible to succeed in the current task using dead reckoning, there are reasons to believe that the task tapped place learning instead. First, dead reckoning is not available to young infants when the movement involves both rotation (spinning on one's axis, as demonstrated when the infants are placed facing the wall of the arena and must turn around) and translation (movement through space, both when infants are passively carried and when they must move themselves) (for a review, see Newcombe & Huttenlocher, 2000). Importantly, when there is a conflict between dead reckoning and place learning, place learning takes precedence (e.g., Etienne, Teroni, Maurer, Portenier, & Saucy, 1985; Goodridge & Taube, 1995). Furthermore, when there is conflict, infants tend to use geometric cues, where they estimate distance and direction within a region of a specifiable geometric shape (Hermer & Spelke, 1996). In this case, infants could use the corners of the square enclosure around the arena as external cues to engage in place learning in addition to the multiple cues around the room. Developmentally speaking, dead reckoning improves between 12 and 16 months of age, but only 16-month-olds were good at using dead reckoning when they had to move (e.g., Acredolo et al., 1984; Newcombe et al., 1998). So, it seems that dead reckoning, although certainly a possibility, would be challenging given the ages of the children involved and the fact that the task required rotation and translation and self-movement. In the end, infants may have used either dead reckoning or place learning, or some combination of the two, but regardless of which strategy they used, the key finding from this study is the relation between locomotor experience and search performance.

Although the 11-month-old experienced crawlers were relatively successful on this place learning task, most of the 8-month-olds were not. One might argue that these

infants were unable to perform the task due to poor locomotor abilities, lack of motivation, or fatigue. The baseline and available posttest data indicate that this is not the case. All of the infants were successful in the baseline trial, where all infants crossed the floor in less than 10 s. The only significant difference in how long infants took to cross the floor was that all age groups spent more time crossing the floor on trials where their mothers were hidden. The fact that there were no differences among the age groups in duration indicates that the 8-month-olds were no slower in crossing the floor than were the older infants. This strongly suggests that the infants were motorically capable of doing this task.

Moreover, the lack of a main effect for trial type on hesitation time for all infants suggests that all of the infants were just as eager to cross the room when they could not see or hear their mothers as they were when they could see and hear their mothers. There was an age effect, with the 8-month-olds hesitating longer than the other groups, but there was no difference in hesitation between the baseline and test trials. Indeed, infants hesitated for less than 11 s on both the baseline and test trials before starting to search. Moreover, few infants refused to search on the test trials. In a total of 30 trials for all of the 8-month-olds, there were only 5 trials in which infants refused. This means that, for the most part, the infants who did not successfully find their mothers tried to find them and failed, implying that the infants were motivated to find their mothers. This motivation also implies that infants remembered that their mothers were hidden.

Finally, the posttest data, combined with the data described previously, rule out fatigue as a factor for the two older groups of infants. Although I could not do statistical tests on the posttest data, there appear to be no differences in latency or duration between the baseline and posttest data in the 11- and 14-month-olds. As mentioned previously, I was unable to collect posttest data from the 8-month-olds due to fussiness. However, there was little difference in their duration scores from the baseline trial to the test trial (10.1 and 11.8 s, respectively). Also, the fact that the infants tried to find their mothers on the test trial and failed suggests that they were able to keep moving across the floor at a reasonable rate for several trials. Although fatigue cannot be ruled out as a factor in their performance, these data suggest that fatigue is an unlikely explanation.

It is also possible that the 8-month-olds' failure to succeed is simply due to the fragility of the object concept at 8 months. Numerous studies, from Piaget's seminal observations through current observations within the context of the looking versus reaching debate, indicate that 8-month-olds do not actively (motorically) search for hidden objects (e.g., Munakata, 1998; Piaget, 1954). Thus, these infants might not have been searching for their mothers at all but rather were just wandering around the arena to explore it. However, the fact that infants' test trials were the same duration as the baseline trials, coupled with the finding that infants generally went directly to the wrong location, suggests that infants did remember that something was hidden and were actively searching for it. In this case, it seems likely that a hidden mother is a stronger stimulus than a hidden toy, so infants were able to keep that goal in mind.

The different patterns of behavior demonstrated in this task suggest that spatial memory may be linked to movement. First, consider that infants did not simply im-

prove at the task with age. Although the 11-month-old expert crawlers outperformed the 8-month-old novice crawlers, they performed the same as the 14-month-old novice walkers. Instead, success was predicted by how long infants had been moving in their particular modes of locomotion. The correlations between locomotor experience and proportion of successes strongly support this. Indeed, it was the 14-month-olds with fewer than 6 weeks of walking experience who had very low success ratios. After 8 weeks of walking experience, however, infants were most likely to succeed on all test trials. This finding is interesting in that not only were the 14-month-olds 3 months older, but they too had just as much crawling experience before they started walking. That is, none of the 14-month-olds skipped crawling. They all spent many months crawling before they began to walk. These data suggest that whatever infants learn about using cues in the environment is at least partly tied to how they move through it.

Moreover, the finding that infants demonstrated different behaviors during the test trials as crawlers and as walkers indicates that how infants use place cues may be tied to how they locomote. Each group of infants seemed to use a different set of behaviors to approach the problem, with each one of them being prudent given the particular postures associated with each form of locomotion. This implies that infants' behaviors in this task may be due to the soft assembly of available perceptual inputs, memory for the spatial location, and locomotor skill. Thus, when locomotor skill is weak (as in the novice crawlers and walkers), and the memory for the location is fragile and the perceptual inputs are weak (i.e., distal cues), the result is poor performance. But given the same levels of memory and perceptual input with improved locomotor skill, performance improves. Interestingly, how these components are assembled appears to be directly linked to the particular type of locomotion used. One might speculate that the older infants may have a stronger memory for the location and may be more attentive to the perceptual inputs due to their months of crawling experience. Still, the fact of being a novice walker seems to have overpowered the improvements in the other components. This points to the importance of locomotor skill in spatial memory.

Experiment 2

Experiment 2 explored the development of spatial memory with a direct landmark. Cue learning has often been portrayed as primitive and eventually overcome. However, cue learning is a simple and effective way in which to keep track of locations, and it is used quite frequently by adults every day. To explore whether adding a direct landmark would improve infants' performance, the procedure of the first experiment was adapted to include a salient landmark that marked the mothers' location throughout the experiment. Based on earlier findings, I predicted that infants would be more likely to successfully find their mothers when a direct landmark marked their location. A second question for this experiment was whether cue learning would be associated with locomotor experience in the same way as place learning. Acredolo (1978) showed that once infants master crawling, they are able to use

landmarks to keep track of a location, at least on a task that does not require loco-motion. This finding suggests that infants should show dramatic improvement across weeks of crawling experience but should show no variability in their performance over the transition from crawling to walking.

Method

Participants

An additional 12 8-month-olds ($M = 8.67$ months, 8 boys and 4 girls), 12 11-month-olds ($M = 11.39$ months, 7 boys and 5 girls), and 12 14-month-olds ($M = 14.28$ months, 5 boys and 7 girls) participated in the study. Infants were recruited in the same manner as in Experiment 1. Nearly all infants (there was 1 exception) were white and of middle-class socioeconomic status. An additional four 11-month-olds and seven 14-month-olds were excluded due to failure to complete the pretest or due to fussiness. All infants received a small prize for their participation.

Again, parents provided motor milestone information about their infants, refer-ring to calendars and baby diaries when available. The baby diary information from the mothers confirmed that the 8-month-olds were considered to be novice crawlers, the 11-month-olds were considered to be expert crawlers, and the 14-month-olds were considered to be novice walkers (after being expert crawlers) (Table 1).

Apparatus

The apparatus was identical to that in Experiment 1, with one exception. An addi-tional direct cue was placed on the black curtain directly above mothers' heads. This cue consisted of an 18 in. quilting ring covered in fluorescent green fabric with brightly colored bugs on it. In addition, glittery stars formed a pattern over the fab-ric and surrounded the edge of the ring. This cue was visible at all times, from the pretest through the test trials, and was comfortably within infants' range of visual acuity.

Procedure

The procedure was identical to that in Experiment 1 except that no posttest was administered.

Data coding

Data coding was identical to that in Experiment 1. With respect to calculation of success ratios, no infants in any age group refused to move, so the formula for suc-cess ratios was successful trials divided by the number of successful and failed trials.

Results

Success rates

Average success ratios. Fig. 5 shows the proportion of successful trials for each age group for the test trials. An ANOVA on the proportion of successful test trials con-firmed a main effect for age, $F(2, 33) = 11.417$, $p < .001$. Fisher's PLSD tests revealed
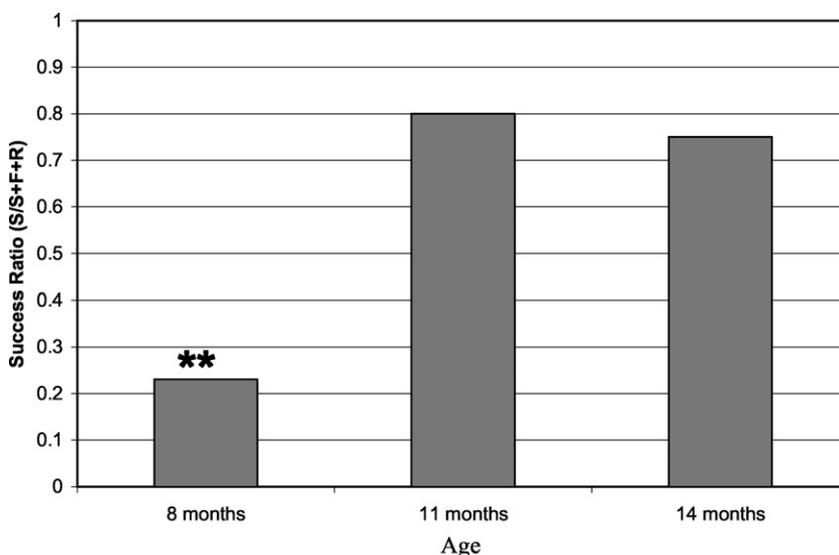
Fig. 5. Average success ratios with a direct landmark. Success ratios for each infant were calculated by the equation S/S + F + R, where S represents successful trials, F represents failed trials, and R represents refusal trials (identical to Adolph, 1997). **$p < .01$.

that the 8-month-olds were significantly less successful than both the 11- and 14-month-olds.

Success ratios and locomotor experience. Infants' individual success ratios were then correlated with weeks of locomotor experience (Fig. 6). Again, note that all of the walking infants were 14-month-olds. The data show a significant correlation of weeks of locomotor experience with successful performance. The infants with the least number of weeks of crawling experience are clustered at the bottom of the graph with a success ratio of zero. After 6 weeks of crawling experience, the ratio increases to approximately .50 and then increases to perfect performance after 13 weeks. A similar pattern was found with the walking infants. Infants with fewer than 6 weeks of walking experience had low success ratios, clustering around zero. After 7 weeks of walking experience, all infants demonstrated perfect performance. Separate Pearson's correlations for the crawlers and the walkers confirmed this pattern for crawlers, $r = .74$, $p < .01$, as well as for walkers, $r = .61$, $p < .01$.

Latency

   Infants' average latencies to move across the floor on the last baseline and first test trial were compared (Table 2). A 2 (Trial Type: baseline or test trial) × 3 (Age: 8, 11, or 14 months) repeated measures ANOVA revealed a main effect for age, $F(2, 33) = 3.96$, $p < .05$. Scheffe's tests confirmed that the 11-month-olds hesitated significantly more than did the 14-month-olds.
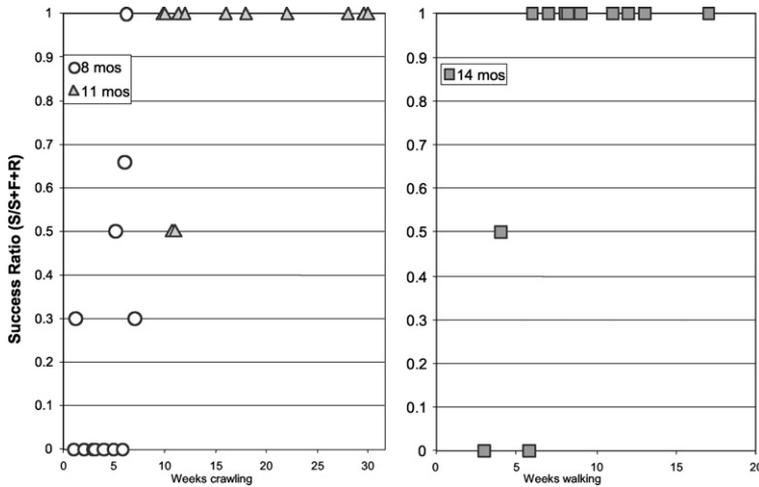
Fig. 6. Success ratios by weeks of locomotor experience. All 8-month-olds were novice crawlers, all 11-month-olds were expert crawlers, and all 14-month-olds were walking. Note that because weeks of locomotor experience were reported in whole numbers only, several of the data points overlapped. Thus, the weeks were altered slightly to show the overlapping points. This was done for visual clarity only, and the correct numbers were used in all analyses.

To determine what infants were doing during their hesitation time, infants' behavior during the latency was catalogued. Fig. 7 shows the breakdown of infants' behavior across trial types. Again, the crawlers engaged in different behaviors during the latency compared with the walkers. Both the 8- and 11-month-olds spent time shift-
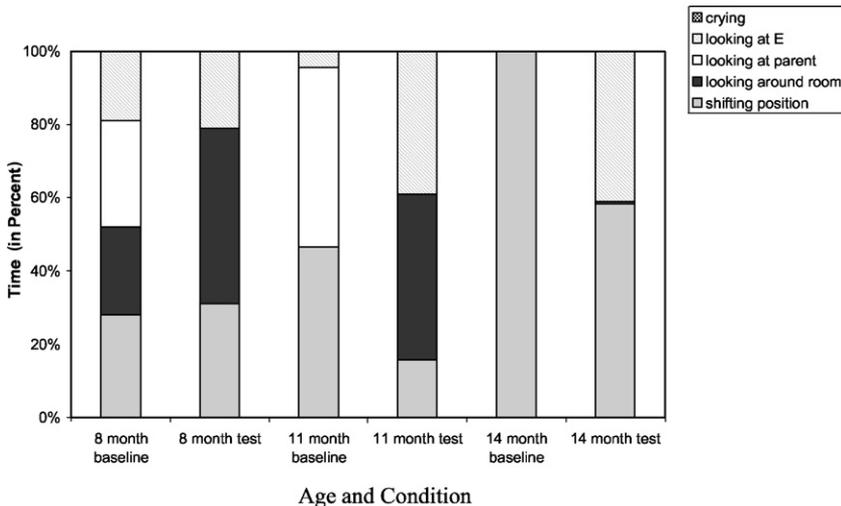

Fig. 7. Exploratory behavior before starting to move with a direct landmark.

ing position (moving from a crawl to a sitting position) and looking at their mothers during the baseline trials. During the test trials, both groups of crawling infants spent the majority of their latency (8 s on average) looking around the room and looking at the experimenter. In contrast, the 14-month-olds had very short latencies (<4 s on average) and spent most of this time shifting position (turning around). Even during the test trials, the 14-month-olds spent most of the time turning around and some time looking at the experimenter. Note that practically no time was devoted to looking around the room before starting to move.

Duration

Recall that movement duration captures how long the infants spent moving across the floor. The bottom half of Table 2 shows infants' duration by age group across the baseline and test trials. A 2 (Trial Type: baseline or test trial) × 3 (Age: 8, 11, or 14 months) ANOVA revealed a main effect for age, $F(2,32) = 12.64$, $p < .001$. Scheffe's S tests reveal that the 8-month-olds were significantly slower than both the 11- and 14-month-olds, regardless of trial type.

Again, on average, infants went directly to the correct or incorrect location. The mean numbers (and standard errors) of sides visited during successful trials were 1.17 (0.16), 1.08 (0.06), and 1.0 (0.0) for the 8-, 11-, and 14-month-olds, respectively, and 1.18 (0.10) for failed trials for the 8-month-olds (there were not enough failed trials for the two older groups to calculate group means). An ANOVA on the number of sides on successful trials only confirmed that there were no age differences, $F(2,27) = 1.26$, $p > .05$. A t test comparing the numbers of sides for the successful and failed trials of the 8-month-olds also revealed no differences, $t(15) < 1$.

Furthermore, the durations suggest that infants did not wander around the arena and just happen on the correct location. The ranges of infants' duration times were not very different between the baseline trials (2.0–36.2 s) and the test trials (3.1–74.9 s). (Again, note that the maximum was an outlier; the next highest was 35.36 s, and all remaining durations were less than 20 s.) To explore this possibility further, I correlated duration with success ratio and found no relation for all of the infants together ($r = -.28, p > .05$) or separated by locomotor style (crawlers: $r = -.23, p > .05$; walkers: $r = -.31, p > .05$). Similarly, I correlated duration and locomotor experience under the hypothesis that infants with more experience might be more likely to cover more ground searching. Again, there was no relation for all infants together ($r = -.19, p > .05$) or separated by locomotor style (crawlers: $r = -.22, p > .05$; walkers: $r = -.08, p > .05$).

Discussion

With a direct landmark, 8-month-old novice crawlers could not find the hidden goal location, and both 11-month-old experienced crawlers and 14-month-old walkers were generally successful, although it is worth noting that the three 14-month-olds who were not successful were the ones with fewer than 6 weeks of walking experience. Overall, these results support previous work indicating that infants are quite skilled at finding a location marked by a direct landmark. Many studies

have found that somewhere around 9–11 months of age, infants are able to use land-marks to find a location. Infants of this age look to the correct window to see a smiling experimenter (Acredolo, 1978), and they search in the correct location for a hidden toy (Bremner, 1978a, 1978b). Thus, it is not surprising that the 11- and 14-month-olds were quite successful at finding their hidden mothers.

However, the 8-month-olds were not at all successful at finding their mothers in the current experiment. Although the previously mentioned studies found no evidence of cue use in infants under 9 months of age, a few studies found that infants can be trained to use cues with enough practice trials (e.g., Cornell & Heth, 1979; McKenzie et al., 1984), suggesting that younger infants may be able to use direct landmarks given the right task and training. This raises the issue of why infants in the current experiment seemed to be unable to use the direct landmark, whereas in other studies they could. The current data suggest that the 8-month-olds did not fail at this task due to lack of motivation or locomotor skills. All of the infants successfully crossed the floor quickly during the baseline trials, suggesting that their locomotor skills were sufficient. Moreover, all of the infants tried to find their mothers when they were hidden, indicating that the infants were motivated to do so. Therefore, any difficulties they had with this task were not due to insufficient crawling skills or motivation.

Instead, one possible reason why the 8-month-olds looked for their mothers in the wrong location was the combination of moving while remembering. Even though the infants were perfectly capable of crossing the room, the added demand of remembering their mothers' location while crawling may have been too difficult. If the infants only had to remember their mothers' location without crawling to them (as in the head-turning task), they may very well have succeeded. And we saw from the baseline trials that when the infants had to move to their mothers without the memory demand, they were also successful. Yet the combination of movement and spatial memory proved to be too difficult for the youngest infants.

This further supports the notion that the behavior required by this task comes from the soft assembly of the perceptual inputs, the memory for the location, and locomotor skill. Here, the act of moving through the environment may prevent newly locomoting infants from attending to a landmark. Alternatively, infants may notice the landmark but might not be able to use it to help them find their mothers. This latter possibility implies a cognitive load problem, where the infants have all of the information but cannot quite put it together to come up with a solution. However, it is critical to remember that finding one's way through the world requires both spatial memory and movement at the same time. When infants want to find their favorite toy from the other room, it is not enough for them to know where it is. They must remember where it is and use that memory to guide their movements.

Further evidence that infants' use of spatial cues is linked to their locomotor experience is the finding that infants' success rates on this task became variable during the transition to walking. After many weeks of crawling experience, infants' performance was at ceiling. That is, their success ratio was 1. However, the 14-month-olds who were just learning to walk had much lower success ratios despite more weeks of

crawling experience. All of the infants with fewer than 6 weeks of walking experience had success ratios of less than .50. All of the infants with more than 6 weeks of walking experience had perfect success ratios. This suggests that the onset of walking disrupts infants' use of landmarks, at least initially. After weeks of practice, infants either recover that ability or relearn it.

General discussion

The first goal of these studies was to track the developmental trajectory of place learning and cue learning in a locomotor task. The second goal was to explore the role of locomotor experience and type of locomotion on their use of distal and direct landmarks. Without a direct landmark, 8-month-old novice crawlers and 14-month-old novice walkers could not find the goal location, whereas both 11-month-old experienced crawlers and 14-month-old experienced walkers were mostly successful. With a direct landmark, 8-month-old novice crawlers and 14-month-old novice walkers were unable to find the goal, whereas 11-month-old experienced crawlers and 14-month-old experienced walkers were highly successful.

Developmental differences between place learning and cue learning

The findings indicate a slight dissociation between place learning and cue learning. This was not evident in the 8-month-olds, who failed at both tasks, nor was it evident in the 14-month-olds, who were, on average, successful in both conditions. However, it was evident in the findings from the 11-month-olds, who were only somewhat successful with distal cues and highly successful with a direct cue. In some ways, this result supports previous findings with infants suggesting that cue learning is easier than place learning. Increased memory for a spatial location marked by a direct cue has been observed in many studies, especially in very young infants (e.g., Acredolo, 1978; Bremner, 1978a, 1978b).

However, the results from the studies by Bremner (1978a, 1978b) suggest that infants should be able to find a location marked with a cue by 8 months of age. Both of these studies by Bremner tested infants of 8 to 9 months of age and found that these infants could use a cue to find a location, although they could not use multiple indirect cues. Thus, it is somewhat curious that the infants in the current studies did not do so.

Notably, the one fundamental difference between those previous studies and the current task is that the current task requires infants to locomote. Although much evidence suggests that the onset of crawling is an important factor in infants' spatial coding systems, few of the studies reported in this article required infants to find a location while crawling across a flat surface. Thus, they might not address how infants remember spatial locations while moving in their normal mode of locomotion. Yet typically, navigational learning occurs in the context of moving through the world. Therefore, it is possible that the additional demand of locomotion in the current studies affected spatial learning.

Locomotor experience and success ratios

Another critical factor in infants' successful search behavior was locomotor experience. This was evidenced in the strong correlations across both experiments between success rates and locomotor experience, especially in the 14-month-old walkers. A relation between the onset of crawling and increased spatial skills is well documented (e.g., Bai & Bertenthal, 1992; Bertenthal et al., 1984; Horobin & Acredolo, 1986). Prior to locomotion, infants are left in one place for long periods of time and are given whatever they desire. Once they start crawling, infants need to keep their desired destination in mind as they move. They need to plan a route and be able to navigate around obstacles.

Based on this, many researchers have hypothesized that the onset of crawling marks an increase in spatial skills and that increased crawling experience will increase spatial memory (e.g., Bertenthal et al., 1984). Interestingly, the current results also suggest that the onset of walking results in a disruption in spatial memory. In the current studies, 14-month-old walking infants with fewer than 6 weeks of walking experience performed much worse than did infants with more than 6 weeks of walking experience. This effect held across both experiments. It is worth noting that although there was not a complete transfer from crawling to walking, it appears that there was some savings. Crawling infants needed at least 12 weeks before they were able to solve the search task consistently, whereas walking infants needed only 7 weeks to achieve perfect performance. Thus, it appears that whatever infants were learning about spatial search behavior, they did not have to start from scratch at walking onset. More important, walkers' success rate was significantly lower despite months of crawling experience. This suggests that it is not the case that any locomoting experience improves spatial memory, as has been proposed (e.g., Bertenthal et al., 1984).

Instead, this finding suggests that, in principle, spatial learning might not be different from other affordance learning. Adolph (1997) reported a similar finding where perceptual knowledge that was gained during crawling experience failed to transfer to walking. The affordances learned by the infants in Adolph's studies are different from those in the current studies. In Adolph's research, infants were judging surface properties; in the current experiments, infants were learning about spatial relations. Critically, the perceptual information in Adolph's task did have very different consequences given the biomechanics of crawling and walking, and this was not the case in the current studies. However, there may be some general principles about learning that underlie the behavior of the infants in both Adolph's studies and the current studies. In both, experience was a critical factor. Experience with the current mode of locomotion predicted success across both conditions of the current studies in that infants with more than 6 weeks of crawling experience were highly successful. Similarly, infants with many weeks of crawling experience were extremely accurate in Adolph's studies. This effect was also reported by Bertenthal et al. (1984) in a version of the object retrieval task. Thus, there is much evidence that locomotor experience is an important part of motor learning.

The second general principle that applies to both Adolph's (1997) studies and the current studies is that cognition is embodied, meaning that knowledge is assembled online, in the context of a task, with contributions from perception, memory, and movement. Thus, what one learns about spatial relations depends on how one moves through the world, where one has gone before, and what one attends to, and those factors are inextricably linked to what has been learned. Spatial memory, or the ability to go to a desired location, might not be something that infants ''have'' in its entirety. Rather, when infants need to remember and go to a location, their attention to the perceptual inputs, memory, and locomotor skill all work together to result in their behavior, and being weaker in one or more components will affect the outcome. Importantly, the current results suggest that locomotor skill plays a critical role in this assembly in that weak locomotor skill (as in the novice walkers) can overpower improvements in memory and perceptual attention gained through months of crawling experience. Despite the focus on locomotor experience, perception, attention, and memory were also critical factors in the current task. Infants needed to attend to the cues in the room, either the direct or indirect landmarks, and remember where the cues were in relation to where their mothers were. Then, they needed to continually update the spatial relations between themselves and the cues as they moved, keeping in mind their goal location.

Importantly, this principle of embodied cognition has been demonstrated across a range of tasks (e.g., Berthier et al., 2001; Boudreau & Bushnell, 2000). In addition to Adolph's (1997) studies with infants on slopes, this principle has been demonstrated in reaching tasks. For example, Diedrich et al. (2001) tested infants on a perseverative reaching task in which infants reached for one of two identical targets many times in a row and then were asked to switch to the second nearby target. Typically, infants of 8–10 months of age perseverate, continuing to reach for the first target. However, adding (or removing) a small weight to the infants' arms before they are asked to switch sides results in correct reaching. Thus, disrupting the motor memory for the feel of the arm disrupted perseveration.

Taken together, these results suggest that the feel of the body during learning is linked to what is learned (Thelen & Smith, 1994). Infants do not just learn disembodied ''concepts'' where what is remembered is abstract. What infants remember about how a space is mapped out is inextricably linked to their movements through that space. And this notion spans a wide range of tasks—from learning about space, to judging slopes, to reaching for targets, and so on. This suggests something fundamental about learning and cognition in general. Learning and memory might not be just about the brain but instead may be processes that occur in the course of moving through the world. Viewed in this way, learning in infants becomes an important window on the developmental status of general processes of exploring, moving, and remembering. This approach enables us to begin to understand the developmental course of the complex interactions of perception, action, and cognition that allow people to think about, and act in, the real world.

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