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Developmental Continuity? Crawling, Cruising, and Walking

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Abstract

This research examined developmental continuity between "cruising" (moving sideways holding onto furniture for support) and walking. Because cruising and walking involve locomotion in an upright posture, researchers have assumed that cruising is functionally related to walking. Study 1 showed that most infants crawl and cruise concurrently prior to walking, amassing several weeks of experience with both skills. Study 2 showed that cruising infants perceive affordances for locomotion over an adjustable gap in a handrail used for manual support, but despite weeks of cruising experience, cruisers are largely oblivious to the dangers of gaps in the floor beneath their feet. Study 3 replicated the floor-gap findings for infants taking their first independent walking steps, and showed that new walkers also misperceive affordances for locomoting between gaps in a handrail. The findings suggest that weeks of cruising do not teach infants a basic fact about walking: the necessity of a floor to support their body. Moreover, this research demonstrated that developmental milestones that are temporally contiguous and structurally similar might have important functional discontinuities.

Keywords

crawling; cruising; walking; locomotion; developmental continuity

Developmental Continuity

The question of developmental continuity—"Where do new skills come from?"—is a central and long-standing issue in developmental psychology. Proponents of developmental continuity claim that new skills grow from the seeds of prior accomplishments. One line of evidence that old and new skills are related is adjacent temporal ordering, where a new skill appears in the footsteps of its predecessor or as one skill disappears another quickly appears on the scene. A second line of evidence is physical similarity, where old and new skills are similar in form or map onto each other structurally. The most important line of evidence is shared psychological function, where the earlier and later appearing skills rely on the same underlying psychological mechanisms to accomplish the same goals. In this case, experience

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performing an earlier developing skill should facilitate adaptive performance of the later developing skill. Conversely, lack of temporal contiguity, formal similarity, or functional relatedness can provide evidence for developmental discontinuity.

Consider, for example, the skills of reaching and pointing. Stretching the arm toward a desired object appears earlier than pointing, and resembles pointing in its structural features. However, pointing and reaching represent qualitatively different psychological functions and the core functions originate from different contexts of communication (Franco & Butterworth, 1996). Reaching expresses a wish to grasp an object, whereas pointing expresses an intention to share reference with another person. Reaching requires sensorimotor knowledge about affordances for contacting an object or surface (von Hofsten, 1993). Pointing requires the inklings of a theory of mind and an understanding of referential intent (Moore & Corkum, 1994). In this case, the temporal contiguity and physical similarity between reaching and pointing mask developmental discontinuity (Langer, 1969). That is, pointing does not grow out of reaching and months of practice with reaching do little to support the psychological mechanisms that underlie pointing.

Continuity Between Crawling, Cruising, and Walking

Since the 1930's, researchers have agreed that the two factors impeding acquisition of walking are leg strength and balance control (e.g, Bril & Breniere, 1992; 1993; McGraw, 1935, 1945; Thelen & Ulrich, 1991). Simply put, infants cannot walk before they are able to maintain body weight and keep balance on one leg while the other leg swings forward. In the weeks prior to independent walking, infants exhibit several transient upright skills that mitigate the requirements of single limb support. They hold furniture and pull up to a vertical position, stand while holding onto furniture, take forward steps while holding a caregiver's hands, and “cruise” sideways in an upright position while holding onto furniture (Frankenburg & Dodds, 1967; Haehl, Vardaxis, & Ulrich, 2000; Vereijken & Adolph, 1999). Each of these skills involves manual support of upright posture. The furniture or caregiver compensates for the missing levels of leg strength and balance control.

Cruising is especially interesting because infants locomote without a caregiver's help. Because of its transient nature, temporal contiguity with walking, and obvious formal similarities to walking, a reasonable assumption is that practice cruising helps teach infants to walk. Granted, practice cruising could strengthen infants' legs, increase sensitivity to perceptual information for balance, facilitate interlimb coordination, motivate a higher vantage point, and so on (Barela, Jeka, & Clark, 1999; Haehl, et al., 2000; Vereijken & Albers, 1998; Vereijken & Waardenburg, 1996). But the assumption of functional continuity only holds true to the extent that critical psychological components of cruising are shared by walking. For example, does experience cruising help infants to perceive affordances for walking, that is, to distinguish safe from risky ground? As Gibson (1982) argued, detecting affordances is a central psychological function because perceiving what the environment affords (or doesn't) is required for adaptive control of behavior.

Research on the transition from belly to hands-and-knees crawling supports the plausibility of functional continuity between two forms of locomotion with contiguous developmental timing and structural similarities. Belly crawling is not obligatory, but when it occurs, it always appears just prior to crawling on hands and knees (Adolph, Vereijken, & Denny, 1998; Berger, Theuring, & Adolph, 2007). Despite the fact that belly crawlers use an inconsistent pattern of limb coordination and move with their abdomens touching the ground and hands-and-knees crawlers move with a consistent diagonal gait pattern and their torso lifted (Adolph, et al., 1998; Freedland & Bertenthal, 1994), detecting affordances for crawling down slopes shows no decrement over the transition from belly to hands-and-knees crawling (Adolph, 1997). In both postures, infants correctly distinguish safe from risky slopes. Similarities such as the prone position may outweigh formal differences between crawling styles and facilitate functional continuity. Likewise, temporal contiguity between cruising and walking and structural similarities such as moving in an upright position could outweigh formal differences such as sideways versus forward steps, using the arms for support versus holding the arms free, and so on.

However, a second line of evidence (Adolph, 1997, 2009) raises the alternative possibility of functional discontinuity between cruising and walking. Infants' motor development is marked by a series of postural milestones: sitting at approximately 6 months of age, hands-and-knees crawling at 8.5 months, and walking at 12 months (Bayley, 1969; Frankenburg, et al., 1992). Learning to perceive affordances shows important functional discontinuities between earlier and later developing postures. For example, 9-month-olds judge precisely how far they can lean forward to span a deep gap in an experienced sitting posture. But when tested in a recently acquired crawling posture, the same infants fall repeatedly into thin air while trying to cross impossibly large gaps (Adolph, 2000).

Similarly, infants show functional discontinuity between crawling and walking postures. Twelve-month-olds precisely gauge their ability to descend slopes or cliffs when tested in an experienced crawling posture, but in a novice walking posture, they step right over the brink and fall (Adolph, Tamis-LeMonda, Ishak, Karasik, & Lobo, 2008; Kretch, Karasik, & Adolph, 2009). Functional discontinuity is most dramatic in longitudinal observations (Adolph, 1997). In their first weeks of crawling, infants plunge headlong over the edge of impossibly steep slopes. Over weeks of crawling, judgments become increasingly accurate. However, after hundreds of trials over months of testing, infants show no evidence of transfer between crawling and walking postures and learning is no faster the second time around. In fact, learning is so posture-specific that hapless new walkers fail to benefit from reminders a few moments earlier facing slopes in their old adaptive crawling posture. These examples of functional discontinuity raise the possibility that cruising may be better considered as a unique—albeit transient—form of upright locomotion that appears prior to walking.

Current Studies

We report three studies that examine developmental continuity and discontinuity across the transition from cruising to walking. In Study 1, we described the extent of temporal contiguity between cruising, crawling, and walking. Of primary interest was the amount of experience that infants acquire in a cruising posture relative to crawling and the extent of overlap between cruising and crawling postures. In Study 2, we tested functional continuity between cruising and walking in cruising infants, and in Study 3, we tested infants who had taken their first walking steps. Our primary focus was on infants' ability to detect affordances for locomotion based on gaps in a handrail used for manual support (a critical aspect of cruising) versus gaps in the floor beneath their feet (a basic necessity for walking).

Study 1: Temporal Contiguity Between Crawling, Cruising, and Walking

Since the work of the early pioneers in motor development, researchers have collected extensive normative and descriptive data on the development of crawling and walking (Ames, 1937; Gesell & Ames, 1940; McGraw, 1940, 1941; Shirley, 1931). However, researchers know relatively little about the developmental timing and formal structure of cruising (Haehl, et al., 2000; Vereijken & Albers, 1998; Vereijken & Waardenburg, 1996). The neglect of cruising in the developmental literature is the result of an historical accident. In the 1930's, when Gesell (1928) decided which milestones to include in his catalog of stages from crawling to walking, he arbitrarily left cruising off the list (Adolph, Karasik, & Tamis-LeMonda, in press). Although he (like fellow pioneers in motor development, McGraw and Shirley) noted that infants cruise prior to walking, he focused on other transitional skills such as standing. Subsequent motor milestone charts developed by psychologists and pediatricians followed Gesell's lead (e.g., Bayley, 1935; 1969), and cruising became the Rodney Dangerfield of motor milestones. Of the major developmental screening tests, only the Denver included normative data on cruising in its first instantiation (Frankenburg & Dodds, 1967). Cruising was not included on the Bayley Scales until 1993. Although parents and modern researchers widely observe cruising prior to walking, little is known about the temporal relations between cruising, crawling, and walking. Thus, we collected information about the age at onset of cruising relative to crawling and walking, experience with cruising prior to walking, and the temporal overlap between cruising and crawling.

Method

Participants—Parents of 603 (302 girls, 301 boys) infants participated in a survey of the timing of infants' motor milestones. The data were culled from several studies originally designed to test visual guidance of locomotion over risky ground surfaces. Families were recruited from the New York City, Pittsburgh, and Bloomington, IN areas via published birth announcements and purchased mailing lists. All infants were healthy and born at term; most were white and from middle to upper income families. We tracked 39 infants (18 girls, 21 boys) prospectively beginning at approximately 4 months of age. We obtained retrospective reports of locomotor milestones from parents of 564 infants (284 girls, 280 boys) when infants were on average 14.05 months of age (*SD* = 2.34 months). Families received small souvenirs of participation.

Onset dates—We adopted relatively strict criteria for defining the onset of each locomotor skill. Crawling onset was the first day infants traveled on hands and knees (or hands and feet) at least 10 feet without their abdomens touching the floor or stopping to rest for more than 1 second. Cruising onset was the first day that infants walked sideways at least 3 feet along the length of a couch or coffee table without stopping for more than 1 second. Walking onset was the first day that infants walked frontward independently at least 10 feet without pausing for more than 1 second. The distance to meet criterion for cruising was shorter than the distances for crawling and walking because infants typically do not have access to greater than 3 feet of continuous support for cruising in the form of furniture arranged around the room.

For the prospective sample, we determined onset dates from daily checklist diaries and weekly telephone calls. All reports were corroborated during home visits and/or laboratory sessions. For the retrospective sample, an experimenter questioned parents with a predetermined series of formal questions in a face-to-face structured interview and infants' abilities were verified in the laboratory. Parents used calendars and “baby books” to supplement their memories. We obtained reports of onset ages for all three milestones for 299 infants, only crawling and cruising for 105 infants, only crawling and walking for 184 infants, and only cruising and walking for 15 infants (missing data resulted from experimenter error, or because some infants had not yet or never achieved the milestones, or parents could not remember onset dates). Results are reported for the subset of data available for each analysis. On average, the time lag between parents' retrospective reports and the reported onset ages was 5.56 months for crawling (*SD* = 3.02), 4.02 months for cruising (*SD* = 3.04), and 2.84 months for walking (*SD* = 2.12).

Results and Discussion

Cruising and hands-and-knees crawling were nearly universal among the infants in our sample. Only 4 parents reported that their infants never cruised and only 5 parents reported that their infants never crawled. On average, infants began crawling (*M* = 8.02 months, *SD* = 1.43) before cruising (*M* = 9.30 months, *SD* = 1.48) and did both before walking (*M* = 11.87 months, *SD* = 1.45); the difference between crawling and cruising onsets was significant, $t(403) = 17.75$, $p < .001$. However, the temporal ordering in average onset ages for the group obscures individual differences in the pattern of acquisition of the three milestones. Of the infants who both crawled and cruised, most (73.5%) began crawling at least 2 weeks before they began cruising, but 9.2% cruised for at least 2 weeks before they began crawling, and 17.3% began crawling and cruising within a two-week window.

The ages at which infants began crawling, cruising, and walking were moderately correlated. Infants who began crawling at younger ages tended to begin cruising ($r(404) = .55$; $p < .001$) and walking at younger ages ($r(483) = .48$; $p < .001$). Infants who began cruising at younger ages tended to begin walking at younger ages ($r(314) = .58$; $p < .001$). Infants' age at cruising onset, however, was a stronger predictor of their age at walking onset than crawling onset age. Controlling for crawling onset age, the partial correlation between cruising and walking onset ages was $r(311) = .43$ ($p < .001$). Controlling for cruising onset age, the partial correlation between crawling and walking onset ages was $r(311) = .24$ ($p < .001$).

Although both crawling and cruising are transient in the sense that they eventually disappear from children's repertoires, most infants exhibited both skills simultaneously for prolonged periods before they began walking (*M* = 2.63 months, *SD* = 1.31). Crawling experience (calculated from crawling to walking onset) ranged from 0 (one infant began crawling and walking on the same day) to 8.51 months (*M* = 3.90 months) and cruising experience (calculated from cruising to walking onset) ranged from 0.20 to 8.91 months (*M* = 2.75 months); the difference in crawling and cruising experience was significant, $t(298) = 15.04$, $p < .001$. For most infants, crawling experience was substantial: 72.05% had at least 3 months of crawling experience—sufficient to respond adaptively to risky ground surfaces in previous work (Mondschein, Adolph, & Tamis-LeMonda, 2000); only 38.85% had a comparable amount of cruising experience, but 69.11% had at least 2 months of cruising experience.

Study 2: Functional Discontinuity Between Manual and Pedal Affordances for Cruising

The normative data confirm that sideways cruising, like crawling, is highly prevalent and temporally contiguous with independent walking. Most infants crawl and cruise concurrently for extended periods prior to walking. However, because crawling involves a prone posture whereas cruising and walking are upright, researchers have assumed that cruising is a closer functional neighbor to walking than to crawling. Indeed, infants apply gradually less force to an instrumented handrail over weeks of cruising and standing experience suggesting that they gradually decrease reliance on the railing as their own capacities for weight-bearing and balance increase (Vereijken & Albers, 1998), and newly walking infants can even use subtle tactile information in their hands for maintaining balance in a standing posture (the trick is to get them to stand in one place!) (Barela, et al., 1999; Metcalfe, et al., 2005; Metcalfe & Clark, 2000; Metcalfe, et al., 2004). On the one hand, these data suggest that experience cruising may help teach infants to detect affordances for locomotion after they begin walking.

On the other hand, there are reasons to suppose that important functional discontinuities may distinguish cruising and walking. First, sideways cruising involves all four limbs for support and propulsion, structurally similar to hands-and-knees crawling. As in crawling, the legs bear some of infants' weight, but may be less critical for balance control compared with the arms. Cruisers apply downward force with their arms (measured with an instrumented handrail) and they increase the force reactively when they momentarily lose balance (Vereijken & Albers, 1998). Lateral sway of the trunk and hips is also controlled by the arms (Haehl, et al., 2000). Infants fall when their bodies drift too far outside the reach of their arms or when they accidentally let go of the manual support; falls while cruising are common (Sugar, Taylor, & Feldman, 1999).

Second, given that most infants have at least 2 months of experience cruising prior to walking, if the two skills were functionally continuous, then experience cruising should facilitate adaptive responses at the edge of a slope or cliff in novice walkers. But, it does not. New walkers repeatedly attempt to walk down impossibly steep slopes and high cliffs (Adolph, 1997; Adolph, et al., 2008; Kretch, et al., 2009).

Thus, we designed an experimental arrangement to test functional discontinuity between cruising and walking. The aim was to pit prospective balance control in the arms against prospective balance control in the legs, that is, affordances for manual versus pedal support. Toward that end, we tested 11-month-old cruising infants on an adjustable gap apparatus in two conditions. In one condition, the apparatus had a continuous floor but an adjustable gap in the handrail that infants held for support. This “handrail-gap” condition was relevant for keeping balance with the upper extremities. In the second condition, the apparatus had a continuous handrail but an adjustable gap in the floor beneath infants' feet. This “floor-gap” condition was relevant for keeping balance with the lower extremities.

Given substantial cruising experience prior to walking, we expected infants to respond adaptively in the handrail-gap condition. That is, they should attempt to cruise over safe gaps in the handrail, within arm's reach, but avoid impossibly wide gaps. We reasoned that if cruising is functionally related to walking, then infants should also show adaptive responses in the floor-gap condition. However, if cruising and walking are functionally distinct, then infants might not take information about their legs and floor into account when gauging affordances for locomotion. That is, they should avoid risky gaps in the handrail, but fall into risky gaps in the floor.

Method

Participants—Twenty-two cruising infants (11 boys, 11 girls) participated. All were 11 months old (± 19 days). We chose the 11-month age group to maximize the likelihood that infants would have both crawling and cruising experience but would not yet have begun walking. Seven additional infants (6 boys, 1 girl) became fussy during testing and did not contribute enough trials to be included in analyses of either test condition. Families were recruited from the NYC area through mailing lists, referrals, and flyers. Most infants were white and of middle to upper income families. All infants could cruise sideways and crawl on hands and knees. None could cruise with their bodies oriented frontward or take independent walking steps. Parents reported their infants' locomotor experience in a structured interview. We defined cruising and crawling onset as in Study 1. Cruising experience ranged from .20 to 4.01 months (*M* = 1.83 months). Crawling experience ranged from .46 to 5.19 months (*M* = 2.73 months). Infants received a certificate and framed photograph as souvenirs of participation.

Gaps apparatus—Infants were tested on an adjustable “gaps” apparatus in two conditions: Gap in the handrail and gap in the floor. In the handrail-gap condition, the floor was continuous and the handrail was interrupted by a gap of variable size (top panel Figure 1). Two interlocking handrail sections (14 cm wide × 105 cm long) were attached to supporting posts along the side of a fixed starting platform (107 cm long × 76 cm wide × 86 cm high) and a movable landing platform (157 cm long × 76 cm wide × 86 cm high). To create gaps in the handrail (0 cm – 90 cm), the landing platform slid along a calibrated track.

A wooden board (244 cm long × 76 cm wide × 2 cm thick) covered both platforms to maintain a continuous floor.

In the floor-gap condition, the handrail was continuous and the floor was interrupted by a gap of variable size (bottom panel Figure 1). A 302-cm long handrail spanned the length of the entire walkway. One end was rigidly attached to the supporting posts on the starting platform. The other end rested on the supporting posts on the landing platform that slid along a hollow track in the rail as the platform moved. To create gaps in the floor (0 cm – 90 cm), the board covering the platforms was removed and the landing platform slid along its track. A ruler affixed to the side of the landing platform indicated gap size. The tops of the platforms and the floorboard were carpeted to provide cushioning. The interior of the gap in the floor was lined with 14 cm of foam padding as a safety precaution creating a 72-cm deep precipice in the floor-gap condition.

Procedure—First, infants demonstrated the ability to cruise the length of the continuous handrail two times in succession. Testing on gaps began with infants standing in a sideways cruising position, holding the handrail on the starting platform. To ensure that infants noticed the gap in both conditions, an assistant waved a toy in the gap at the start of each trial and said, “Look, baby, there's a gap in the floor/handrail.” The experimenter held infants until the assistant confirmed that infants saw the gap. Parents and the assistant stood at the far side of the landing platform and encouraged infants to cross the gap to retrieve toys and treats. Adults never cautioned infants or instructed them how to navigate the gap. The experimenter followed alongside infants to ensure their safety. Another assistant videotaped trials by panning a camera positioned perpendicular to the walkway. A stationary camera recorded gap size from the sliding ruler. Both camera views were mixed into a single video frame. Trials lasted 30 seconds or until infants attempted to cruise over the gap, whichever occurred first. Condition order was counterbalanced with 11 infants in each order.

Body dimensions and motor skill vary widely among infants of the same age so that a risky gap size for smaller, poorly skilled cruisers might be safe for larger, more proficient cruisers. Moreover, a risky gap size in the floor condition was likely to be safe in the handrail condition. To circumvent the problem of equating risk levels across infants and gap conditions, we used a normalization procedure to estimate safe and risky gaps for each infant in each condition. As in previous work, the experimenter used a modified psychophysical staircase procedure (Adolph, 1995, 1997, 2000) to identify the largest gap over which infants could cruise in each condition—their “cruising thresholds.” In general, a staircase procedure estimates a threshold or change point, while minimizing the total number of necessary trials. The rule of thumb is to present more difficult increments after successful responses and less difficult increments after unsuccessful responses. Typically, staircase procedures are used to estimate a perceptual threshold on a response curve for which the probability of success ranges from 100% accuracy to 50% guessing (e.g., Cornsweet, 1962). In this case, the procedure was modified to estimate a “motor threshold” on a response curve for which the probability of success ranged from 100% to 0%.

All staircase protocols began with an easy baseline gap (2 cm in the floor condition and 16 cm in the handrail condition). In the floor condition, 2 cm was smaller than infants' foot widths so that they would not fall even when they inadvertently stepped into the gap. In the handrail condition, 16 cm was small enough that infants could cruise as easily as they did with a continuous handrail. Trials were coded online as a success (cruised safely across the gap), failure (attempted to cruise but fell into the gap), or refusal (avoided going or crawled across the gap). The experimenter determined gap size for each trial based on the outcome of the previous trial. For the purpose of estimating cruising thresholds, failures and refusals were treated as equivalent unsuccessful outcomes. After a successful trial, the experimenter increased gap size by 6 cm. After an unsuccessful trial, the experimenter repeated the increment for reliability. After a second failure or refusal, the experimenter presented an easy baseline gap at which infants were assured success, to maintain their motivation to cruise. Then, the experimenter decreased gap size by 4 cm. The procedure of presenting larger and smaller gaps continued until converging on a cruising threshold to a 67% success criterion—the largest gap size at which infants cruised successfully on at least 2/3 trials and failed or refused on at least 2/3 trials at each of the next 3 increments of gap size. As in earlier studies that required infants to participate over dozens of trials (Adolph, 1995, 1997, 2000), we adopted the practice of presenting baseline trials after unsuccessful attempts and asking parents to encourage infants at every gap size. The staircase procedure provides a conservative estimate of locomotor ability because infants could refuse to cruise over perfectly safe gaps.

By definition, the cruising threshold marked the boundary between safe and increasingly risky gaps. The probability of success was high on gap sizes smaller than the threshold gap and decreased on gap sizes larger than the threshold gap. After identifying infants' cruising thresholds, the experimenter presented a series of probe trials on increasingly risky gaps to determine whether infants' responses were scaled to the relative amount of risk: 6 cm, 12 cm, and 18 cm larger than each infant's individual threshold. In addition, infants were tested on the largest 90-cm gap width allowed by the apparatus. Two probe trials were presented at each risky increment and baseline trials followed each pair of probes.

Results and Discussion

Eighteen infants completed staircase protocols and probe trials in both conditions (8 girls, 10 boys), 3 completed only the handrail condition, and 1 contributed data only to the floor condition (due to fussiness, experimenter error, and because a mother had to leave early). Preliminary analyses showed no differences on outcome measures between infants who completed both conditions and infants who completed only one condition. Thus, graphs represent all available data and ANOVAs were performed on the subset of infants contributing data to both conditions. Because of the individualized nature of the staircase procedure, the total number of trials varied across children and the handrail (M = 31.67 trials, SD= 4.99) and floor conditions (M = 24.11 trials, SD = 5.91); larger gap thresholds in the handrail condition required more trials to converge on the threshold gap size.

Navigating safe and risky gaps—Coders used a computerized video coding software, MacSHAPA (OpenSHAPA.org), which records the categories and durations of events on a frame-by-frame basis (Sanderson, et al., 1994). A primary coder rescored each trial as a success, failure, or refusal and recalculated cruising thresholds. There was 100% agreement between thresholds calculated online and those scored from videotape. A secondary coder scored 20% of the trials. Inter-rater agreement was 99%.

Cruising thresholds varied widely in both the handrail (28 cm to 62 cm) and floor (2 cm to 18 cm) conditions, highlighting the importance of the normalization procedure for determining relative amount of risk (see Figure 2). As expected, every infant had larger cruising thresholds in the handrail condition (M = 44.8 cm) than in the floor condition (M = 8.0 cm) and there was no overlap in thresholds between the two conditions. The large difference appeared due to two reasons: Infants' arm spans are considerably larger than their step length, and infants could take multiple cruising steps with their feet while spread-eagled between the two rails whereas they could not recover with their arms if their leading leg fell downward into the gap.

We used a “cruise ratio” to index infants' ability to gauge threats to balance in a cruising posture (Adolph, 1995, 1997, 2000). The cruise ratio is the number of attempts to cruise divided by the total number of trials (successes + failures) / (successes + failures + refusals). Note that the inverse refuse-to-cruise ratio yields the same information. We calculated a cruise ratio for each infant over all available trials at the baseline gap size, the largest 90-cm gap, and at 4 risk levels normalized to the cruising threshold: the threshold gap (denoted by 0), slightly risky gaps 2 cm to 6 cm larger than the threshold gap (denoted by +6), moderately risky gaps 8 cm to 12 cm larger than the threshold gap (+12), and impossibly risky gaps 14 cm to 18 cm larger than the threshold gap (+18). By definition, the cruise ratio was .67 or higher at the cruising threshold, but the ratio could vary freely at other risk levels.

If infants gauged the gap size accurately, they would attempt to cruise over safe gaps and refuse to cruise over risky ones. Perfectly calibrated responses would be indicated by a cruise ratio that exactly matched the probability of success at each gap group, that is, by scaling attempts to cruise to the cruising threshold. Alternatively, if infants did not accurately perceive affordances, then they would fall into impossibly large gaps. Most important, if cruising and walking are functionally discontinuous, infants should avoid risky gaps in the handrail but fall into risky gaps in the floor.

Infants showed functional discontinuity between cruising and walking: Attempts to cruise differed by condition. As shown in Figure 3A, cruise ratios for both conditions decreased on increasingly risky gaps, but ratios were higher in the floor-gap than handrail-gap condition at every risky gap size. In the handrail-gap condition, average cruise ratios decreased from 0.88 at the gap boundary to 0.04 at the +18-cm risk level. Only 3 infants (14%) attempted to cruise over the +18-cm handrail and none attempted to cruise over the 90-cm gap in the handrail. In the floor condition, average cruise ratios decreased from 0.96 at the gap boundary to 0.58 at the +18-cm risk level. Twelve infants (63%) attempted to cruise over impossibly large gaps in the floor at the +18-cm gap group and 9 infants (47%) attempted to cruise over the 90-cm gap in the floor. Infants appeared utterly surprised to find themselves hanging from the handrail by their fingertips with their feet dangling into the precipice. A 2 (handrail and floor conditions) × 4 (0, +6, +12, +18 gap groups) repeated measures ANOVA on attempts confirmed main effects for condition ($F(1,17) = 72.34$, $p < .001$) and gap group ($F(3,51) = 64.50$, $p < .001$) and an interaction between condition and gap group ($F(3,51) = 9.60$, $p < .001$). Trend analyses showed linear ($F(1,17) = 94.55$, $p < .001$) and quadratic effects ($F(1,17) = 70.98$, $p < .001$) indicating that cruise ratios decreased on increasingly risky gaps. Paired comparisons between handrail and floor conditions showed differences at each risky gap size (all *p*s < .001).

Why infants succeeded in the handrail condition—One explanation for adaptive responding in the handrail condition is that experience cruising (e.g., between furniture) may have facilitated perception of affordances. More generally, practice cruising may have attuned infants to the information relevant for controlling balance with their arms.

A complementary possibility is that experience crawling facilitated adaptive responding in a cruising posture. If cruising, like crawling, is controlled primarily with the upper extremities (Haehl, et al., 2000; Vereijken & Albers, 1998), then experience in a crawling posture may transfer to cruising despite being upright rather than prone.

Why infants fell in the floor condition—Perhaps infants fell into the precipice because they lacked alternative methods for crossing the gap, or because they were unable to inhibit ongoing locomotion. A primary coder scored alternative methods of locomotion on trials where infants refused to cruise: Crawling (on hands and knees), kneeling (on one or both knees), sitting (and sliding into the gap), backing (into the gap feet first), and holding onto the experimenter while attempting to cruise the gap. She scored avoidance (remaining on the near side of the gap for the duration of the trial), as a clear sign of inhibition. A secondary coder scored 20% of the trials. Inter-rater agreement was 99%.

Neither motivational explanation was supported. Twenty infants demonstrated at least one alternative method of locomotion on refusal trials, indicating that alternative strategies were in their repertoires and could be drawn on in potentially risky situations. Seven infants demonstrated two alternative strategies, and 4 demonstrated three or four. Eighteen infants avoided the gap at least once, indicating that they could inhibit forward locomotion. In the handrail condition, infants used alternative strategies on 75.0% of refusal trials. Typically, they released the rail on the near side of the gap, crawled between rails, and then pulled themselves back into an upright cruising position on the far side of the gap. In the floor condition, they avoided going on 63.6% of refusal trials and stood gripping the rail on the starting platform until the end of the trial.

We also considered three perceptually based explanations for why infants might have fared so poorly in the floor-gap condition. One possibility is that the handrail obscured infants' view of their feet and the floor. Accordingly, we might expect a functional dissociation in the developmental transition from cruising to walking if infants lack visual information about their legs and the floor until they begin to face forward with an unobstructed view. Although we drew infants' attention to the gap at the start of each trial, it is possible that they forgot about the gap after the trial began.

An alternative perceptual explanation is that infants had ample perceptual information to discriminate the size of the gaps in both conditions, but their ability to perceive affordances was limited to the handrail condition. If cruisers control balance prospectively with their arms, not their legs, they may not yet recognize the critical parameters for controlling balance in a walking posture or they may lack sufficient experience to calibrate the parameter settings. In previous studies of infants' locomotion over gaps in the floor (Adolph, 2000), novice crawlers spontaneously produced the movements to generate perceptual information for their ability to span gaps in the floor, but failed to profit from it. They stretched their arm over the gap and then retracted it. Moments later, they leaned forward and tumbled into the gap. Similarly, novice crawlers and walkers failed to profit from spontaneous, self-initiated exploratory activity (Adolph, 1997). They peered over the edge of steep slopes and rocked vigorously over their wrists or ankles at the brink. Moments later, they plunged forward and fell.

To distinguish the “no-information” and “failure to perceive affordances” accounts, a primary coder scored two measures of spontaneous exploratory activity. We reasoned that increased levels of exploration at the same gap sizes where infants erred would provide evidence that perceptual information was continuously available but infants failed to profit from it. Exploratory *limb extensions* reflected infants' efforts to obtain haptic/proprioceptive information about their ability to span the gap: Stretching and retracting the leading arm/leg over the gap or dipping the foot into the precipice. *Latency* was the time from the start of the trial until infants began moving over the gap or 30 s, whichever occurred first. It included the time that infants peered into the gap, stretched their limbs into the gap, and moved around on the starting platform. A second coder scored 20% of trials for limb extensions and latency. The percentage of interrater agreement for limb extensions was 98% and the correlation coefficient for latency was .99.

The data indicate lack of perceptual understanding not lack of perceptual information. In addition to seeing the gap at the start of the trial, infants could feel a lack of support by spontaneously exploring the gaps. Infants performed more exploratory limb extensions in the floor condition than the handrail condition (Figure 3B). A 2 (handrail and floor conditions) × 4 (0, +6, +12, +18 gap groups) repeated measures ANOVA on the proportion of trials with exploratory limb extensions revealed only a main effect for condition ($F(1,15) = 5.34$, $p < .035$). The ANOVA on latency showed only an interaction between condition and gap group ($F(3,45) = 3.50$, $p < .023$). As shown in Figure 3C, infants ruminated equally long when confronted with impossibly risky gaps in the floor as they did when encountering the same relative risk in the handrail at the 0, +6, and +12 gap groups, but they hesitated longer in the floor condition at the +18 gap group. In summary, having the information about a hole in the floor did not ensure that infants knew what to do with it.

A third perceptually based explanation supported by the data is that information about the gap prior to navigating it is not enough. Perhaps infants require information about the gap while navigating it. Although we did not directly measure where infants looked, it is likely that it was easier for them to see the gap in the handrail condition than in the floor condition. In the handrail condition, infants would see the gap as they navigated it with their arms, whereas in the floor condition, infants may not have been able to see the gap in the floor while attending to the handrail. Infants may have had an advantage in the handrail condition because they received redundant visual and proprioceptive information that was unavailable in the floor condition.

Study 3: Further Evidence for Functional Discontinuity in Infants Taking Independent Steps

Usually, infants' first walking steps are into a caregiver's arms or from one piece of furniture to the next. Like a beginning ice skater clinging to the wall between small forays into the rink, small bouts of walking are flanked by periods of manual support. Between bursts of wobbly walking steps, infants cruise and crawl. This transitional period—when infants can take a few steps but also rely on cruising and crawling to get around—is especially interesting for investigating functional continuities between forms of locomotion.

Could infants wear a cruising hat one minute and a walking hat the next? Or do they now confront locomotor challenges as walkers? Both outcomes may be true (Adolph, 1997). When new walkers are tested in their new walking posture and their old crawling posture at the edge of a 36° slope (impossible in both postures), they march straight over the edge and fall as walkers but avoid the slope as crawlers. They perceive affordances in an experienced crawling posture but not in a novice walking posture. Ironically, on half the trials, new walkers stand themselves up from the more adaptive crawling position as if they preferred to face the slopes as inopportune walkers. Then they walk over the edge and fall.

Method

An additional subset of four infants (3 boys, 1 girl) that came in for testing could already take a few independent steps, although none met our criterion for walking onset (independent walking over a 10-foot distance). Three had begun taking steps between the time they were recruited and the time they arrived at the lab for testing. One infant took her first steps during the testing session. We capitalized on this mischance by examining their perception of affordances in the floor-gap and handrail-gap conditions.

Infants' age ranged from 10.88 to 11.44 months ($M = 11.16$ months). Crawling experience ranged from 1.02 to 5.59 months ($M = 3.44$ months), and cruising experience ranged from 1.02 to 3.19 months ($M = 1.78$ months). These infants were tested in both conditions using the same gaps apparatus as sideways cruisers. The experimenters estimated infants' gap boundaries (largest gap crossed safely with a 67% criterion) using the same procedure described above. The experimenter began each trial with infants standing sideways holding the handrail, but infants spontaneously turned to face forward on some trials and took independent walking steps. Each of the infants completed both conditions. One infant could not be tested with probe trials on risky gaps in the handrail condition because she took steps from one handrail to the other at 90 cm.

Results and Discussion

In the floor-gap condition, gap thresholds for near-walkers were comparable to those for cruisers (4 cm to 14 cm). Thresholds in the handrail condition were considerably larger (54 cm to 90 cm) because infants could release the handrail and take a step or two (or for one infant, a short string of steps). In fact, seeing the gap in the handrail appeared to elicit more stepping than cruising behaviors whereas seeing the continuous handrail elicited more cruising than stepping.

Infants taking steps differed from sideways cruisers in their use of information for balance control. Similar to cruisers, these infants showed maladaptive responses in the floor condition by attempting to cross risky gaps and falling into the precipice. However, unlike cruisers, these near-walkers also showed maladaptive responses in the handrail condition (see Figure 4A). Sometimes infants cruised from one edge of the handrail to the other, and on these trials, they rarely erred. But sometimes they released the rail on one side and tried to toddle to the other rail; on these trials, they frequently fell before getting to the other side, as if not perceiving the limits of their new abilities.

Infants taking steps rarely explored gaps in the rail. Exploratory arm extensions were rare in the handrail condition and latency was shorter in the handrail than floor condition (see Figures 4B and 4C). Extensions and retractions of the legs into the gap in the floor occurred on about 25% of the trials in almost each gap group, indicating that perceptual information for the lack of a floor did not stop infants from stepping into the hole.

General Discussion

Three studies examined developmental continuity in infant locomotion. Study 1 focused on temporal continuity. We found that cruising and crawling are nearly universal, and most infants acquire considerable overlapping experience with both skills prior to walking. Study 2 revealed important functional discontinuities between cruising and walking. Results indicate that practice cruising does not teach infants a basic fact about walking—that they need a floor to support their body. Apparently, seeing and feeling a hole in the floor does not deter infants from stepping into the gap so long as they grip a sturdy handrail with their hands. A gap in the handrail is a different story: Cruisers gauge quite precisely whether a gap in the handrail is navigable. Study 3 replicated the findings for the floor-gap condition with infants who could take a few walking steps. However, the ability to take independent steps caused near-walkers to err when gauging affordances for crossing a gap in the handrail. They no longer explored gaps in the handrail by stretching and retracting their arm, as if—as near walkers—they no longer relied on information for controlling balance with their arms. Our results suggest some provocative conclusions about the relations among cruising, crawling, and walking.

Cruising and Crawling

The first conclusion is that cruising may have more in common with hands-and-knees crawling than with walking. Both cruising and crawling use the arms for support and require coordination among all four limbs. Even pre-onset movements are similar in form—bouncing and rocking while holding a support prior to taking cruising steps (Vereijken & Adolph, 1999) and rocking on hands and knees prior to taking crawling steps (Adolph, et al., 1998; Goldfield, 1989). Moreover, cruisers' accurate responses to gaps in the handrail condition and experienced crawlers' accurate responses to slopes and cliffs (Bertenthal, Campos, & Barrett, 1984; Kretch, et al., 2009; Mondschein, et al., 2000) suggest that cruising and crawling may share a critical psychological function—the ability to perceive affordances for manual support.

An alternative possibility, also consistent with the current work, is that cruising and crawling are distinct perception-action systems such that concurrent experience with each facilitates perception of affordances in that posture. While cruising, infants have a higher vantage point and can easily scan the environment, but while crawling, infants face the floor and must fight gravity to raise their heads. Cruisers move sideways initially using separate, successive limb movements (Haehl, et al., 2000; Vereijken & Waardenburg, 1996), but crawlers face forward and coordinate their limbs in a diagonal gait pattern (Adolph, et al., 1998; Freedland & Bertenthal, 1994). Rotation around the elbows and shoulders may play a more important role in generating information for maintaining balance while cruising (Haehl, et al., 2000; Vereijken & Albers, 1998), whereas rotation around the wrists may be more important while crawling (Adolph, 2009).

Cruising and Walking

A second conclusion is that cruising may share less with walking than previously supposed. Temporal and structural continuities between transient and permanent upright skills have led researchers to assume that manual support of upright posture is functionally continuous with walking (Barela, et al., 1999; Haehl, et al., 2000; McGraw, 1945). Surely practice cruising could help to strengthen the relevant musculature for weight bearing during single limb support and provide infants with valuable experiences keeping their upright bodies in balance while moving toward a goal. Moreover, the higher vantage point in cruising may be intrinsically rewarding and spur infants to walk.

However, with their arms free from supporting functions, walking infants control balance at their ankles and hips (Stoffregen, Adolph, Thelen, Gorday, & Sheng, 1997; Woollacott & Sveistrup, 1992). Cruising, which relies on manual support of balance may fail to teach infants some important aspects about balance control with the legs, in particular, to perceive affordances for support beneath the feet. The fact that most infants repeatedly fell into gaps in the floor indicates that cruisers and novice walkers do not base decisions for action on information relevant for lower limb balance control. While cruising, infants focus on availability of manual support. As infants begin taking independent steps, learning may begin anew about affordances for walking.

Eventually, walking infants do perceive threats to balance based on variations in the ground surface and again rely on manual supports to augment balance. By 14 months of age, when most infants have acquired several weeks of walking experience, they grab a support post when balance is in jeopardy (Stoffregen, et al., 1997). By 16 months of age, infants use a handrail to augment balance on precariously narrow bridges and demonstrate a sophisticated understanding of the material and spatial properties that make a functional handrail (Berger & Adolph, 2003; Berger, Adolph, & Kavookjian, 2009; Berger, Adolph, & Lobo, 2005).

Crawling and Walking

A third conclusion is that crawling experience, like cruising, may fail to prepare infants to perceive affordances when they begin walking. Although we did not test infants in a crawling posture, most had extensive experience as crawlers and previous work indicates that experienced 11- and 12-month-old crawlers avoid crawling over the edge of a drop-off or steep slope (Adolph, et al., 2008; Kretch, et al., 2009; Mondschein, et al., 2000). Nonetheless, in Study 3, infants taking their first walking steps repeatedly fell into the gap.

These findings speak to an ongoing debate in the literature. In previous work, 12-month-old novice walkers repeatedly fell over the brink of steep slopes and impossibly high cliffs (Adolph, et al., 2008; Kretch, et al., 2009). In contrast, when infants were tested on a “visual cliff” (an apparent drop-off covered in safety glass), 12-month-old novice walkers avoided the apparent drop-off (Witherington, Campos, Anderson, Lejeune, & Seah, 2005). Methodological differences may explain the discrepant findings. For example, a real drop-off is less forgiving than a glass-covered cliff: On a real drop-off, as soon as infants put their weight over the edge, they fall. But when the cliff is covered in safety glass, infants are not scored as attempting until they venture onto the glass with both feet.

Understanding Discontinuity

Posture-specific learning between motor milestones occurs in contexts other than locomotion across gaps. Over longitudinal observations, sitting infants reached around a barrier to retrieve a target object several weeks before they demonstrated the ability to crawl around the barrier (Lockman, 1984). When tested cross-sectionally, 10- and 12-month-olds were more successful at retrieving objects from behind a barrier when they were tested in a sitting position than when they had to execute the detour by crawling (Lockman & Adams, 2001).

Previously, Adolph proposed that each postural milestone in development constitutes a distinct balance control system such that experience with an earlier developing skill does not transfer automatically to a later developing skill (e.g., Adolph, 2009; Adolph & Berger, 2006). In every postural configuration, infants must maintain their bodies within a dynamic base of support. Sitting, crawling, and walking postures involve different key pivots around which the body rotates, different muscle groups for executing movements and for generating compensatory sway, different vantage points for viewing the ground, and different extremities for obtaining haptic information. Each posture generates different patterns of optic flow, stretching and deforming of the skin and muscles, and stimulation to the vestibular system. Thus, for each new posture in development, infants must first identify the defining parameters for the new balance control system and then learn to calibrate the settings of the various parameters.

The current work suggests that cruising may also constitute a distinct balance control system with its own defining parameters. We demonstrated that despite adjacent temporal ordering between cruising and walking, an extended period of cruising prior to walking, the obvious physical similarities of upright posture and alternating leg movements, and common-sense assumptions regarding functional continuity, cruising is not merely a transitional skill which serves as a functional bridge to walking. Rather, sideways cruising, like crawling, may be a bonafide form of locomotion in its own right. More generally, transient skills such as cruising and crawling may represent a brief time window in which children find temporary but developmentally unique solutions.

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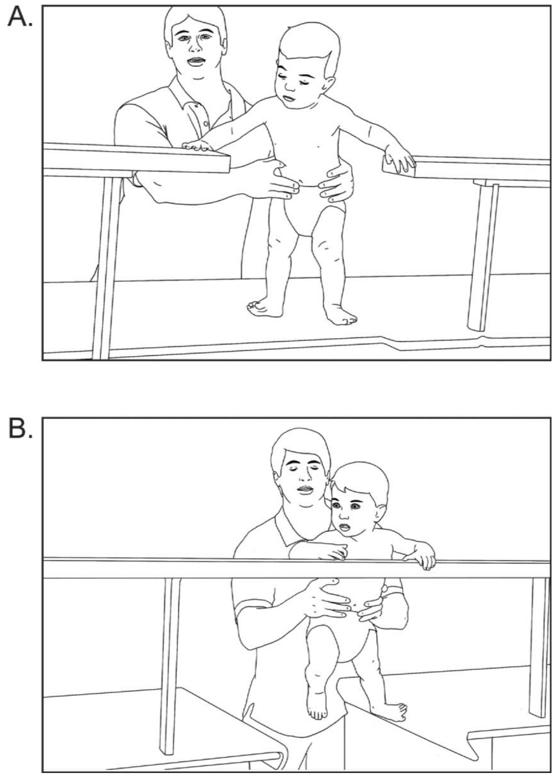

Figure 1.

Gaps apparatus used to test infants' use of upper and lower limb information. (A) Handrail-gap condition with adjustable gap in the handrail (0 cm – 90 cm) and a continuous floor. (B) Floor-gap condition with adjustable gap in the floor (0 cm – 90 cm) and a continuous handrail.

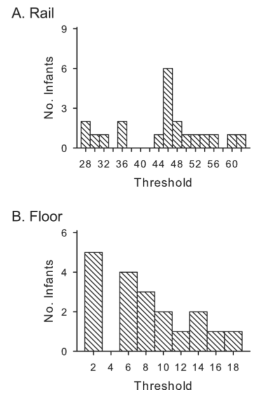

Figure 2.
Cruising thresholds in the (A) handrail (N = 21) and (B) floor condition (N = 19).

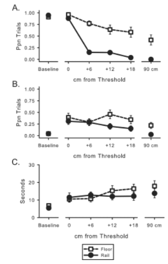

Figure 3.

Cruisers' attempts and exploration on safe and risky gaps. (A) Cruise ratio: (successful + failed attempts to cruise)/(successes + failures + refusals to cruise). (B) Exploratory limb extensions into gaps. (C) Latency to embark over gaps. Data are plotted according to relative amount of risk. The 0 point on the x-axis represents each infant's gap threshold in each condition. Baseline gap size was 2 cm in the floor-gap condition and 16 cm in the handrail-gap condition. Error bars represent standard errors.

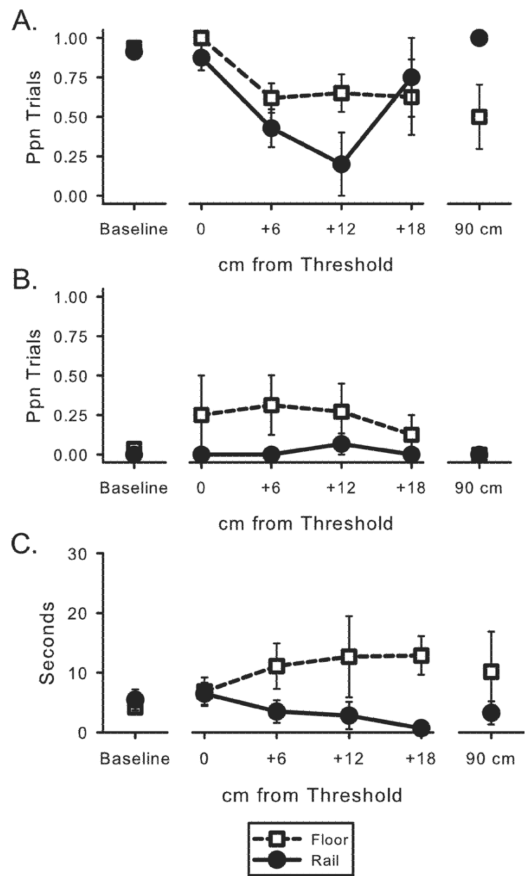

Figure 4.

Near-walkers' attempts and exploration on safe and risky gaps. (A) Walk/cruise ratio: (successful + failed attempts)/(successes + failures + refusals). (B) Exploratory limb extensions into gaps. (C) Latency to embark over gaps. Data are plotted according to relative amount of risk. The 0 point on the x-axis represents each infant's gap threshold in each condition. Baseline gap size was 2 cm in the floor-gap condition and 16 cm in the handrail-gap condition. Error bars represent standard errors.