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Crawling and walking infants see the world differently

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Abstract

How does visual experience change over development? To investigate changes in visual input over the developmental transition from crawling to walking, thirty 13-month-olds crawled or walked down a straight path wearing a head-mounted eye-tracker that recorded gaze direction and head-centered field of view. Thirteen additional infants wore a motion-tracker that recorded head orientation. Compared with walkers, crawlers' field of view contained less walls and more floor. Walkers directed gaze straight ahead at caregivers, whereas crawlers looked down at the floor. Crawlers obtained visual information about targets at higher elevations—caregivers and toys—by craning their heads upward and sitting up to bring the room into view. Findings indicate that visual experiences are intimately tied to infants' posture.

Much of what infants learn depends on what they see: Natural vision provides opportunities for learning about the properties and affordances of places, surfaces, objects, and people (Franchak, Kretch, Soska, & Adolph, 2011), and for establishing words and concepts that provide cognitive links with the visible denizens of the environment. For example, infants' understanding of causal and self-propelled motion is related to the frequency with which they observe these types of motion in their everyday environment (Cicchino, Aslin, & Rakison, 2011). Similarly, toddlers are more likely to learn the name of an object if the object is large and prominent in their field of view at the moment it is named—visual input that occurs naturally when infants hold objects up for visual inspection (Yu & Smith, 2012).

How do opportunities for learning from visual input change from moment to moment and over development? Shifts in body posture may contribute to real-time changes in visual input. This is particularly relevant to development because the amount of time infants spend in different activities such as lying prone, sitting, crawling, cruising, and walking changes with developmental improvements in motor skill. In particular, crawling and walking have unique effects on infants' experiences and cognitive outcomes (e.g., Adolph et al., 2012; Campos et al., 2000; Walle & Campos, in press). Many researchers have speculated that such effects stem from differences in visual input (Adolph, 1997; E. J. Gibson & Pick, 2000; Iverson, 2010; Karasik, Tamis-LeMonda, & Adolph, 2011; Newcombe & Learmonth, 1999), but the presence of such differences has never been confirmed empirically.

Different postures change infants' vantage point, but these differences could be negated or exaggerated by infants' own head and eye movements within a given posture. For example,

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crawling infants might crane their heads upwards to compensate for being low to the ground. Whether posture has real, functional effects on what infants see and where they choose to look has not been studied. Advances in head-mounted eye-tracking technology have made it possible to describe infants' visual experiences while they move around the world, and have challenged many of our long-held assumptions about where infants look during everyday activities (Franchak et al., 2011). Here, we take advantage of this new technology to ask whether and how infants' visual experiences differ while crawling, walking, and sitting.

Locomotor Development Affects Opportunities for Learning

The onset of crawling is a major milestone, and crawling experience facilitates psychological advances. Crawling allows self-initiated access to the larger world (Campos et al., 2000; E. J. Gibson, 1988; Piaget, 1954), which is linked with improvements in cognitive skills such as spatial search (Horobin & Acredolo, 1986; Kermoian & Campos, 1988), position constancy (Bai & Bertenthal, 1992; Bertenthal, Campos, & Barrett, 1984), optic flow perception (Anderson et al., 2001; Higgins, Campos, & Kermoian, 1996; Uchiyama et al., 2008), and memory retrieval (Herbert, Gross, & Hayne, 2007). The changes brought about by independent mobility also have implications for social development: Crawlers display more attachment behaviors (Campos, Kermoian, & Zumbahlen, 1992) and are more adept at following a gaze/pointing gesture (Campos, Kermoian, Witherington, Chen, & Dong, 1997) than pre-crawlers.

Opportunities for learning change again with the transition from crawling to walking. Novice walkers take more steps, travel greater distances, and visit more places than experienced crawlers (Adolph et al., 2012; Clearfield, 2011). Walkers are more likely to cross the room to engage with distal objects, to carry objects across the room, and to cross the room to share objects with caregivers (Karasik, Adolph, Tamis-LeMonda, & Zuckerman, 2012; Karasik et al., 2011). As a consequence, walkers receive more verbal feedback from their mothers (Karasik, Tamis-LeMonda, & Adolph, in press). Walkers also engage in more bids for social interaction, produce more caregiver-directed vocalizations and gestures, spend more time interacting with caregivers, and experience more frequent emotional interactions with caregivers (Biringen, Emde, Campos, & Applebaum, 1995; Clearfield, 2011; Clearfield, Osborne, & Mullen, 2008). And recent studies suggest that language development is accelerated when infants begin to walk (Ellis-Davies, Sakkalou, Fowler, Hilbrink, & Gattis, 2012; Walle & Campos, in press).

Vision Is a Whole Body Process

To describe how infants acquire visual information, researchers have spent decades studying infants' eye movements (Aslin & McMurray, 2004; Haith, 1969; Johnson, Amso, & Slemmer, 2003; Salapatek & Kessen, 1966; von Hofsten & Rosander, 1997). But vision involves more than eye movements. It is a whole body process involving movements of the eyes, head, and body (J. J. Gibson, 1966, 1979; Land, 2004). To see a target—an upcoming flight of stairs, a toy on a shelf, or a parent's face—infants must orient their bodies toward the target, rotate their heads to bring the target into the field of view, and point their eyes to fixate the target. The geometry of the body can facilitate or hinder this process by constraining where the eyes are in space and where they point. In particular, the projection of the visual field depends on both the height of the head relative to the ground (imagine raising or lowering a flashlight without changing the angle) and the up-and-down (pitch) rotation of the head relative to parallel (akin to tilting the flashlight toward the ceiling or floor). Although the eyes rotate within the head, they are biased to return to the more comfortable center position (Fuller, 1996; Pare & Munoz, 2001). Therefore, developmental changes in eye height and range of head motion may influence what infants see.

Height differences alone may be sufficient to alter the visual world. When facing straight ahead, a 174-cm tall adult loses sight of an obstacle on the floor at a distance of 75 cm, whereas a 128-cm tall child does not lose sight of an obstacle until it is 55 cm ahead. Accordingly, adults are less likely to fixate upcoming obstacles than children and adults fixate objects from farther away (Franchak & Adolph, 2010). Toddlers are even more likely to fixate obstacles and sometimes sustain fixation through the moment of foot contact. In a crawling posture, infants are still more likely to fixate upcoming obstacles and to keep them in their field of view (Franchak et al., 2011). While crawling, infants' eyes are even lower to the ground. But how much lower, and possible consequences for visual input, are not known.

Differences in the head's range of motion while crawling versus walking may also contribute to differences in access to visual information. Walkers' erect spines are perpendicular to the ground, whereas crawlers' spines are closer to parallel. Thus, with the neck in a neutral position, walkers' faces are pointed straight ahead, but crawlers' faces are pointed toward the ground. The total range of up-down motion of the neck is approximately 150 degrees, comprising about 70 degrees of flexion to rotate the head downward and 80 degrees of extension to rotate the head upward (Klinich & Reed, 2013; Lewandowski & Szulc, 2003; Lynch-Caris, Majeske, Brelin-Fornari, & Nashi, 2008; Ohman & Beckung, 2008; Youdas et al., 1992). To point their faces straight ahead (that is, to bring the absolute pitch angle of the head to parallel), crawlers would need to extend their necks to the outer reaches of the range of motion. This fight against gravity is not trivial, because infants' heads are large and heavy relative to their bodies (Ounsted & Moar, 1986; Snyder, Spencer, Owings, & Schneider, 1975). How much crawlers actively extend their necks while they crawl is still an open question.

Possibly, visual input is not different between crawling and walking. The height gained with an upright posture may not be enough of a change in vantage point to cause functional differences in visual input. Moreover, while crawling, infants may be able to compensate for the difference in height by craning their necks upward and pointing their faces toward the ceiling. Conversely, new walkers might fail to exploit their increase in height by pointing their heads down to help maintain balance or avoid obstacles (Franchak et al., 2011).

Current Studies

The current studies investigated whether there are differences in visual input between crawling and walking, and which physical factors contribute to these potential differences. Two existing studies indicate that visual input may differ between the two postures during natural, spontaneous activity: Infants are more likely to have faces in their field of view while walking than while crawling (Frank, Simmons, Yurovsky, & Pusiol, in press), and are more likely to fixate obstacles on the floor while crawling than while walking (Franchak et al., 2011). But to determine whether differences are due directly to real-time, physical differences in locomotor posture, it is necessary to standardize the testing situation for both crawlers and walkers, holding everything constant (age, task, social information) except locomotor posture.

In a naturalistic setting, informative visual stimuli might be at any height relative to infants' bodies: on the floor, on a shelf or table, or atop adult shoulders. Differences in visual access to people and objects while crawling and walking may depend on the location of people and objects in the environment. Thus, it was important to examine how crawling and walking infants are affected by different visual target locations. We manipulated the height of visual stimuli (caregivers' faces and toys) to examine whether crawlers and walkers gain view of visual targets at different locations and whether they adapt their eye, head, and body movements to do so.

Experiment 1: What Infants See

In Experiment 1, we used head-mounted eye tracking to describe the visual information accessed by infants while crawling and walking. Infants crawled or walked down a uniform, controlled path so that we could use calibrated markings on the floor and walls to measure how much of the environment was in view. We also examined functional consequences of different fields of view—how frequently people and objects were visible for crawlers and walkers—and where in the room crawlers and walkers directed their gaze.

Method

Participants—Thirty infants participated within a week of their 13-month birthday. Infants were recruited from local hospitals and families received small souvenirs for their participation. Fifteen infants crawled on hands and knees as their primary form of locomotion (8 boys, 7 girls; M = 4.6 months of crawling experience dating from the first day infants crawled 10 feet continuously, as reported by parents) and 15 had begun to walk (7 boys, 8 girls; M = 1.9 months of walking experience dating from the first day infants walked 10 feet continuously). Data from an additional 17 infants were excluded: 6 infants refused to crawl or walk on the raised walkway during the warm-up period, 2 refused to wear the head-mounted eye tracker, 6 became fussy while wearing the eye tracker, and 3 infants' data were lost due to equipment failure.

Head-mounted eye tracker—We used a Positive Science head-mounted eye tracker to record infants' eye gaze and head-centered field of view (Franchak et al., 2011; Franchak, Kretch, Soska, Babcock, & Adolph, 2010). The eye tracker consisted of two miniature cameras mounted on a rounded band that attached securely to a fitted spandex hat with Velcro (Figure 1a). The *scene camera* was mounted on the band slightly above the infant's right eye, and pointed outward to record the scene in front of the infant (with a 54.4° horizontal × 42.2° vertical field of view). The infrared *eye camera* was mounted on a flexible wire and pointed inward to record the infant's right eye, which was illuminated by an infrared emitting diode (IRED).

Infants also wore a fitted vest with a small (8 × 4 × 2 cm) breakout box attached to the back. Video feeds from the eye tracker were routed through the breakout box into a laptop computer several feet away. The wires were long enough to allow unconstrained movement on the walkway, and an assistant followed behind infants to hold the wires out of the way. Videos from both camera feeds—the *scene video* and the *eye video*—were captured on the laptop for later processing.

After the session, Yarbus software (Positive Science) was used to calculate infants' point of gaze within the scene video using estimations of the location of the center of the pupil and the corneal reflection. The software constructed a *gaze video* (30 frames/s) with a crosshair overlaid on each frame indicating the point of gaze with a spatial accuracy of ~2° (Figure 1b).

Walkway and procedure—Infants were tested on a raised walkway (65 cm high × 98 cm wide × 490 cm long; Figure 1c). To facilitate precise measurement of locations, the walkway was covered with high-density foam with stripes of alternating colors spaced 15 cm apart (32 stripes in total). Colors repeated every five stripes, and numbered labels (1–7) were placed along the length of the walkway at every fifth stripe so that stripes could be uniquely identified by the combination of number and color. An 82-cm wide curtain hung from the ceiling 63 cm from the far end of the walkway and was covered with 14 stripes, identified by the same five colors and the numbers 1–3. The curtain stretched from the ceiling to the top of the walkway so that the lowest stripe was 65 cm high (level with the walkway surface) and the highest stripe was 260 cm high (195 cm above the walkway surface).

Caregivers sat on a chair placed between the walkway and the curtain. To familiarize infants with the experimental setup, caregivers encouraged infants to crawl or walk the length of the walkway several times without the eye tracking equipment, while an experimenter followed alongside to ensure infants' safety. Then, an assistant distracted infants with toys while the experimenter placed the eye-tracking equipment on the infant and adjusted the eye camera and IRED until the image of the eye was centered and brightly illuminated. Once the equipment was in place and infants were comfortable, calibration data were collected: The assistant called infants' attention to various locations by squeaking toys or shaking rattles in windows cut out of a large poster board. Infants sat approximately four feet away from the calibration board, and the experimenter calibrated the scene camera by adjusting its position so that the entire board was visible in the scene video. Although we could not guarantee that the angle of the scene camera was exactly the same for every infant, the small range of motion of the scene camera and the constraints on the placement of the attached eye camera for gaze calculations ensured that the inter-infant differences were minimal—most likely within 5–10 degrees. These variations likely added noise to the data but would not be expected to differ between crawlers and walkers.

After calibration, infants were again encouraged to crawl or walk several times toward their caregivers. Caregivers enticed infants by calling to them from the end of the walkway and holding attractive toys and snacks. To present infants with different visual target locations, we varied the height of caregivers and toys on alternating blocked trials. In the *low* toy condition, caregivers sat in the chair and held toys on the surface of the walkway. In the *middle* toy condition, caregivers sat and held toys up at their own eye height. And in the *high* toy condition, caregivers stood up and held toys at their elevated eye height. Each infant received 1–4 blocks of three trials ($M = 8.20$ total trials) and trial order was counterbalanced across infants. Number of trials did not differ significantly between crawlers ($M = 7.27$) and walkers ($M = 9.13$), $t(28) = 1.59$, $p = .12$. An assistant wheeled a video camera on a dolly alongside the walkway to record infants' locomotion; these videos were later synchronized with gaze videos to facilitate data coding.

Data coding—With a head-mounted eye tracker, infants are free to locomote and move their heads, so that the field of view shifts continuously throughout the session. Thus, automatic data processing methods developed for remote eye tracking systems are not feasible, and data must be scored by hand from video. We used the open source video coding software Datavyu (www.datavyu.org) to score infants' locomotor and visual behaviors. A primary coder scored 100% of the data, and a second coder scored 33% of each infant's data to ensure inter-rater reliability.

Locomotion and posture: Coders first identified each video frame when infants took a forward step: the first frame when a hand (for crawlers) or a foot (for walkers) contacted the walkway surface. For each step, coders scored infants' location on the walkway based on the stripe region in which infants placed their hand or foot. Coders also scored each time crawlers shifted into a sitting posture (walkers never did this), and identified the stripe region where the farthest forward body part fell (knees or feet). Coders agreed within one stripe on 99.2% of steps, and on the exact stripe on 96.5% of steps ($\kappa = .96$).

Field of view: For each video frame identified as a step, the coders scored various aspects of the scene video as an approximation of infants' field of view. Preliminary data indicated that the contents of the scene video showed little change within the duration of a step, so more detailed frame-by-frame coding was unnecessary. Additionally, to obtain samples of field of view data when infants were sitting, coders selected the first and last frames when infants were sitting and facing forward, and scored all outcome measures for those video frames. In total, coders scored field of view measures for 6,313 video frames.

To measure the orientation of infants' field of view, coders used the colored stripes to identify where the top of the scene camera field of view intersected the vertical plane (the curtain), and where the bottom of the scene camera field of view intersected the horizontal plane (the floor). If the curtain was in view, the coders identified the *highest point visible*: the uppermost stripe at the top of the scene video (Figure 1b–c). Coders agreed within one stripe on 97.7% of steps, and on the exact stripe on 89.7% of steps ($\kappa = .89$). If the floor was in view, the coders identified the lowermost stripe at the bottom of the scene video (Figure 1b–c); the *closest point visible* was the distance between that stripe and the stripe at infants' hands or feet. Coders agreed within one stripe on 98.1% of steps, and on the exact stripe on

92.8% of steps ($\kappa = .93$). Frames where infants had their heads turned to the side such that no stripes were visible were eliminated from analysis. Finally, coders scored whether the *caregiver's face* and the *toy* held by the caregiver were visible in the scene video—coders agreed on 98.3% of samples, $\kappa = .96$.

Gaze location: Frame-by-frame coding of the location of the crosshair is necessary to determine where infants direct their gaze within the field of view. However, because such coding is extremely laborious, coders scored only a subset of trials for gaze location. Four infants did not produce useable gaze data because of poor calibration. For the remaining 26 infants, 57/190 trials were not useable because of poor eye tracking data quality (due to suboptimal camera placement, inadequate illumination of the eye, or infants crying or squinting). Coders scored eye gaze data for the first useable trial in each condition, and for crawlers, coders also scored each trial that contained a sit (88 trials in total). Overall, coders scored gaze location in 28,962 video frames.

For each frame of those trials, coders scored whether the gaze crosshair was on the *caregiver*, the *floor*, or the *wall* ahead. We allowed a margin of error for looks to the caregiver by including any frames where the crosshair was on the curtain, within 2 stripes from the top of the caregiver's head (1b); these criteria are similar to automated areas of interest commonly used in remote eye-tracking (e.g., Johnson, Slemmer, & Amso, 2004). Coders agreed on 98% of frames. Frames where infants were looking off the side of the walkway or outside the boundaries of the scene video were excluded from analysis.

Results and Discussion

Our primary questions were whether visual input differs between crawlers and walkers and how infants are affected by changes in target location. We tested for effects of posture and target location using generalized estimating equations (GEEs), a type of linear model that accounts for covariance between repeated measures and allows for testing of non-normal distributions. All categorical dependent variables (field of view contents and eye gaze targets) were analyzed using a binomial probit model. Entering infants' location on the walkway as a covariate in the models did not change any of the findings for posture and target location, so we did not include location in the analyses reported here. Data from the first 75 cm and the last 75 cm of the walkway were eliminated because few infants contributed data at those locations. We used Sidak-corrected pairwise comparisons to follow up on significant effects. Main effects and interactions from the GEEs are presented in Table 1.

Crawling vs. walking: Scene camera field of view—Portions of the environment in view differed for crawlers and walkers. Figure 2 is drawn to scale based on our data to illustrate the average visual fields of crawlers and walkers in the current study.

Highest point visible: For us to measure the point of intersection with the curtain (Point A in Figure 2), infants had to hold their heads high enough that the curtain was visible in the scene camera. For walkers, this was nearly always the case, but crawlers repeatedly lost sight of the curtain: On 25.7% of steps, crawlers' entire scene video contained only the floor, indicating that while crawling, infants may miss visual input from distal parts of the room around them.

When crawlers did see across the room, they saw much less of it than walkers: The highest point visible in the scene camera was about twice as high for walkers (*M* = 135.17 cm) as for crawlers (*M* = 65.94 cm; Figure 3a; Table 1, row 1). Both crawlers and walkers responded to changes in target location, as indicated by a main effect of toy height condition and the absence of a posture × condition interaction: As the location of people and objects moved upward, both crawlers and walkers tilted their heads up to compensate. Pairwise comparisons indicated that the high toy condition (with the caregiver standing up) was significantly different from both other conditions (*p*s< .01), and the difference between the other two conditions was marginally significant (*p* = .08).

The findings represent a conservative estimate of the differences between crawlers and walkers. For measurements of the highest point visible, the range was restricted: The largest possible value was the top of the curtain. However, the highest point visible, particularly for walkers, was often higher than the top of the curtain (418 video frames for walkers and 36 video frames for crawlers were scored as the maximum 195 cm), so that the data suffered from a literal ceiling effect. If we had tested infants in a room with an infinitely high ceiling, the disparity between crawlers and walkers would have been even larger.

Although on average, walkers' view was higher than crawlers' view, infants in both groups showed substantial within-subject variability (Figure 4). The large ranges of values obtained for each infant indicate that constraints on crawlers' and walkers' visual fields were not absolute. Crawlers could tilt their heads up and occasionally did, giving them intermittent glimpses of parts of the environment that were typically out of view.

Closest point visible: Whereas walkers had greater visual access to distal and elevated locations, crawlers had a better view of the floor in front of their hands. The closest point visible at the bottom of the scene camera was closer to crawlers' hands (*M* = 20.89 cm) than to walkers' feet (*M* = 83.00 cm; Figure 3b; Table 1, row 2). The GEE revealed a main effect of condition and a posture × condition interaction: As walkers tilted their heads up in the high toy condition, the lower boundary of the field of view was pushed farther forward than in the low condition (*p*< .01); the conditions did not differ for crawlers (*p*s> .10).

Crawling vs. walking: Caregivers and toys in the field of view—Differences in the field of view for crawlers and walkers had important functional consequences. Walkers had caregivers and toys—the goal at the end of the walkway—in their field of view, but crawlers frequently did not.

Caregiver: Walkers had their caregiver's face in view twice as often as crawlers (*M* = 89.3% vs. 43.7%; Figure 3c; Table 1, row 3). The analysis revealed only a main effect of condition, but no posture × condition interaction: Both crawlers and walkers were less likely to have their caregivers in view in the high toy condition, when they stood up, than in the low toy condition, when they were sitting and closer to infants' eye level, *p*< .01.

Toy: Crawlers had toys in view less frequently than walkers (*M* = 92.2% vs. 52.5%), and only crawlers were affected by toy location: For crawlers, all three conditions differed from each other (*p*s< .02), but none differed for walkers (Figure 3d; Table 1, row 4). This finding suggests that crawlers have adequate visual access to objects on the floor, but objects placed on furniture or affixed to walls are unlikely to be seen while crawling.

Crawling vs. walking: Gaze location—The availability of information in the field of view influenced where crawlers and walkers directed their gaze (Figure 5; Table 1, rows 5–6). Crawlers spent more time than walkers—in fact, a majority of video frames—looking down at the floor (*M* = 54.4% of frames overall vs. *M* = 28.5% of frames), and less time than walkers looking ahead at the caregiver (*M* = 36.6% of frames vs. *M* = 54.1% of frames; the remaining 9% of frames for crawlers and 17.4% of frames for walkers were spent looking at the wall behind the caregiver). This finding is particularly striking because the experimental procedure biased infants to look at their caregivers, who called to their infants throughout the trial and waved toys for them to retrieve. The GEE confirmed a main effect of toy height condition: Infants looked less frequently at the floor and more frequently at the caregiver in the high toy condition than the other two conditions (*p*s< .05), when their attention was pulled upwards. Significant (looking toward floor) and marginally significant (looking toward caregiver) posture × condition interactions and pairwise comparisons suggest that the condition effects were only reliable for walkers, *p*s< .01. The field of view data indicate shifts in the availability of visual information; the crawler-walker differences in gaze behavior are notable because they indicate shifts in infants' active visual attention.

Sitting—Nine of the 15 crawlers switched from all fours to a sitting posture mid-trial. Eight infants sat once or twice, one sat four times, and one sat seven times. What prompted infants to sit up? Possibly, it was the lack of visual information obtained in a crawling posture: Out of the 22 sits in the data set, eight occurred in the high toy condition and 12 in the middle toy condition, but only two occurred in the low toy condition. A GEE with a Poisson link function confirmed a significant effect of condition on the rate of infants' spontaneous sits: Infants were significantly more likely to sit in the middle condition than the low condition, *OR* = 6.33, *p* = .01, and marginally more likely to sit in the high condition than the low condition, *OR* = 4.50, *p* = .07. Although infants may have intentionally sat up to see the toys (sit-to-see), it is also possible that infants sat up for other reasons (e.g., discomfort of crawling) and then took advantage of the more upright posture to obtain a different view (sit-and-see). Regardless of their intentions, the data from the head-mounted eye tracker illustrate an important consequence of this phenomenon.

When infants sat up, their visual world changed dramatically. For two infants (and three trials from two other infants), field of view data were not available because infants faced away from the curtain when they sat up. The seven infants for whom data are available had more of the curtain in view while sitting (*M* = 160.22 cm) than while crawling (*M* = 72.21 cm), *t*(6) = 4.86, *p*< .01. While sitting, infants were also more likely to have their caregiver's face (*M* = 90.8% of frames) and the toy in view (*M* = 92.8%) than while crawling (*M*s = 51.1% and 58.2%, for face and toy, respectively), *t*s(6) > 3.24, *p*s≤ .02. The six infants for whom eye tracking data were available were less likely to look at the floor while sitting (*M*

= 12.0% of frames) than while crawling ($M = 48.4\%$), $t(5) = 2.72$, $p = .04$. They were also more likely to look at the caregiver while sitting ($M = 62.6\%$) than while crawling ($M = 40.0\%$), but this effect did not reach significance in the small subsample, $t(5) = 1.65$, $p = .16$.

Summary—Even in an identical physical and social context, the visual experiences of 13-month-old crawlers and walkers were very different. Crawlers' visual world was dominated by the floor, whereas walkers had continuous visual access to distal and elevated people and objects. Crawlers got a better view of the room when they interrupted locomotion to sit up and take a look around.

Although the primary comparisons in this experiment were between subjects, the effects should be attributed to the real-time physical constraints of different postures rather than group differences between crawlers and walkers. The transition to sitting immediately transformed the visual world of crawlers; while sitting up, those same crawlers had a similar view of the room, people, and objects as did walkers. In fact, crawlers spontaneously stop crawling to sit up after only a few seconds of crawling in both standard crawling tasks and free play situations (Soska, Robinson, & Adolph, 2013), indicating that crawlers' floor-centered view of the world is intermittent. Moreover, in everyday life, crawlers have additional postures available—standing or cruising upright—and they can view the world from a higher vantage point while being carried. Similarly, we were able to entice three of the crawlers and three of the walkers to perform a trial or two in the opposite posture (one crawler was just barely able to string several independent steps together across the walkway; the others happily walked holding the experimenter's hands). These infants' data resembled the crawler group while crawling and the walker group while walking. Thus, the visual effects of the transition from crawling to walking appear to be instantaneous.

Experiment 2: Body Constraints on Visual Experience

Differences in visual experience between crawlers and walkers could, in theory, stem from two separate body constraints: eye height and head angle. However, the relative contributions of these two factors have not been examined. Eye height is clearly highest in walking, lowest in crawling, and somewhere in between in sitting, but how different are the three postures and to what extent are differences in visual input driven by height differences alone? Is crawlers' height disadvantage compounded by incomplete neck extension so that their faces point toward the ground, or do they strain their necks to compensate? Where do infants point their heads in the upright postures of walking and sitting?

To examine the contributions of height and head angle on the different visual experiences illustrated in Experiment 1, we ran a small sample of infants in the same crawling/walking protocol and measured the position and orientation of the head throughout each trial.

Method

Participants—Thirteen 13-month-old infants were recruited and compensated in the same manner as Experiment 1. Nine infants were crawlers ($M = 3.38$ months crawling experience) and 4 infants were walkers ($M = 1.81$ months walking experience). Data from 4 additional infants were excluded for refusal to crawl on the raised walkway (*n* = 3) or equipment failure (*n* = 1).

Motion capture system and procedure—

The walkway and task were identical to Experiment 1: Infants crawled or walked to their caregivers several times over the striped platform. We used an electromagnetic motion tracking system (Ascension TrakSTAR) to track the position and orientation of infants' heads while crawling and walking. The system collects six-degree-of-freedom measurements—three dimensions of position (x, y, z) and three axes of orientation (pitch, yaw, and roll)—of small sensors with reference to a fixed magnetic field transmitter. Measurements were collected at 240 Hz using custom software.

Because sensor accuracy is a function of proximity to the transmitter, the transmitter was placed next to the raised platform and elevated 43 cm from the ground on a plastic stand. The most accurate measurements were obtained within a 150-cm portion of the walkway (approximately 378 cm from the curtain to 228 cm from the curtain) and only data within this portion were analyzed.

After infants crawled or walked a few times on the platform to become comfortable with the task, the experimenter placed the equipment. Infants wore the same hat and vest used with the head-mounted eye tracker (see Figure 1A), and a sensor was secured to the right side of the hat with Velcro. The sensor was oriented parallel to an imaginary line running from the junction of the ear and the head to the corner of the eye. This is approximately parallel to the standard anatomical Frankfort plane, thus ensuring that when the sensor was parallel to the ground the head was in the anatomically neutral position. The sensor was connected to the computer via a long cable that was secured with Velcro to the infants' backs to allow enough slack for head movements; the cable was held out of the way by an assistant who followed behind infants during the trials.

Measurements from only one sensor provide data only about the orientation of the sensor relative to the ground surface. Because it was also important for us to know how much infants extended their necks, that is, the orientation of crawlers' heads relative to their trunks, four crawlers were also outfitted with a second sensor attached to the back of the Velcro vest.

Data reduction—

As in Experiment 1, coders scored the timing and location of infants' steps from video. Readings from the motion capture sensors were averaged over the duration of each step for analysis, so that the data resolution was the same as in Experiment 1. Coders also identified periods of time when crawling infants spontaneously sat up (there were 14 spontaneous sits produced by 5 crawlers); these data were analyzed separately.

Results and Discussion

Height—

To our knowledge, this is the first study to quantify infants' functional height during crawling and walking. We found that walkers were twice as tall while walking (*M*sensor height = 68.78 cm) than crawlers were while crawling (*M* = 33.94 cm). When they sat up, crawlers' height was larger than while crawling but still relatively low, ranging from

35.77–55.26 cm depending on whether infants knelt with their bottoms resting on their heels or sat with their bottoms on the platform surface.

Head pitch angle—Figure 6a–b shows the distributions of head pitch angles for crawlers and walkers, with 0 degrees representing a head orientation parallel to the ground. Head pitch angles for walkers were centered around 0 degrees, as would be expected from a neutral head position in an upright posture. Crawlers' head pitch angles were lower than walkers on average, but there was a great deal of overlap and the difference did not reach statistical significance in this sample ($p = .12$)—surprisingly, most crawlers managed to bring their heads to parallel at some point. Crawlers did not point their heads toward the ceiling to compensate for being half as tall in a crawling posture. However, they nearly always did so while sitting (Figure 6c).

Crawlers displayed more variability in head position than did the walkers (Figure 6a). Crawlers had larger within-trial standard deviations in head pitch angle *M*s = 6.90 for crawlers and 4.33 for walkers, Wald $\chi^2 = 7.57$, $p < .01$. Crawlers also displayed larger deviations in head pitch angle between consecutive steps, *M*s = 4.87 degrees for crawlers and 3.47 degrees for crawlers, Wald $\chi^2 = 18.34$, $p < .01$. This indicates that crawlers flexed and extended their necks repeatedly, but walkers kept their heads more stable.

Trunk orientation and neck extension—Crawlers' shoulders were propped up slightly higher than their bottoms, resulting in average trunk angles ranging from 15.56 to 18.63 degrees from parallel for the four infants tested with the extra marker on their backs. To obtain a rough measure of neck extension, we compared infants' trunk angle to the complement of their head pitch angle. While crawling, infants craned their necks at about the maximum extension (60–90 degrees) reported in the literature for children and adults in a stationary standing or sitting position (Klinich & Reed, 2013; Lewandowski & Szulc, 2003; Lynch-Caris et al., 2008; Ohman & Beckung, 2008; Youdas et al., 1992): average extension for the four infants ranged from 49.19 to 81.65 degrees. This indicates that infants failed to point their heads up while crawling because they had reached their physical limits. Note that the infants in this study were mature, experienced crawlers. Earlier in development, as younger, weaker, less coordinated crawlers, lifting the head may be even more difficult; it may be especially difficult for infants who crawl on their bellies.

Calculated head rotation for Experiment 1 infants—Once we had a measure of average height (h_{head}) for crawlers and walkers, we were able to use the field of view data to estimate head pitch angles (θ) for infants in Experiment 1. For each step, we used measurements of the highest point visible ($h_{visible}$) and the distance from the curtain (d) at each step to create a triangle that could be solved using the following equation:

$$\theta = \tan^{-1}\frac{h_{visible} - h_{head}}{d} - 21$$

The first part of this equation yields the pitch angle of the upper boundary of the scene camera field of view; to estimate the pitch angle of the center of the scene camera, the constant of 21 degrees (half the vertical field of view of the scene camera) was subtracted.

Walkers (M = -9.13 degrees) in Experiment 1 pointed their heads significantly higher than did crawlers (M = -21.76 degrees), $t(28) = 5.29$, $p < .01$. Although reliable, the difference between crawlers and walkers was far smaller than would have been expected if crawlers had kept their heads in an effortless, neutral posture.

General Discussion

Using head-mounted eye tracking and motion tracking, we documented differences in visual input during crawling and walking. While crawling, infants mostly see the ground in front of their hands; while walking, they see the whole room and its inhabitants. These differences in visual input result directly from the different constraints of infants' bodies while crawling and walking.

Human bodies are not well built for quadrupedal locomotion. The evolution of upright walking produced modifications in the anatomy of the human spine (Tobias, 1992). The spine attaches to the base of the skull in humans. In contrast, the spine attaches to the back of the skull in horses, cats, nonhuman primates, and other mammals. Our anatomy is optimal for the bipedal walking and other upright postures, but restricts visual access to the environment while crawling. Crawlers struggle to exploit the full range of motion of their necks—straining against gravity to do so—but still see the world differently than walkers do; that is, unless they sit up and tilt their heads toward the ceiling.

Visual input in everyday situations

Should we expect the results from this controlled laboratory experiment to generalize to infants' actual everyday experiences? We tested infants in a highly controlled setting for two reasons: to isolate postural contributions to infants' visual experience, and to facilitate measurement of infants' visual fields. Spontaneous locomotion differs dramatically between 12- to 13-month-old crawlers and walkers: Walkers spend more time in motion, travel three times the distance, explore more areas of the environment, and interact differently with their caregivers (Adolph et al., 2012; Clearfield, 2011; Karasik et al., in press). So in the current study, we held number of trips, path, and the caregiver's interaction constant. We also covered the walkway with colored stripes to make it easier for coders to score infants' field of view from video. But could our particular experimental setup have biased the results?

One possibility is that the colored stripes on the walkway encouraged crawlers to look down more than they otherwise would have. However, walkers traveled down the same walkway with the same colored stripes and looked at the floor significantly less frequently than crawlers. If the stripes did indeed draw crawlers' attention down, this would suggest that salient objects on the floor are more likely to attract the attention of crawlers than walkers, another potential consequence of their different views of the world.

Another artificial aspect of the design was that the caregiver sat or stood on a lower surface than the infants. This means that our experimental setup actually made it *easier* for crawlers to see the caregiver's face than if they were on the same surface. In the low and middle conditions, caregivers' faces were closer to infants' eye level than if they sat on the floor with their infants. Despite contriving the situation so that caregiver's faces were maximally available to crawling infants, crawlers only had their caregivers' face in view 43.7% of the time and only fixated the caregiver 36.6% of the time. In a natural environment, the height of caregivers relative to infants changes as the caregivers themselves change posture; we manipulated caregiver height to simulate these changes. An intriguing possibility currently being investigated in our laboratory is that caregivers are sensitive to infants' point of view and adapt their posture to impose themselves in infants' visual fields. In this way, the transition from crawling to walking might reorganize parents' behavior.

We tested infants moving down an uncluttered, uniform path. Would the differences we documented between crawlers and walkers generalize to a more complex natural environment? Fortunately, our findings converge with recent data from naturalistic studies. During spontaneous play in a laboratory playroom, toddlers are more likely to look at the floor while crawling than while walking (Franchak et al., 2011), and walkers are more likely to have faces in their field of view than are crawlers (Frank et al., in press). Our kinematic data suggests that the differences between crawlers and walkers are a product of the shape of their bodies in motion, rather than the specific experimental context.

Advantages of walkers' viewpoint

Our findings indicate that while walking, infants see distal and elevated objects and people. Visual access to these particular parts of the environment during locomotion may contribute to previously documented psychological advances that accompany the onset of walking.

Visual access to distal parts of the environment might increase engagement with distal objects and people. Previous research revealed that walkers travel across the room to retrieve objects and share them with caregivers, whereas crawlers interact with proximal objects and caregivers (Karasik et al., 2011). As a result, walkers receive more verbal feedback from caregivers (Karasik et al., in press). This may in turn be related to recent findings that the onset of walking accelerates language development (Ellis-Davies et al., 2012; Iverson, 2010; Walle & Campos, in press).

Increased visual access to distal objects may also facilitate the development of spatial cognition. Place learning (the coding of locations relative to distal landmarks) is not evident until about 21 months of age (Newcombe, Huttenlocher, Drummey, & Wiley, 1998). Possibly, the ability to see more of the environment while walking increases infants' attention to the relations between distal objects and landmarks necessary for place learning (Newcombe & Learmonth, 1999).

Differences in eye level have previously been implicated in toddlers' surprisingly low rates of visual attention to their mothers' faces (Franchak et al., 2011). The current study and previous work (Frank et al., in press) suggests that crawlers experience even less frequent visual access to faces than walkers. The transition from crawling to walking may therefore increase opportunities for some types of social learning such as joint attention or social referencing.

Although crawlers can access some of the same visual information as walkers, doing so incurs a greater cost and is organized differently in time: Crawlers must repeatedly crane their necks up and down or stop moving and sit up to sample visual information that can be accessed continuously and largely for free while walking. This distinction is important, because some learning experiences may depend on viewing objects or events at specific times or viewing a continuously changing display. For example, learning the mapping between an object and its name presumably depends on seeing the object within a certain time frame of the naming event (Yu & Smith, 2012). Walking infants may be more likely to have objects in view at just the right moment, which may make these mappings easier. Additionally, processes that rely on continuous visual tracking of objects, such as spatial reorientation following body movement (Acredolo, Adams, & Goodwyn, 1984), may be improved in walkers compared to crawlers.

Our findings also help to explain an enduring question in motor development: Why do expert crawlers forsake a skill they have mastered for a new, initially difficult mode of locomotion? Prewalking infants have plenty of access to the visual world while sitting, cruising, and being carried. However, the promise of enhanced visual access the wider environment during locomotion may motivate infants to stand up and begin to walk. The ability to see more of the room while moving may contribute to the fact that novice walkers take more steps, travel father distances, and spend twice as much time in motion than experienced crawlers (Adolph et al., 2012).

Advantages of crawlers’ viewpoint

Crawlers’ view of the world has its own benefits. We found that while crawling, infants had effortless visual access to the floor in front of their hands; while walking, they lost sight of the floor close to their feet. This represents a significant advantage for crawlers for visual guidance of locomotion. Upcoming obstacles or changes in the ground surface can be easily detected if they remain in the field of view throughout the approach, and appropriate locomotor responses may be more easily planned if visual contact is maintained during the action (Adolph, 1997). Accordingly, infants display different visual strategies for guiding locomotion over obstacles depending on their posture: They are more likely to fixate obstacles in advance while crawling than while walking (Franchak et al., 2011).

Different views of the ground ahead may contribute to posture-specific learning in visually guided locomotion. Whereas experienced crawlers accurately perceive affordances for locomotion over slopes and cliffs, novice walkers make large errors in their new upright posture (Adolph, 1997; Kretch & Adolph, 2013). The current study suggests that an important challenge of the transition from crawling to walking is learning to interpret substantially different visual information for guiding locomotion. Different viewing angles create different correlations among visual, proprioceptive, and vestibular information; different viewing angles also generate different patterns of optic flow to specify the layout of objects and surfaces and infants’ movement through the environment (Bertenthal & Campos, 1990; J. J. Gibson, 1950, 1979). In addition, timing of locomotor planning might need to be adjusted because obstacles or edges exit the bottom of the field of view earlier while walking than while crawling, similar to the earlier exit of obstacles from the visual field of adults compared with shorter children (Franchak & Adolph, 2010). Indeed, the timing of obstacle fixations is different between adults and children to take the flow of available information into account. Newly walking infants may need weeks of practice to successfully use visual information about the surface layout from their new upright posture.

In some ways, a limited view of the wider environment while crawling may also be an advantage for learning about the world. Fewer objects and surfaces in view at a time also means fewer distractions, and may serve as a kind of spotlight on the immediate surrounds and the current task. Moreover, not being able to see objects during locomotion may encourage infants to hold them in memory; repeated practice may contribute to improvements in memory following crawling onset (Herbert et al., 2007).

Conclusion

Many researchers have argued that “travel broadens the mind” (Bertenthal et al., 1984; Campos et al., 2000; E. J. Gibson, 1988). Our findings demonstrate that different forms of travel are not on equal footing. Different views of the world may lead infants to have divergent experiences and different opportunities for learning while crawling or walking.

Infants experience a variety of postures at every point in development: lying supine or prone, being carried, sitting, crawling, cruising, and walking upright. Motor development changes the frequency with which infants experience different postures; in particular, the onset of independent walking increases the amount of time infants spend upright. This leads to different experiences that facilitate a variety of developmental outcomes. Our data suggest that differences in visual experience may be a part of the suite of changes that accompany the transition from crawling to walking.

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References

Acredolo L, Adams A, Goodwyn SW. The role of self-produced movement and visual tracking in infant spatial orientation. Journal of Experimental Child Psychology. 1984; 38:312–327. [PubMed: 6491598]

Adolph KE. Learning in the development of infant locomotion. Monographs of the Society for Research in Child Development. 1997; 62(3 Serial No 251)

Adolph KE, Cole WG, Komati M, Garciaguirre JS, Badaly D, Lingeman JM, Chan GLY, Sotsky RB. How do you learn to walk? Thousands of steps and hundreds of falls per day. Psychological Science. 2012; 23:1387–1394. [PubMed: 23085640]

Anderson DI, Campos JJ, Anderson DE, Thomas TD, Witherington DC, Uchiyama I, Barbu-Roth MA. The flip side of perception-action coupling: Locomotor experience and the ontogeny of visual-postural coupling. Human Movement Science. 2001; 20:461–487. [PubMed: 11750673]

Aslin RN, McMurray B. Automated corneal-reflection eye tracking in infancy: Methodological developments and applications to cognition. Infancy. 2004; 6:155–163.

Bai DL, Bertenthal BI. Locomotor status and the development of spatial search skills. Child Development. 1992; 63:215–226. [PubMed: 1551326]

Bertenthal, BI.; Campos, JJ. A systems approach to the organizing effects of self-produced locomotion during infancy. In: Rovee-Collier, CK.; Lipsitt, LP., editors. Advances in infancy research. Vol. 6. Norwood, NJ: Ablex; 1990. p. 1-60.

Bertenthal, BI.; Campos, JJ.; Barrett, KC. Self-produced locomotion: An organizer of emotional, cognitive, and social development in infancy. In: Emde, RN.; Harmon, RJ., editors. Continuities and discontinuities in development. New York: Plenum Press; 1984. p. 175-210.

Biringen Z, Emde RN, Campos JJ, Applebaum MI. Affective reorganization in the infant, the mother, and the dyad: The role of upright locomotion and its timing. Child Development. 1995; 66:499–514. [PubMed: 7750380]

Campos JJ, Anderson DI, Barbu-Roth MA, Hubbard EM, Hertenstein MJ, Witherington DC. Travel broadens the mind. Infancy. 2000; 1:149–219.

Campos, JJ.; Kermoian, R.; Witherington, D.; Chen, H.; Dong, Q. Activity, attention, and developmental transitions in infancy. In: Lang, PJ.; Simons, RF., editors. Attention and orienting: Sensory and motivational processes. Mahwah, NJ: Lawrence Erlbaum Associates; 1997. p. 393-415.

Campos JJ, Kermoian R, Zumbahlen MR. Socioemotional transformations in the family system following infant crawling onset. Emotion and its regulation in early development. New directions for child development. 1992:25–40.

Cicchino JB, Aslin RN, Rakison DH. Correspondences between what infants see and know about causal and self-propelled motion. Cognition. 2011; 118:171–192. [PubMed: 21122832]

Clearfield MW. Learning to walk changes infants' social interactions. Infant Behavior & Development. 2011; 34:15–25. [PubMed: 20478619]

Clearfield MW, Osborne CN, Mullen M. Learning by looking: Infants' social looking behavior across the transition from crawling to walking. Journal of Experimental Child Psychology. 2008; 100:297–307. [PubMed: 18452944]

Ellis-Davies, K.; Sakkalou, E.; Fowler, N.; Hilbrink, E.; Gattis, M. I can walk, I can talk: Emerging motor development predicts language development. Paper presented at the International Conference on Infant Studies; Minneapolis, MN. 2012 Jun.

Franchak JM, Adolph KE. Visually guided navigation: Head-mounted eye-tracking of natural locomotion in children and adults. Vision Research. 2010; 50:2766–2774. [PubMed: 20932993]

Franchak JM, Kretch KS, Soska KC, Adolph KE. Head-mounted eye tracking: A new method to describe infant looking. Child Development. 2011; 82:1738–1750. [PubMed: 22023310]

Franchak, JM.; Kretch, KS.; Soska, KC.; Babcock, JS.; Adolph, KE. Head-mounted eye-tracking in infants' natural interactions: A new method. Paper presented at the Proceedings of the 2010 Symposium on Eye Tracking Research and Applications; Austin, TX. 2010.

Frank, MC.; Simmons, K.; Yurovsky, D.; Pusiol, G. Developmental and postural changes in children's visual access to faces. In: Knauff, M.; Pauen, M.; Sebanz, N.; Wachsmuth, I., editors. Proceedings of the 35th Annual Meeting of the Cognitive Science Society. Austin, TX: Cognitive Science Society; 2013. p. 454-459.

Fuller JH. Eye position and target amplitude effects on human visual saccadic latencies. Experimental Brain Research. 1996; 109:457–466. [PubMed: 8817276]

Gibson EJ. Exploratory behavior in the development of perceiving, acting, and the acquiring of knowledge. Annual Review of Psychology. 1988; 39:1–41.

Gibson, EJ.; Pick, AD. An ecological approach to perceptual learning and development. New York: Oxford University Press; 2000.

Gibson, JJ. The perception of the visual world. Oxford: Houghton Mifflin; 1950.

Gibson, JJ. The senses considered as perceptual systems. Boston: Houghton-Mifflin; 1966.

Gibson, JJ. The ecological approach to visual perception. Boston: Houghton Mifflin Company; 1979.

Haith MM. Infrared television recording and measurement of ocular behavior in the human infant. American Psychologist. 1969; 24:279–283. [PubMed: 5767582]

Herbert J, Gross J, Hayne H. Crawling is associated with more flexible memory retrieval by 9-month-old infants. Developmental Science. 2007; 10:183–189. [PubMed: 17286842]

Higgins CI, Campos JJ, Kermoian R. Effect of self-produced locomotion on infant postural compensation to optic flow. Developmental Psychology. 1996; 32:836–841.

Horobin K, Acredolo L. The role of attentiveness, mobility history, and separation of hiding sites on Stage IV search behavior. Journal of Experimental Child Psychology. 1986; 41:114–127.

Iverson JM. Developing language in a developing body: The relationship between motor development and language. Journal of Child Language. 2010; 37:229–261. [PubMed: 20096145]

Johnson SP, Amso D, Slemmer JA. Development of object concepts in infancy: Evidence for early learning in an eye tracking paradigm. Proceedings of the National Academy of Sciences. 2003; 100:10568–10573.

Johnson SP, Slemmer JA, Amso D. Where infants look determines how they see: Eye movements and object perception performance in 3-month-olds. Infancy. 2004; 6:185–201.

Karasik LB, Adolph KE, Tamis-LeMonda CS, Zuckerman A. Carry on: Spontaneous object carrying in 13-month-old crawling and walking infants. Developental Psychology. 2012; 48:389–397.

Karasik LB, Tamis-LeMonda CS, Adolph KE. Transition from crawling to walking and infants' actions with objects and people. Child Development. 2011; 82:1199–1209. [PubMed: 21545581]

Karasik LB, Tamis-LeMonda CS, Adolph KE. Crawling and walking infants elicit different verbal responses from mothers. Developmental Science. in press.

Kermoian R, Campos JJ. Locomotor experience: A facilitator of spatial cognitive development. Child Development. 1988; 59:908–917. [PubMed: 3168629]

Klinich, KD.; Reed, MP. Pediatric anthropometry. In: Crandall, JR.; Myers, BS.; Meaney, DF.; Zellers Schmidtke, S., editors. Pediatric injury biomechanics. New York: Springer Science+Business Media; 2013. p. 1-32.

Kretch KS, Adolph KE. Cliff or step? Posture-specific learning at the edge of a drop-off. Child Development. 2013; 84:226–240. [PubMed: 22906143]

Land MF. The coordination of rotations of the eyes, head and trunk in saccadic turns produced in natural situations. Experimental Brain Research. 2004; 159:151–160. [PubMed: 15221164]

Lewandowski J, Szulc P. The range of motion of the cervical spine in children aged from 3 to 7 years —an electrogoniometric study. Folia Morphologica. 2003; 62:459–461. [PubMed: 14655141]

Lynch-Caris T, Majeske KD, Brelin-Fornari J, Nashi S. Establishing reference values for cervical spine range of motion in pre-pubescent children. Journal of Biomechanics. 2008; 41:2714–2719. [PubMed: 18675420]

Newcombe NS, Huttenlocher J, Drummey AB, Wiley JG. The development of spatial location coding: Place learning and dead reckoning in the second and third years. Cognitive Development. 1998; 13:185–200.

Newcombe NS, Learmonth A. Change and continuity in early spatial development: Claiming the "radical middle". Infant Behavior & Development. 1999; 22:457–474.

Ohman AM, Beckung ERE. Reference values for range of motion and muscle function of the neck in infants. Pediatric Physical Therapy. 2008; 20:53–58. [PubMed: 18300934]

Ounsted M, Moar VA. Proportionality changes in the first year of life: The influence of weight for gestational age at birth. Acta Paediatrics Scandinavia. 1986; 75:811–818.

Pare M, Munoz DP. Expression of a re-centering bias in saccade regulation by superior colliculus neurons. Experimental Brain Research. 2001; 137:354–368. [PubMed: 11355382]

Piaget, J. The construction of reality in the child. New York: Basic Books; 1954.

Salapatek P, Kessen W. Visual scanning of triangles by the human newborn. Journal of Experimental Child Psychology. 1966; 3:155–167. [PubMed: 5939107]

Snyder, RG.; Spencer, ML.; Owings, CL.; Schneider, LW. Anthropometry of US infants and children. (Paper No. 750423). Warrendale, PA: Society of Automotive Engineers; 1975.

Soska KC, Robinson SR, Adolph KE. A new twist on old ideas: How sitting reorients crawlers. 2013 Manuscript under review.

Tobias, PV. The upright head in hominid evolution. In: Berthoz, A.; Graf, W.; Vidal, P., editors. The head-neck sensory motor system. New York: Oxford University Press; 1992. p. 5-16.

Uchiyama I, Anderson DI, Campos JJ, Witherington D, Frankel CB, Lejeune L, Barbu-Roth M. Locomotor experience affects self and emotion. Developmental Psychology. 2008; 44:1225–1231. [PubMed: 18793056]

von Hofsten C, Rosander K. Development of smooth pursuit tracking in young infants. Vision Research. 1997; 37:1799–1810. [PubMed: 9274766]

Walle EA, Campos JJ. Infant language development is related to the acquisition of walking. Developmental Psychology. in press.

Youdas JW, Garrett TR, Suman VJ, Bogard CL, Hallman HO, Carey JR. Normal range of motion of the cervical spine: An initial goniometric study. Physical Therapy. 1992; 72:770–780. [PubMed: 1409874]

Yu C, Smith LB. Embodied attention and word learning by toddlers. Cognition. 2012; 125:244–262. [PubMed: 22878116]

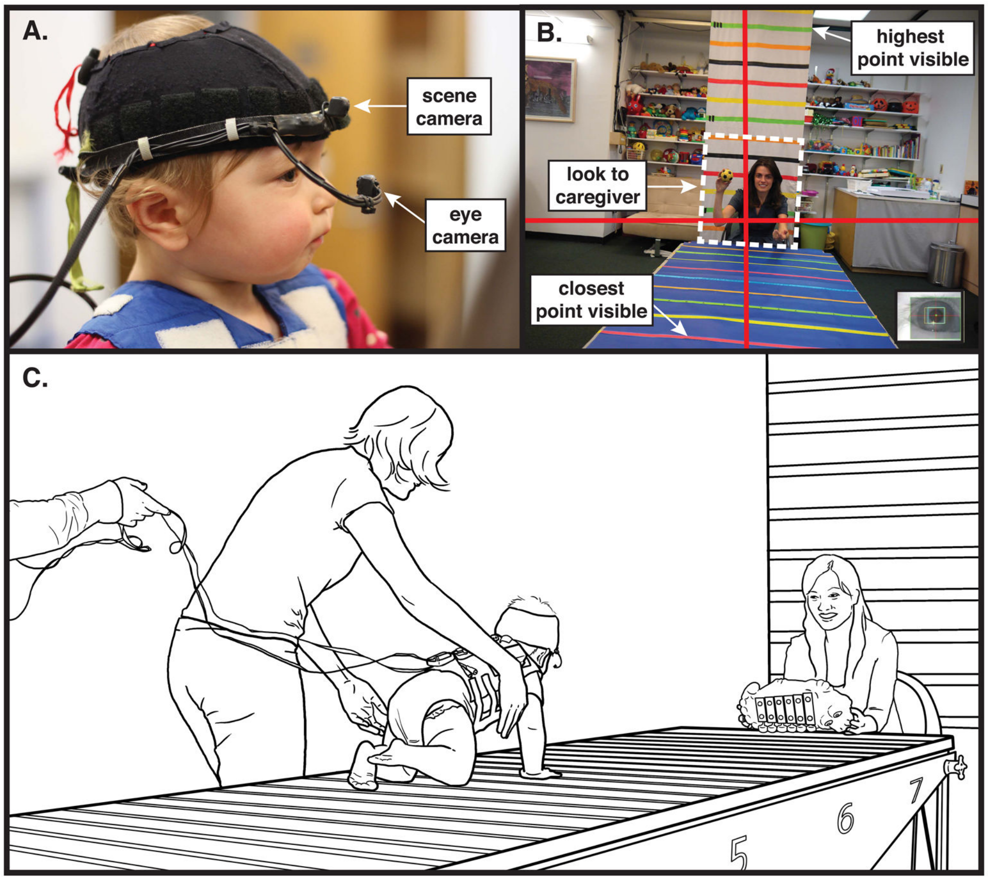

Figure 1.

(A) Infant wearing head-mounted eye-tracker. (B) Example gaze video frame exported from Yarbus software. Caregiver is pictured in the middle toy height condition. Red crosshairs indicate infant's point of gaze; white dotted line indicates gaze locations that were scored as looks to the caregiver. (C) Striped walkway and curtain apparatus. Caregiver is pictured in the low toy height condition. The experimenter followed behind infants to ensure their safety on the walkway and an assistant followed to keep the wires out of the way.

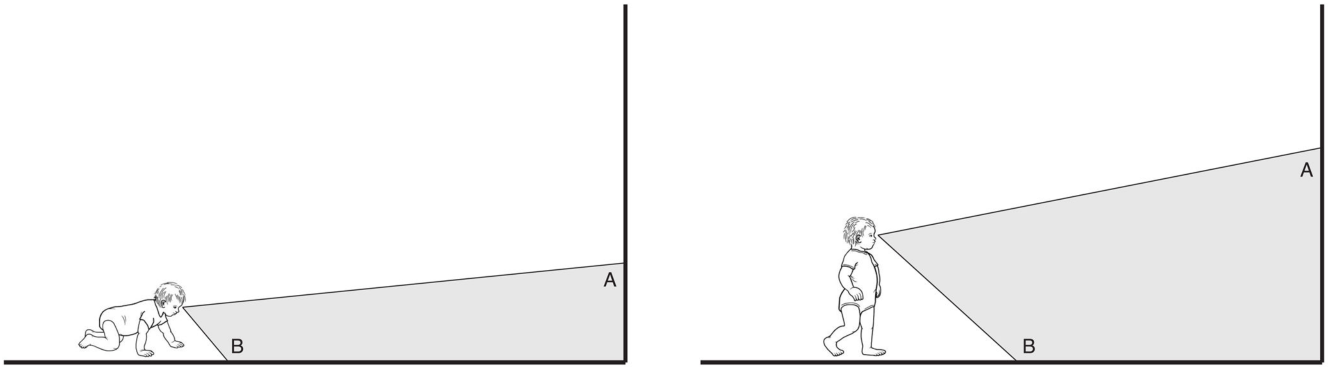

Figure 2.

Scale drawings of the boundaries of the scene camera field of view for crawlers and walkers. (A) Highest point visible. (B) Closest point visible. Dimensions were calculated using group means for the middle toy height condition.

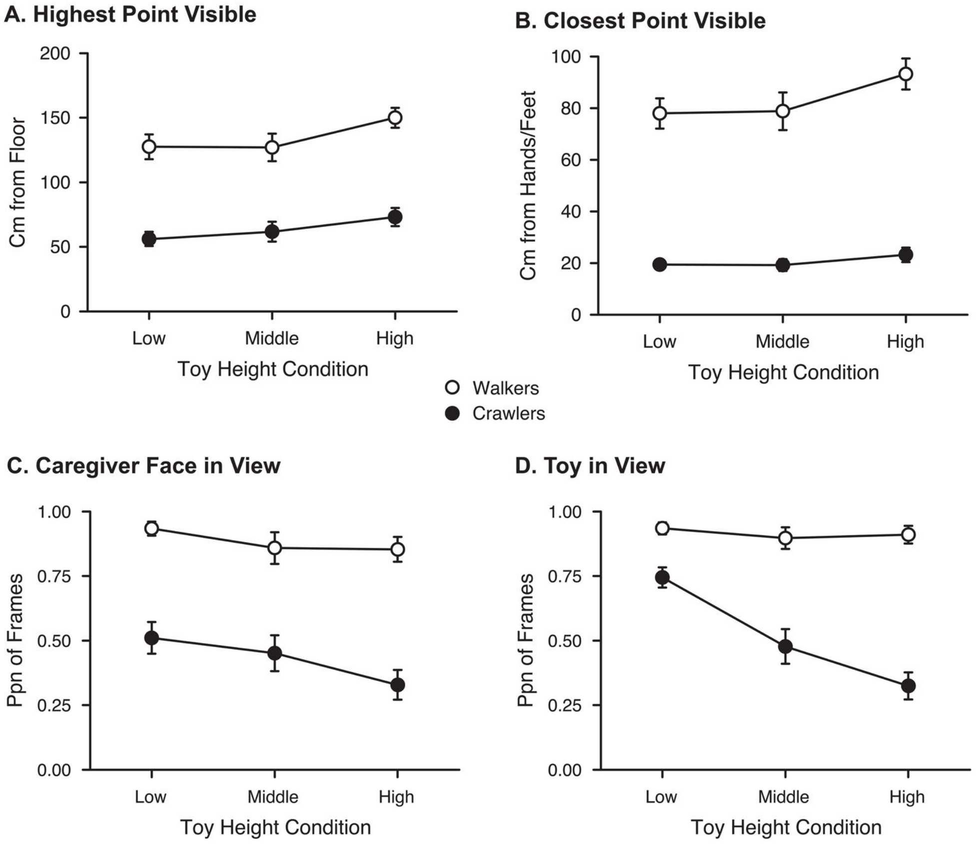

Figure 3.

Outcome measures by posture and toy height condition. (A) Highest point visible in the scene camera (in cm from the floor). (B) Closest point visible from the scene camera (in cm from the infant). (C) Proportion of steps where the caregiver's face was visible in the scene camera. (D) Proportion of steps where the toy was visible in the scene camera. Error bars denote standard errors.

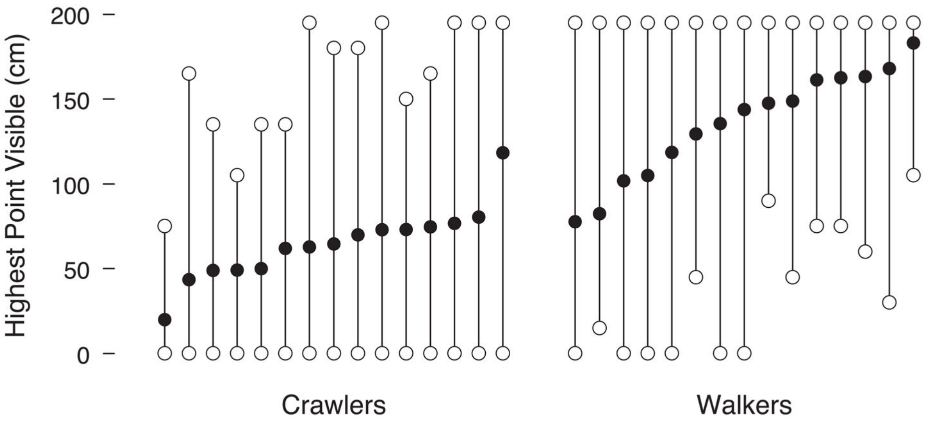

Figure 4.

Individual ranges for the highest point visible. Each line represents one infant. Open circles denote minimum and maximum values, and filled circles denote mean values.

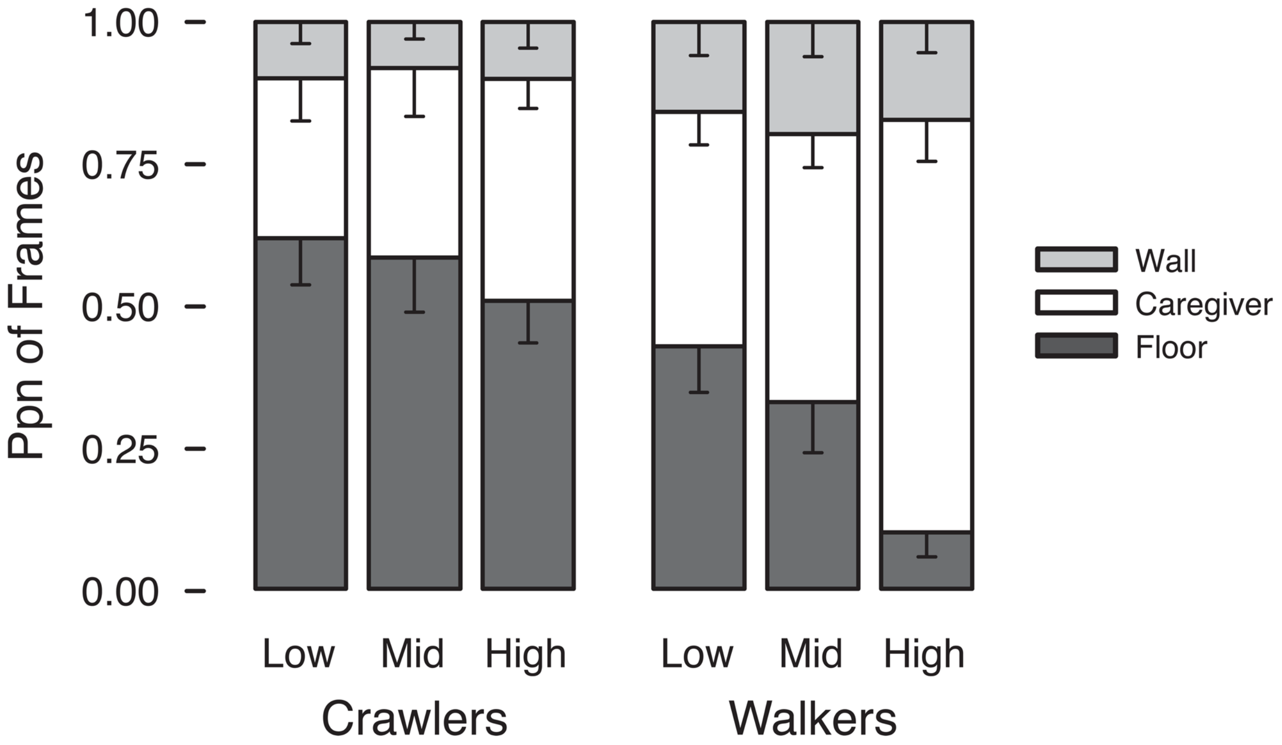

Figure 5.

Proportion of video frames where eye gaze was directed toward the floor (dark gray), the caregiver (white), and the wall behind the caregiver (light gray), by posture and toy height condition.

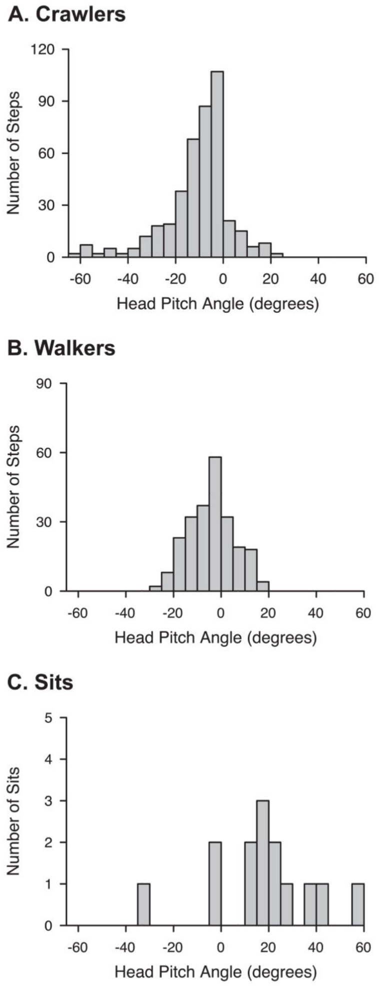

Figure 6.

Distribution of head pitch angle measurements pooled over infants and trials for (A) crawlers, (B) walkers, and (C) crawlers while sitting.

Table 1

Wald χ^2 Values for All GEE Model Effects

Variable	**Posture**	**Toy Height Condition**	**Posture × Condition**
Highest point visible	52.84^{**}	40.19^{**}	0.45
Closest point visible	112.35^{**}	26.34^{**}	7.56^{*}
Face in view	46.17^{**}	12.62^{**}	1.75
Toy in view	77.95^{**}	12.30^{**}	5.99^{*}
Looking toward floor	5.81^{*}	16.09^{**}	8.18^{*}
Looking toward caregiver	$3.31^{\#}$	10.02^{**}	$5.55^{\#}$

Note.

$^{\#}p < .07$.

$^{*}p < .05$.

$^{**}p < .01$.