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Visually guided navigation: Head-mounted eye-tracking of natural locomotion in children and adults

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A B S T R A C T

The current study showed that visual fixation of obstacles is not required for rapid and adaptive navigation of obstacles. Children and adults wore a wireless, head-mounted eye-tracker during a visual search task in a room cluttered with obstacles. They spontaneously walked, jumped, and ran through the room, stepping up, down, and over obstacles. Both children and adults navigated adaptively without fixating obstacles, however, adults fixated less often than children. We discuss several possibilities for why obstacle navigation may shift from foveal to peripheral control over development.

1. Introduction

In a little known study published in an obscure Russian volume on sport, physiologist Aleksei N. Krestovnikov demonstrated that expert athletes can perform skilled actions without central vision, but they are severely hampered without peripheral vision (Graybiel, Jokl, & Trapp, 1955; Krestovnikov, 1951). Glasses with black circles glued to the center of each lens occluded central vision and goggles with protruding tubes occluded peripheral vision. Without central vision, slalom skiers easily managed a 150-m course, javelin throwers hurled their javelins far distances, and figure skaters executed neat spiral patterns on the ice. Without peripheral vision, skiers veered hopelessly off course, javelin throws fell short, and skating patterns were erratic. These results are remarkable because one might have expected the opposite: Visual acuity is greatest in the fovea (the 2° region centered in the retina) and declines rapidly in the periphery of the retina (Burbeck & Yap, 1990; Hochberg, 1978; Levi & Klein, 1996). Consequently, the resolution of information available for visual guidance of action varies widely depending on centrality or eccentricity relative to the point of fixation.

Perhaps Krestovnikov's study has languished for so long because a long history of laboratory researchers have touted the role of foveal vision in guiding action (e.g., Prablanc, Echallier, Komilis, & Jeannerod, 1979). Using a new head-mounted eye-tracking technology, the current study provides confirmatory evidence that foveal vision is not required to navigate obstacles adaptively. Moreover, we found that foveal vision plays a surprisingly minor role in visual guidance of locomotion under normal viewing conditions in children and adults.

2. The role of foveal vision in limb placement

Visual information is critical for planning and guiding locomotion. Visual information provides advance notice about the size, composition, and location of obstacles in the environment so that we can control locomotion prospectively (Adolph & Eppler, 1998; Gibson, 1958). Outside the laboratory, visual exploration is active. Eye movements are voluntary—we choose where to point our eyes. Observers obtain visual information by orienting the body, head, and eyes to bring relevant features of the environment into view (Kowler, 1990; Land, 2004). Guiding foot placement while navigating obstacles and maneuvering the hand while reaching and grasping require a high degree of spatial accuracy. Consequently, it seems reasonable to assume that limb placement depends on observers directing their gaze to obstacles and objects so as to take advantage of the superior resolution of foveal vision.

Accordingly, laboratory studies of reaching show that restricting foveal vision incurs a cost. Contact lenses that occlude foveal vision disrupt reach trajectory and grip formation (Sivak & MacKenzie, 1990). Results are similar when participants reach for targets presented in the periphery of the visual field: Maximum grip aperture increases linearly with target eccentricity, meaning that grasps become less efficient when objects are seen from far out in the periphery (Ma-Wyatt & McKee, 2006; Schlicht & Schrater, 2007).

Studies of voluntary direction of eye gaze while reaching provide converging evidence for the critical role of foveal vision. Using

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head-mounted eye-trackers so that participants could move freely, researchers showed that adults spontaneously fixate objects during self-guided reaching tasks. While planning and guiding manual actions—preparing a cup of tea (Land, Mennie, & Rusted, 1999), making a peanut–butter sandwich (Hayhoe, Shrivastava, Mruczek, & Pelz, 2003), and washing their hands (Pelz & Canosa, 2001)—adults spontaneously fixate objects before reaching to them (Hayhoe & Ballard, 2005; Land & Hayhoe, 2001).

As in reaching, guiding the foot up, down, or over an obstacle would seem to require foveal vision. Foot placement must be precisely scaled to the height and extent of the obstacle. During stair descent, for example, adults' foot clearance (distance between sole of the foot and the edge of the step) may be as little as 3.7 mm (Simoneau, Cavanagh, Ulbrecht, Leibowitz, & Tyrrell, 1991). Errors in foot placement can be costly—falls while ascending or descending stairs account for the greatest proportion of fall-related fatalities (Startzell, Owens, Mulfinger, & Cavanagh, 2000). Moreover, visual information prompts preparatory muscle activations that precede foot placement (Craik, Cozzens, & Freedman, 1982). Stepping without vision (Buckley, MacLellan, Tucker, Scally, & Bennett, 2008), with blurred vision (Buckley, Heasley, Twigg, & Elliott, 2005), or monocular vision (Cowie, Braddick, & Atkinson, 2008; Hayhoe, Gillam, Chajka, & Vecellio, 2008) disrupts the trajectory of the foot as it approaches the obstacle.

As with manual actions, to describe spontaneous visual exploration under free-viewing conditions, participants must wear a head-mounted eye-tracker. In laboratory tasks where participants were instructed to walk, trial after trial, over a single obstacle, they fixated a raised platform on 83% of trials before stepping onto the obstacle (Di Fabio, Zampieri, & Greany, 2003) and they fixated a barrier in the path on 78% of trials before stepping over the obstacle (Patla & Vickers, 1997). Fixations ended before foot placement, often 2–3 steps in advance, providing feedforward information about the obstacle.

In contrast to Land and Hayhoe's (2001) classic studies using head-mounted eye-tracking during self-guided manual actions, researchers have not yet measured the contribution of foveal vision during *natural* locomotion. Actions in the real world are spontaneous and self-generated, unfolding in a context of varied and overlapping tasks and goals. To our knowledge, there is no locomotor analog to the natural reaching studies conducted by Land and Hayhoe (2001). A description of spontaneous visual exploration during unconstrained locomotion would bear on the generalizability of laboratory findings regarding visual guidance of obstacle navigation.

3. The development of obstacle navigation

Like all actions, visual guidance of limb placement develops. Part of the developmental problem is biomechanical—acquiring the strength and balance to hoist an arm against gravity or to maintain balance on one leg while swinging the other leg forward. And part of the problem is perceptual—steering the hand to the object or navigating the foot over the obstacle.

The start-and-stop, speed up-and-slow down pattern of infants' first reaches led early researchers to speculate that the jerky kinematics were due to visually guided corrections of the reach trajectory (e.g., White, Castle, & Held, 1964). Later work questioned whether visually guided reaching is a myth (Clifton, Muir, Ashmead, & Clarkson, 1993): Infants begin reaching in the light to a visible object and reaching in the dark to a glowing object at the same age and their reaches in the dark are equally fast and successful compared with reaching in the light. Only infants' precision reaching (e.g., for a tiny bite of food) appears to require continual visual guidance of the hand (Carrico & Berthier, 2008).

However, even under the best of conditions, infants' reaches are not comparable to those of adults. Children do not achieve adult levels of manual control, as determined from the reaching kinematics, until 10–12 years of age (Kuthz-Bushbeck, Stolze, Johnk, Boczek-Funcke, & Illert, 1998), and visual feedback may be the critical factor. Five- to six-year-old children rely more on visual feedback of the hand's movement to correct errors in the trajectory of the reach. With their eyes closed, children's reaching trajectories are more disrupted than in adults.

Obstacle navigation also involves a long developmental course. Modeled after the adult work where participants repeatedly encounter an obstacle in their path, numerous laboratory studies with infants and children have examined visually-guided locomotion over and under barriers (Schmuckler, 1996; van der Meer, 1997), across gaps in the surface of support (Adolph, 2000; Adolph, Berger, & Leo, in press), and down cliffs, slopes, and stairs (Adolph, 1997; Cowie, Atkinson, & Braddick, 2010; Kretch, Karasik, & Adolph, 2009). Novice infant walkers fare poorly, frequently tripping over barriers and falling over the edge of a drop-off. But their failings do not stem from lack of visual information. Visual contact with an obstacle—as scored from video recordings—does not ensure adaptive obstacle navigation. Even after experimenters tell infants to "look at this slope," or "see this gap," newly walking infants make visual contact with the obstacle and then plunge over the brink.

By 14–18 months of age, when most infants have a few months of walking experience, they cope with obstacles more adaptively, walking successfully over slopes, bridges, drop-offs, and barriers, and scaling their attempts to the size of the obstacle (Adolph & Berger, 2006). By 3–4 years of age, children scale the amplitude of their steps to the height of stair risers and they perform similarly to adults under full viewing conditions (Cowie et al., 2010). But with their eyes closed, children's steps were not positioned as adaptively as those of adults. However, researchers compared conditions of full vision to no vision. How foveal and peripheral vision contribute to guiding children's steps is unknown.

In collaboration with Positive Science (www.positive-science.com), our lab recently developed a head-mounted eye-tracking system that allowed us to observe infants' spontaneous eye movements during self-initiated obstacle navigation (Franchak, Kretch, Soska, Babcock, & Adolph, 2010; Franchak, Kretch, Soska, & Adolph, in press). Infants walked through a room cluttered with obstacles while playing with toys and their mothers. To our surprise, infants fixated obstacles only 72% of the time before stepping up, down, or over obstacles—a fixation rate less frequent than the 78–83% reported for adults in previous studies (Di Fabio et al., 2003; Patla & Vickers, 1997). Moreover, infants' low fixation rate did not reflect poor performance: They were no more likely to trip or fall when they did not fixate obstacles, suggesting that they guided locomotion adaptively using peripheral vision.

These results call into question the high fixation rates in previous work with adults. It seems unlikely that infants use vision more efficiently than adults. An alternative explanation is that task demands in previous research with adults led to high fixation rates. Participants were in a laboratory setting with a single obstacle and instructed to step on or over it—where else would they look? If adults do use vision more efficiently than infants, they should fixate obstacles less often when tested under similar free-viewing conditions.

4. Current study

This study is the first to describe spontaneous visual exploration during self-initiated locomotion. Participants wore a wireless, head-mounted eye-tracker that allowed us to measure visual behaviors during free, unfettered locomotion. One aim was to compare foveal versus peripheral guidance of obstacle navigation. We modeled the study after Hayhoe and Land's (Land & Hayhoe, 2001) previous work on natural vision and manual action while making a sandwich or a cup of tea. Similarly, we created a task context that encouraged self-initiated obstacle navigation—a "scavenger hunt" in which participants walked freely to search for star stickers in a large room filled with various platforms and barriers. Thus, participants charted their own paths through the room, choosing if and when to navigate obstacles. Like Patla's and Di Fabio's laboratory studies of visually-guided locomotion (1997, 2003), we scored fixations of obstacles before participants stepped up, down, or over them, and compared the frequency of encounters guided by foveal versus peripheral vision. If locomotion is guided similarly to manual action, participants should fixate obstacles during their approach. However, we also entertained the possibility that spontaneous visual exploration during self-guided locomotion might look more like Krestovnikov's slalom skiers wearing occluder goggles that prevented visual fixations.

The second aim of the study was to examine age-related changes in visually-guided locomotion by comparing 4–8-year-old children with adults. Comparing both age groups to infants from our previous study allows us to anchor the role of foveal vision in obstacle navigation across the lifespan. By 5–7 years of age, children are indistinguishable from adults on standard measures of walking skill (Bril & Breniere, 1992; Sutherland, Olshen, Biden, & Wyatt, 1988). However, as in manual actions, children may be more reliant on visual information for planning and guiding locomotion adaptively (Cowie et al., 2010). If so, children might spontaneously fixate obstacles more often than adults. Furthermore, if children, like infants, rely on feedback from foveal vision, they may have shorter latencies between fixation and foot contact because they cannot cope with a long delay between vision and action.

5. Method

5.1. Participants

Six children (4.7, 6.4, 7.6, 7.9, 8.0, and 8.2 years of age) and eight adults (20–22 years of age) participated. Sex was balanced in each age group. Adults received $10 or course credit as compensation and children received a framed photograph of their participation in the study.

5.2. Head-mounted eye-tracker

Participants wore a Positive Science (www.positivescience.com) ultra-light head-mounted eye-tracker (Fig. 1), which consisted of a headgear, wireless transmitter, and battery pack (total weight = 375 g). Children were told they were wearing a "robot costume" and this ensured their ease with the apparatus. The eye-tracker headgear contained a miniature, infrared *eye camera* focused on the participant's right eye and a miniature *field of view camera* (54.4° horizontal by 42.2° vertical) mounted above the right eye that recorded the world from the participant's perspective. A small infrared emitting diode (IRED) on the headgear illuminated the eye. The eye-tracker wirelessly transmitted videos of participants' right eye and approximate field of view to a computer running Yarbus software (Positive Science).

Yarbus software calibrated the eye-tracker and calculated gaze direction online during the task. Participants fixated a matrix of nine known points to calibrate the eye-tracker. The points were presented 1.5 m away and distributed across the central 27° of the visual field. The software calculated gaze angle based on pupil location and corneal reflection, and superimposed a crosshair over the scene camera view to indicate gaze direction. The temporal resolution of the eye-tracker was 33.3 ms (one video frame) and the spatial resolution was previously determined to be 1.5°. After calibration, the participant fixated the points again to verify that the

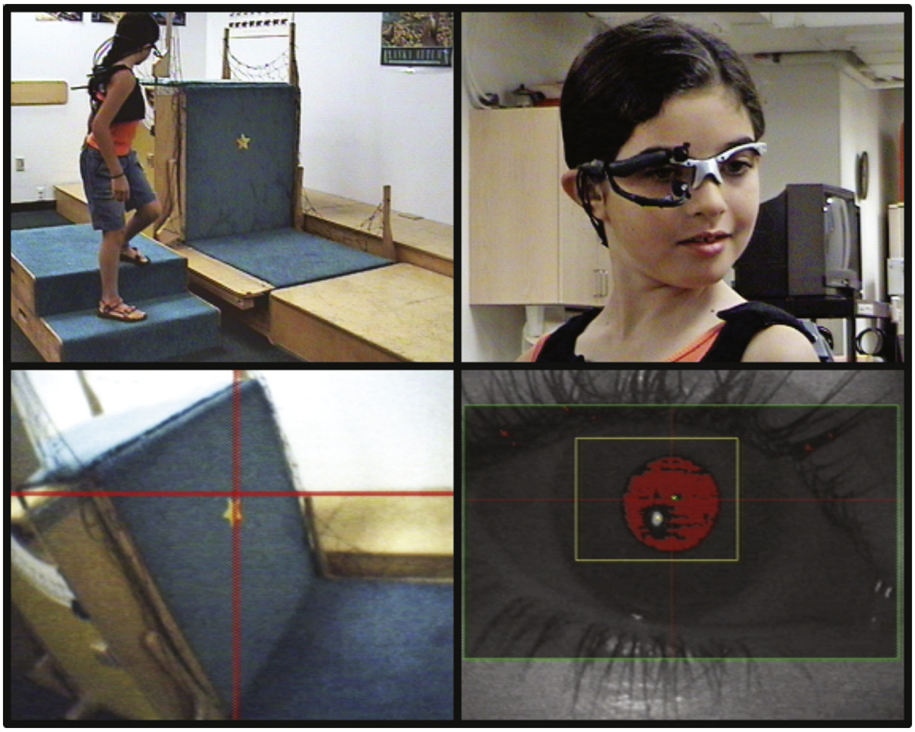

Fig. 1. Head-mounted eye-tracker. Top panels show a child wearing headgear, wireless transmitter, and battery supply. Bottom-left panel shows the image from the field of view camera with observer's gaze direction indicated by a red crosshair. Bottom-right panel shows the image from the eye camera.

maximum spatial error was less than 1.5°; if not, the calibration procedure was repeated. A second computer digitally captured the gaze video along with three other video feeds: Two fixed cameras recorded wide views of the room, and a third, hand-held camera captured a close-up third person view of the participant.

5.3. Procedure

After calibration, children and adults completed a scavenger hunt in a 6.3 m by 8.6 m room cluttered with obstacles and barriers (Fig. 2A). Traversable obstacles varied in height from 4.4 to 63.8 cm and included platforms, stairs, rails, and a slide (Fig. 2B). The room also contained numerous large barriers (>70 cm high) that prevented participants from viewing the whole room at once and required them to steer a complex path as they searched high and low for stars. Participants were instructed to find 30 star stickers, each 10 cm in diameter, and to place them into a basket. They searched freely without time constraint.

5.4. Data coding

We scored all behaviors from digital video using a computerized video coding system, OpenSHAPA (www.openshapa.org). Obstacle encounters began at the moment the foot landed on a surface of a different height (*stepping up* onto an obstacle and *stepping down* from an obstacle) or landed on a surface of the same height after passing over a raised surface (*stepping over* an obstacle).

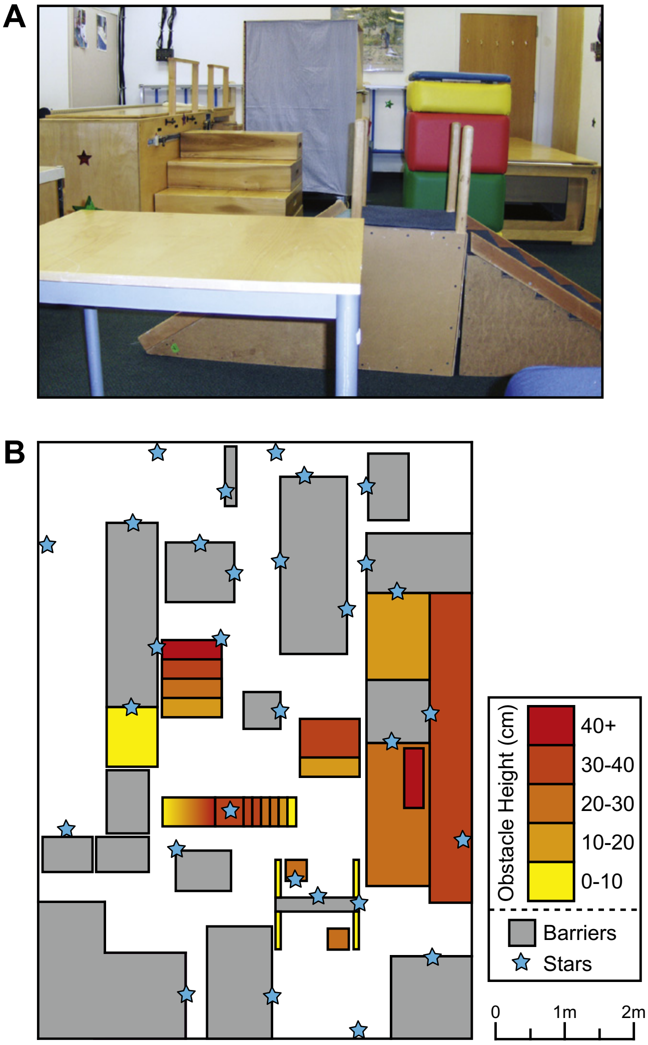

Fig. 2. Cluttered testing room from child's perspective. (B) Topographical map of room, drawn to scale. Impassable barriers are depicted in gray; traversable obstacles are colored according to obstacle height. Locations of star stickers are marked by blue stars.

We defined fixations as three or more video frames (99.99 ms) of stable gaze (within a radius of 3°), following the criteria used in previous investigations of eye movements during locomotion (Patla & Vickers, 1997). Because of the spatial accuracy of the eye-tracker, saccades less than 3° may not have been detected. To determine if obstacles were fixated within the 5 s prior to encounters, the coders searched backwards, frame-by-frame from the moment of the obstacle encounter, until finding a fixation on the obstacle or arriving at the edge of the 5-s window. Thus, each obstacle fixation identified by the coders was the final obstacle fixation before the encounter. If no fixation was scored in the 5-s window, then participants did not acquire foveal information of the obstacle during the approach. Note, although foveal vision may "sweep over" the obstacle during a saccade, participants could not have gathered information during such episodes because perceptual experience is suppressed during saccades (Matin, 1974). The criterion for obstacle fixations was generous—any fixation that fell on the landing surface within 1 step of the actual point of footfall was counted. Coders scored fixations for stepping over an obstacle if the obstacle was fixated rather than the landing surface. Coders scored star fixations any time a star sticker was fixated while still on the wall or surface where it was placed; fixations of the stars once they were in participants' hands were not included.

During data collection in the child sample, we encountered occasional tracking losses due to wireless signal interference. To be conservative, we excluded 24 obstacle encounters where no fixation was found due to tracking loss greater than one video frame (33.33 ms) during the 5-s period. We excluded three encounters with fixations from temporal analyses due to tracking loss greater than one frame between the fixation and the encounter because there might have been a fixation nearer to the event.[1]

We corrected the interference issue before collecting data with adults. However, eye-tracking with adults presented a different problem: Because adults had a much higher vantage point than children, we were unable to detect some looks to obstacles on the floor when obstacles were near the feet. As is the case with all video-based eye-tracking systems, the eyelid and eyelashes obstruct the pupil and corneal reflection when the eye is pointed down past a certain degree of rotation. To ensure a conservative estimate of obstacle fixations, we counted obstacle fixations if the eyes moved below the range of eye-tracker during the approach (coded from the eye video). These "looks downs" accounted for 61.4% of adults' obstacle fixations.

If participants fixated an obstacle, we coded the number of steps back from the obstacle when the fixation was initiated. The footfall defining the encounter was considered "step 0" (Fig. 3) and each previous step was considered "step 0–*n*". For example, if an obstacle was fixated 1 step back, the fixation occurred during the swing phase as the foot approached the obstacle.

We scored peripheral visual information in the same way as obstacle fixations, but scored whether obstacles were present anywhere in the field of view camera. Since the 54.4° (horizontal) by 42.2° (vertical) field of the camera spans a small region of the binocular visual field, 200° (horizontal) by 130° (vertical) (Harrington, 1981), our measurements underestimate what is actually present in the visual field. We played videos backwards from the moment of the encounter until the obstacle was in view anywhere in the field of view video. Thus, we coded the last frame during which

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[1] Without accounting for missing data, children fixated obstacles before 52.8% of encounters. However, removing missing data did not change the direction or significance of any effects.

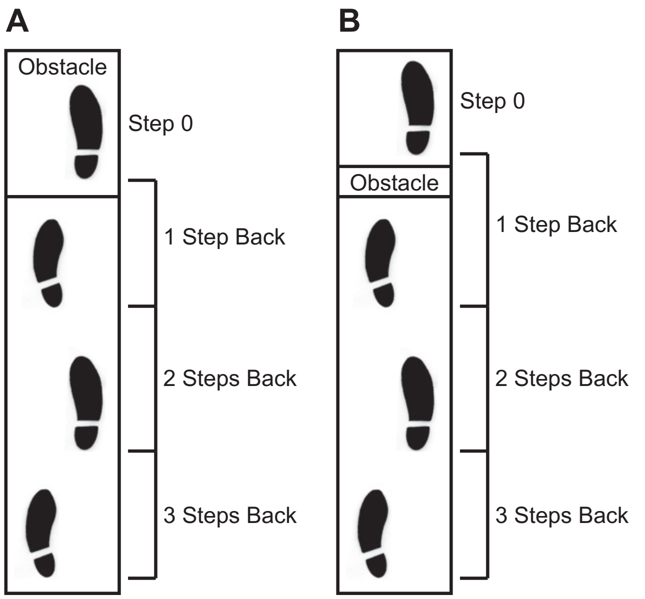

Fig. 3. Schematic diagram of footfalls leading to an encounter (A) up onto or down from an obstacle and (B) over an obstacle.

the obstacle was in view before the encounter. Similar to coding obstacle fixations, any point on the obstacle within 1 step's length of the footfall was considered viewing the obstacle. We determined steps back from the obstacle for peripheral vision in the same manner as steps back for obstacle fixations.

A second, reliability coder scored 100% of encounters independently of the primary coder. Agreement for categorical variables in the 5-s interval preceding obstacle encounters (occurrence of obstacle fixations, whether obstacles were visible in the periphery, type of walking step, trips/falls) was >93%. Correlations between primary and reliability coders' durations for timing variables (fixation initiations and terminations, latencies between fixation events and steps over obstacles, latencies between obstacles appearing in the periphery and steps over obstacles) were >.92. All disagreements between coders were resolved through discussion.

6. Results

6.1. Rapid, adaptive navigation

Children and adults moved rapidly through the room, walking, running, leaping, pivoting, and climbing, spontaneously charting their own paths and navigating obstacles of their own choosing. Adults completed the scavenger hunt in $M = 242.7$ s ($SD = 99.5$), significantly faster than children ($M = 527.5$ s; $SD = 255.5$), $t(6.15) = 2.59$, $p = .04$ (Table 1). Children accrued significantly more encounters with obstacles ($M = 38.2$; $SD = 13.1$) compared to adults ($M = 23.4$; $SD = 5.4$), $t(12) = 2.91$, $p = .013$. The rate of obstacle encounters did not differ between age groups ($p = .3$). Collapsed across both age groups, participants displayed $M = 2.9$ step-ups/min ($SD = 2.2$), $M = 2.5$ step-downs/min ($SD = 1.8$), and $M = 3.5$ step-overs/min ($SD = 2.2$). Participants dealt with obstacles adaptively: Adults never tripped or fell in 184 obstacle encounters; two children tripped and one fell in 195 obstacle encounters.[2]

Table 1
Means and standard deviations for locomotor and visual behaviors.

	Age group	
	Children	Adults
Locomotor behaviors		
Task completion time (s)	527.5 (255.0)	242.7 (99.5)*
No. of obs. encounters	38.2 (13.1)	23.4 (5.4)*
Obs. encounters rate (per min)	5.0 (2.3)	6.2 (2.1)
Foveal vision		
% of obs. fixated	58.9 (9.2)	31.2 (19.1)**
Obs. fixation duration (s)	0.26 (0.04)	0.20 (0.03)
Star fixation duration (s)	1.08 (0.08)	0.53 (0.07)***
Peripheral vision		
% of obs. in FOV	96.2 (3.7)	86.1 (10.9)
FOV termination (s)	1.14 (0.37)	1.91 (0.24)***

Note: *SD* indicated in parentheses. Abbreviations: Obs. = obstacle, FOV = field of view.
* $p < .05$.
** $p < .01$.
*** $p < .001$.

6.2. Obstacle fixations

Children and adults did not consistently rely on obstacle fixations to plan steps up, down, or over obstacles. For example, one child leapt down from a 22-cm high platform while scanning for a star target and never looked down at the ground (see Supplementary Movie 1). Children fixated obstacles in the 5 s interval before stepping during only $M = 58.9\%$ ($SD = 9.2$) of encounters, suggesting that peripheral vision may be sufficient for planning and guiding obstacle navigation. Adults produced even fewer fixations than children ($M = 31.8\%$ of obstacles, $SD = 20.1$), $t(10.6) = 3.51$, $p = .005$ (Table 1). At the extreme, one adult navigated 23 obstacles and fixated only 2 (8.7%).

We found no effect on fixation rate based on whether participants stepped up, down, or over obstacles. One child never stepped over an obstacle and was excluded from statistical analyses. A 2 (age) × 3 (step type) ANOVA showed no effects for age or step type, $p > .05$. Collapsed across age groups, participants fixated obstacles before $M = 57.0\%$ ($SD = 5.9$) of steps up, $M = 48.1\%$ ($SD = 8.4$) of steps down, and $M = 39.1\%$ ($SD = 9.8$) of steps over. However, it is possible that an effect would have been found with a larger sample size.

6.3. Timing of obstacle fixations

When children fixated obstacles, they initiated the fixations $M = 1.72$ s ($SD = 0.19$) before the encounter, $M = 3.2$ steps ($SD = 0.2$) in advance (Fig. 4). Adults timed their fixations earlier than children, $M = 2.24$ s ($SD = 0.51$) before the encounter, $t(9.4) = -2.65$, $p = .025$. But adults initiated fixations roughly the same number of steps away from obstacles, $M = 3.0$ steps ($SD = 0.6$), $p = .325$, presumably because adults' step frequency was slower.

Foveal vision provided feedforward, not feedback, information for guiding foot placement—fixations seldom ended after the foot landed on or over the obstacle. Only two of children's and one of adults' obstacle fixations accompanied the final footstep (1.2% and 0.5%, respectively). Children's fixations ended $M = 1.45$ s ($SD = 0.23$) before the encounter and $M = 2.8$ steps ($SD = 0.2$) away from the obstacle. Similar to fixation initiation, adults terminated fixations earlier than children, $M = 2.04$ s ($SD = 0.56$), $t(9.7) = -2.72$, $p = .022$. But adults' fixations ended $M = 2.6$ steps ($SD = 0.7$) away from obstacles, not significantly different than children's, $p = .711$.

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[2] Of the three failed obstacle encounters, two were preceded by prospective fixations. Despite fixating the obstacle one step away for .45 s, one child caught his foot on an obstacle as he stepped over. Another child fell as he tried to climb onto a platform even though he fixated the platform for .30 s 5 steps in advance. Only one failed encounter could possibly have resulted from lack of fixation—one child tripped while stepping over an obstacle. Most likely, these trips resulted from errors in motor execution rather than impoverished visual information.

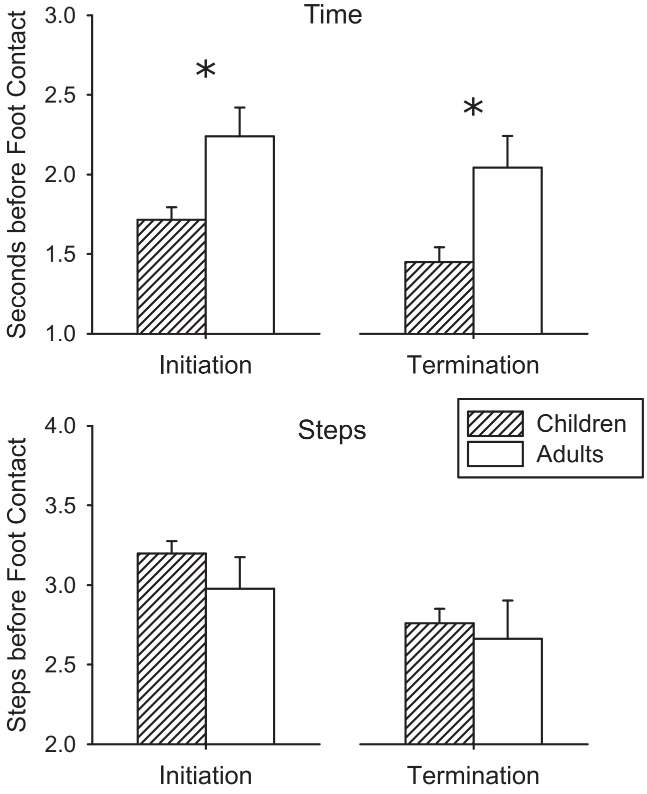

Fig. 4. Mean fixation initiation and termination times for children and adults. Top panel shows fixation timing measured in seconds. Bottom panel shows fixation timing measured in steps.

6.4. Peripheral vision of obstacles

We used the eye-tracker's field of view camera as a rough approximation of the visual field. Obstacles were visible in the 5 s before navigating obstacles on *M* = 96.2% (*SD* = 3.7) of children's and *M* = 86.1% (*SD* = 10.9) of adults' encounters. The proportion of obstacles visible in children's and adults' periphery was marginally different, $t(12) = 2.06$, $p = .062$. For children, obstacles remained in the field of view camera until *M* = 1.14 s (*SD* = 0.37) before the encounter. For adults, obstacles left the field of view camera significantly earlier compared to children, *M* = 1.91 s (*SD* = 0.24) before the encounter, $t(12) = -4.74$, $p < .001$.

However, these differences must be taken with caution: Because the field of view camera only records 20° below horizontal, the bottom 45° of the periphery is beyond the limits of the field of view camera, consequently, less of the ground surface is visible in the field of view camera than is present in participants' peripheral vision. As such, our reported numbers necessarily underestimate how often and for how long obstacles are in the periphery.

6.5. Duration of fixations

Participants distributed visual attention very differently between stars and obstacles. Fixations lasted three times longer, on average, for stars (*M* = 0.81 s, *SD* = 0.05) than for obstacles (*M* = 0.23 s, *SD* = 0.02), and children's fixations to stars (*M* = 1.08 s, *SD* = 0.08) were longer than adults' fixations (*M* = 0.53 s, *SD* = 0.07). A 2 (age) × 2 (target) ANOVA confirmed main effects for age, $F(1, 12) = 30.30$, $p < .001$, and target, $F(1, 12) = 117.22$, $p < .001$, moderated by an age × target interaction, $F(1, 12) = 20.25$, $p = .001$. Simple main effects of age showed no difference in the duration of obstacle fixations in children (*M* = 0.26 s, *SD* = 0.04) and adults (*M* = 0.20 s, *SD* = 0.03), $p = .175$, but confirmed longer fixations by children to stars compared with adults, $F(1, 12) = 30.51$, $p < .001$.

7. Discussion

The current study provides the first report of spontaneous eye movements in children and adults during self-initiated locomotion through a cluttered environment. Coping with obstacles was frequent, requiring participants to lift and lower their feet in a relatively precise manner to step up, down, and over obstacles in their path. In 41% of children's and 68% of adults' obstacle encounters, participants guided locomotion adaptively without fixating the obstacles. Like Krestovnikov's expert skiers and figure skaters, we demonstrated that ordinary pedestrians can navigate obstacles without relying on foveal vision—presumably using peripheral vision and/or memory to guide locomotion.

Our findings resolve the discrepancy between adults' high rate of fixations of obstacles in laboratory studies and infants' lower rate of fixations while locomoting freely. During self-guided locomotion in the current study, adults relied less on foveal vision than children, who in turn, relied less on foveal vision than infants observed in previous work (Franchak et al., in press).

7.1. The role of foveal vision in obstacle navigation

In contrast to laboratory studies of obstacle navigation (Di Fabio et al., 2003; Patla & Vickers, 1997), adults only fixated obstacles on 32% of encounters. However, there is no way to ascertain the function of these fixations. Since stars were scattered throughout the room, some obstacle fixations likely served visual search rather than locomotor planning functions. Furthermore, over 60% of adults' obstacle fixations were coded from "looks down" beyond the field of view camera's bounds, so we cannot determine if adults actually fixated obstacles in those instances. Thus, 31.8% is likely an overestimate of how frequently adults fixate obstacles before stepping, and might be as low as 15% (if looks down are excluded). Regardless of the exact number, it is clear that adults must have relied on an information source other than foveal vision; we argue that peripheral vision is the most likely candidate.

It comes as no surprise that peripheral vision may be sufficient for controlling some aspects of locomotion. Translation and rotation of the body produce changes in the speed and direction of optic flow falling over the entire visual field (Gibson, 1950), and peripheral vision comprises most of the area of the visual field. Walkers use optic flow in the periphery to control the direction of heading, speed of locomotion, and upright balance (Stoffregen, Schmuckler, & Gibson, 1987; Warren & Hannon, 1988; Warren, Kay, Zosh, Duchon, & Sahue, 2001). Self-generated motion can allow walkers to extract 3D information about obstacles in the environment.

What's new is our demonstration that peripheral vision is sufficient for precisely guiding foot placement during obstacle navigation. A small deviation in foot trajectory might result in participants tripping on the obstacle. But our participants did not. Unlike Krestovnikov's elite sport sample, we demonstrate that peripheral vision supports adaptive obstacle navigation during typical pedestrian locomotion in both children and adults. Moreover, our results are based on spontaneous visual exploration, not vision restricted by goggles or contact lenses, indicating that peripheral vision might be more than a mere "backup" system for when foveal vision is unavailable. Adults, more often than not, chose to navigate without fixating obstacles.

The importance of peripheral vision is also well attested by deficits in clinical populations. Our results are mirrored by clinical cases of vision loss that show differential effects of restricting central and peripheral vision on skilled motor action. Patients with loss of central vision due to macular degeneration navigate through the environment with little disruption (Hassan, Lovie-Kitchin, & Woods, 2002). In contrast, patients with loss of peripheral vision—so-called "tunnel vision"—due to retinitis pigmentosa have great difficulty moving through the world, often stumbling and bumping into obstacles in their paths (Geruschat, Turano, & Stahl, 1998).

A reasonable criticism of our claim regarding the important role of peripheral vision and subsidiary role of foveal vision is that participants could have used memory of obstacle height and location during previous fixations to guide foot placement a while later. Indeed, prior viewing of obstacles from previous encounters could be recalled in subsequent obstacle encounters. Although we cannot exclude this possibility, it seems unlikely that visual memory alone can account for the low rate of obstacle fixations in the 5 s prior to the encounters. Participants navigated obstacles that they had never previously fixated or even seen in the field of view camera (partly due to the large barriers blocking full view of the room), and we found no difference in the rates of obstacle fixations during the first and second half of the session. Also, because obstacles varied in height, past experience with one obstacle could not help on encounters with a different obstacle. Furthermore, memory of obstacle dimensions is subject to rapid decay over time; accuracy of foot placement for remembered targets suffers even when visual information is available just 3 s before step initiation (McCarville & Westwood, 2006). In contrast, peripheral vision of obstacles is ubiquitous, and peripheral information is available when it is most needed—during the approach to the obstacle.

If participants are able to rely on peripheral vision to navigate obstacles, what accounts for the high rates of obstacle fixations in previous laboratory studies? It is unlikely that the locomotor tasks in previous studies were more demanding—participants walked repeatedly over a single obstacle of intermediate (and predictable) height. Most likely, previous studies overestimate the rate of obstacle fixations because participants had no reason to look at anything other than the obstacle.

Previous studies of natural vision show that observers predominantly direct their eyes towards task-relevant locations (Hayhoe & Ballard, 2005; Hayhoe et al., 2003; Land & Hayhoe, 2001; Land et al., 1999; Pelz & Canosa, 2001). In other words, people look at what they are doing. In contrast to the previous laboratory studies of obstacle navigation where stepping over the obstacle was participants' primary aim, obstacle navigation in the current study was a subsidiary goal to finding star stickers in the scavenger hunt. The search task may have drawn participants' visual attention from the task of navigating obstacles. Indeed, fixations of star stickers lasted longer than fixations of obstacles. Although a feasible solution for coping with multiple tasks is to distribute visual resources based on task priority (Sprague & Ballard, 2003), our participants often chose to focus on the search task at the exclusion of others. They frequently used foveal vision to scan the room while weaving between barriers and obstacles that they never fixated.

We do not claim, however, that the low rate of fixations in this study should be taken as a gold standard for the frequency of fixations during self-initiated locomotion. Instead, these data argue that visual exploration should be considered with respect to a given task and environment. How frequently observers look to a target area depends on task goals and the allure of the surrounding environment. Under less demanding circumstances (e.g., more familiar obstacles), fixation rates may have been lower. Under more demanding conditions (hiking on rocky terrain, hopping from stone to stone across a river), fixation rates may have been higher.

Furthermore, foveal vision may have provided a benefit to walking precision too subtle to detect. Previous studies with adults have found that decreasing visual certainty by having participants view obstacles in a monocular condition prompted participants to walk slower and raise their feet higher when stepping onto obstacles (Hayhoe et al., 2008). However, we did not measure foot clearance—our only outcome measure for walking accuracy was tripping and falling. Possibly, walking on large, stationary obstacles did not require high precision to avoid trips and falls. Future research should compare foot clearance when navigating obstacles that have been fixated compared to those seen only in peripheral vision. Similarly, although patients with macular degeneration may not have much difficulty navigating large, well-marked obstacles, they may lift their feet higher when navigating obstacles compared to individuals with no visual deficit.

7.2. What develops

Our current findings, taken together with our prior investigation of infants (Franchak et al., in press), reveal an age-related progression in visually-guided locomotion. From infancy to adulthood, obstacle navigation shifts from foveal to peripheral control: Infants fixated 72% of obstacles, children fixated 59%, and adults fixated 32%. We offer several explanations that might account for these age-related changes in visual exploration.

First, previous research has documented that children rely on visual feedback more than adults (Cowie et al., 2010; Shumway-Cook & Woollacott, 1985). Children stepping down from a platform scale their steps accurately with full vision but have difficulty when their eyes are closed. Children may have fixated obstacles more often than adults because foveal vision bolsters movement accuracy. Although fixations almost always ended before foot placement for both age groups, children terminated obstacle fixations nearer to the moment of foot contact than adults: Children may not be able cope with a long delay between fixation and footfall.

Second, guiding navigation peripherally meant that participants could devote foveal vision to scanning the room to locate the star stickers. Adults' lower obstacle fixation rates might mean that they distributed visual attention more efficiently than children. Children's long fixations of star stickers may indicate a lack of efficiency. Star stickers were large and stationary—a brief glance to the target should be sufficient for participants to steer to the correct location in the room. Yet, children kept their eyes on the stickers for long periods of time, which could have interfered with searching for subsequent targets. More efficient use of visual resources may have helped adults complete the task more quickly than children.

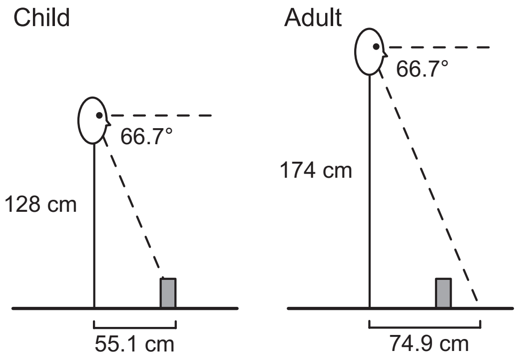

Fig. 5. Theoretical effects of height on the lower bound of the visual field for child and adult observers looking straight ahead. Heights are CDC 50th percentiles for 8-year-old girls and 20-year-old women. Gray rectangles represent 20-cm obstacles located 45 cm in front of the feet, visible to the child but not the adult.

A third possibility is that differences in body dimensions account for both the rate and timing of fixations. Specifically, changes in eye height necessarily affect what information is available in the visual field, because eye height is inversely related to the extent of the lower boundary of the periphery (Fig. 5). With the head at the same angle and on level ground, the lower bound of the field of view extends farther from the feet for individuals who are taller—every 5 cm increase in height increases the "blind spot" in front of the feet by 2.15 cm. This might mean that adults have less opportunity to fixate obstacles during the approach. Indeed, our measurements from the field of view camera confirm this notion: Obstacles were present in the field of view camera slightly less often for adults and disappeared from view earlier compared to children. Children's higher rate of obstacle fixations may reflect a greater opportunity to view obstacles, simply because they are shorter than adults. Similar logic may also account for why participants across both age groups fixated obstacles more frequently when stepping up than down—a step up always occurs on a surface that is higher in the visual field.

Observers are opportunistic. Participants readily fixate objects when they are present in the field of view, but are less likely to fixate objects if it requires a turn of the head (Ballard, Hayhoe, & Pelz, 1995). Likewise, when descending a flight of stairs, adults often glance down when they are 3 or more from the bottom, but rarely do so when they are only 1 or 2 steps away, purportedly because looking down would require a head tilt (Rosenbaum, 2009). But what's wrong with tilting the head down? In the current study, participants searched for star stickers scattered throughout the room. Keeping the head tilted down would hinder participants' ability to scan the room for the stars, which were placed on the walls, never on the floor.

The timing of obstacle fixations might similarly depend on differences in body dimensions. Although adults fixated obstacles earlier than children when measured in absolute time, both children and adults initiated and terminated fixations the same number of steps away from the obstacle. Children have shorter legs than adults and take smaller steps. If children fixate the obstacles 3 steps away, they will be closer to reaching the obstacle than adults. Shorter lags between fixation and footfall for children may simply reflect closer proximity to the obstacle rather than a deficit in visual guidance.

Because of the unconstrained nature of our study, we cannot easily distinguish between these three possibilities. Most likely, participants' reliance on visual feedback, attentional efficiency, and body dimensions all play a role in accounted for differences in visual exploration of obstacles. Children may depend more on visual information for guiding foot placement, but eye-height differences provide a very simple way to account for these age-related changes. One intriguing possibility is that infants and children rely more heavily on foveal vision because they do not have to turn their heads to see obstacles. Gains in height may catalyze the development of peripheral navigation—children may literally "grow out of" guiding locomotion foveally.

8. Conclusion

The current study demonstrates that even in a complex navigational task in a cluttered environment, perceptual-motor control can be achieved flexibly. Both child and adult walkers can fixate obstacles from 3 steps away, or might forgo obstacle fixation altogether and rely on peripheral information or memory. However, from infancy to adulthood, walkers increasingly rely on peripheral vision to navigate obstacles. Flexible and efficient allocation of visual and attentional resources allows observers to use foveal fixations to support high-level tasks while guiding navigation "under the radar" using other informational sources.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.visres.2010.09.024.

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