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Head-mounted eye-tracking of infants' natural interactions: A new method

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Abstract

Currently, developmental psychologists rely on paradigms that use infants' looking behavior as the primary measure. Despite hundreds of studies describing infants' visual exploration of experimental stimuli, researchers know little about where infants look during everyday interactions. Head-mounted eye-trackers have provided many insights into natural vision in adults, but methods and equipment that work well with adults are not suitable for infants—the equipment is prohibitively big and calibration procedures too demanding. We outline the first method for studying mobile infants' visual behavior during natural interactions. We used a new, specially designed head-mounted eye-tracker to record 6 infants' gaze as they played with mothers in a room full of toys and obstacles. Using this method, we measured how infants employed gaze while navigating obstacles, manipulating objects, and interacting with mothers. Results revealed new insights into visually guided locomotor and manual action and social interaction.

Keywords: Head-mounted eye-tracking, infants, natural vision

1 Introduction

1.1 Tracking Gaze during Natural Behavior

Over-reliance on highly controlled laboratory tasks runs the risk of jeopardizing the validity of the research. In typical studies, perception is divorced from function and context. Participants view displays on a computer monitor while sitting in an office chair. However, outside the lab, people perceive the world as they move through it. Visual information is obtained, not imposed. People choose where to look.

Head-mounted eye-tracking methods provide a good solution for studying perception with the freedom of movement and variable contexts that characterize natural vision. Researchers can obtain precise measurements of eye movements during natural behaviors such as controlling gaze while driving a car [Land and Lee 1994], making a cup of tea [Land et al. 1999] or a sandwich [Hayhoe et al. 2003], washing hands [Pelz and Canosa 2001], playing table tennis [Land and Furneaux 1997] and cricket [Land and McLeod 2000], and walking through a room cluttered with obstacles [Franchak et al. 2009]. Findings from natural vision studies share a common theme: Eye movements are actions, and gaze control is closely linked to the task at hand. The idea that the eye is a passive organ that receives information is simply not true. Observers actively coordinate movements of the body, head, and eyes to bring relevant features of the environment in view [Land 2004].

Natural vision is especially relevant for studying eye movements in relation to motor actions and social interactions. Perception and action form a continuous loop: Perceptual information guides real-time actions, and movements generate new perceptual information for planning the next action [Gibson 1979]. Fixations of obstacles, objects, and people are potential sources of information for guiding locomotor, manual, and social actions. Modifying gait to navigate an obstacle, reaching for, grasping and manipulating an object, and communicating with others all depend on visual information.

Eye movements are an especially rich source of information for research in infant development. Looking is one of the first actions in infants' repertoires. Months before infants can talk, walk, or pick up objects, they can move their eyes to inspect interesting things in the world. Consequently, looking behaviors are the most frequently used measure in studies with infants. Where infants look and for how long supports inferences about infants' perception, cognition, and social development.

Despite half a century of reliance on infants' looking behaviors, researchers know little about infants' natural vision. A fundamental question remains unanswered: Where do infants look during everyday interactions? Methodological limitations have constrained the types of tasks that can be studied while recording infants' gaze. Desk-mounted eye-trackers are easy to use with infants [e.g., Aslin and McMurray 2004; Falck-Ytter et al. 2006; Johnson et al. 2003]; however, infants' movements are severely restricted and experimenters have to provide visual displays in a predefined space. Remote eye-trackers cannot track infants' gaze as they walk and turn their bodies in a large space. Recently, a number of research groups [Yoshida and Smith 2008; Yu et al. 2008] have approximated gaze tracking by affixing small, lipstick-sized "headcams" (small video cameras with a 90° field of view) to infants' foreheads. While wearing headcams, infants can move freely and interact with caregivers. Nonetheless, headcams are not eye-trackers. Infants (or adults for that matter) cannot attend to the entire visual field captured by the headcam and their attention constantly shifts between areas of the visual field.

1.2 Methodological Challenges to Mobile Eye-Tracking in Infants

Head-mounted eye-trackers used previously with adults—even the most portable models [Babcock and Pelz 2004]—are illsuited for studying infants: The equipment is too big, too heavy, and too uncomfortable. Infants' noses and ears are too small to support regular glasses. The combined weight of adult-sized headgear, video recorder or transmitter, and battery pack is relatively heavy and load carriage interferes with infants' precarious balance control [Adolph et al. 2003; Garciaguirre et al. 2007]. Comfort is imperative. Whereas adults can tolerate bulky, unwieldy equipment, infants are not so accommodating. Anyone who has ever dressed a baby understands the struggle; matters are only worsened when trying to get infants to wear something on their head or face. Each component of the eye-tracker must be precisely positioned to ensure a good calibration. If the eye-tracker is too difficult to adjust quickly, infants will become bored or irritated and refuse to cooperate. Typical calibration procedures are too demanding and time-consuming for infants' limited patience.

1.3 New Method for Tracking Infants' Gaze during Natural Interactions

In this paper, we outline a novel methodology for recording infants' gaze during spontaneous movement. This is the first study to use a head-mounted eye-tracker with walking infants. In collaboration with Positive Science, LLC, we developed a lightweight and comfortable headgear, transmitter, and battery pack, and a procedure for placing the equipment on infants. New eye-tracking software facilitated a quick and flexible calibration procedure. Using this method, we recorded 6 infants' eye gaze while they played with their caregivers in a large room cluttered with toys and obstacles. Infants' and caregivers' interactions were spontaneously produced. Rather than imposing a task or providing specific stimuli, infants chose what to do and where to look. We focused our analysis on three areas of interest: where infants look during obstacle navigation, object exploration, and in response to mothers' vocalizations.

2 Eye-Tracker and Software

Figure 1 shows an infant wearing the Positive Science [www.positivescience.com] eye-tracking headgear. Like some adult eye-trackers [Babcock and Pelz 2004; Pelz et al. 2000], the headgear consists of two miniature cameras: an infrared eye camera that records the participants' right eye and a scene camera mounted above the right eye facing outward that records infants' view of the world. The field of view of the scene camera is 54.4° horizontal by 42.2° vertical. An infrared emitting diode (IRED) illuminated the infant's eye allowing for a dark-pupil tracking approach. Placement of the scene camera over the right eye minimized horizontal parallax. Because some infants' noses barely protrude from their heads, the headgear could not be mounted on eyeglasses. Instead, the cameras and IRED are mounted on a flexible, padded band that rests slightly above infants' eyebrows. Because their ears are small and bendy, the headgear could not hang on infants' ears. Instead, we attached the headgear to a stretchy spandex cap with Velcro tabs. This design secured the eye-tracker while infants moved, and also helped to prevent infants from removing the headgear. The entire headgear and cap weighed 46 g.

A single cable from the headgear connected to a wireless transmitter and battery pack (combined weight was 271 g). Wireless video transmission was essential to allow infants to move unfettered through the room. The transmitter and battery pack attached to a small fitted vest with Velcro tabs. Previous work showed that 14-month-olds fall an average of 16 times an hour, frequently on their face [Adolph et al. 2009]. Given that the eye-camera sat in front of infants' eye, a spotter held straps attached to the vest to ensure infants' safety by catching them if they fell forward (top panel of Figure 2). The spotter also dissuaded infants from touching or moving the headgear.

Figure 1 *Infant wearing the Positive Science eye-tracker*

Videos transmitted wirelessly to receivers mounted on the ceiling, providing good line-of-sight for the transmitter at any location in the room. The maximum distance between the transmitter and receiver was 9m, providing stable video signals within the system's transmission range. Direct line-of-sight and close proximity to the receivers greatly reduced video frame drops. We used Yarbus software designed by Positive Science to compute infants' gaze direction in real time from the two videos. Like other eye-tracking software, algorithms track both the pupil and corneal reflection simultaneously. Tracking both points provides a more robust track, but in cases where we failed to get a reliable corneal reflection, the software could default to pupil-only tracking. Figure 3 shows the layout of the default LiveCapture user interface of the latest version of Yarbus. The software digitally captured a video of the infants' field of view superimposed with a crosshair indicating gaze location (bottom panel of Figure 2).

3 Method

3.1 Putting Equipment on Infants

First, infants played with their mothers for 10 minutes to become comfortable in the playroom. Then, while the mother and an assistant played with the infants, an experimenter added the equipment piece by piece (vest, hat, headgear, transmitter). Pilot testing showed that infants were more likely to tolerate the equipment if they could walk around and play after each new piece of gear was added rather than confining them to their

Figure 2 *Top panel: View from the handheld camera that recorded mother-infant interactions. Bottom panel: Gaze video created using Yarbus software with inset eye image. Red crosshair indicates infants' gaze*

mothers' lap or a highchair. We let infants walk around for another few minutes before starting the calibration procedure. Our success rate for getting infants to wear the equipment was high: 6 of 8 infants tolerated the equipment, completed the calibration procedure, and generated over 20 minutes of data.

3.2 Calibration

We modeled our calibration procedure after infant studies that used desk-mounted eye-trackers. Infants sat on their mother's lap 60 cm from a large computer monitor. The monitor was mounted on an articulating arm, facilitating adjustments that situated the display in the center of infants' field of view. A *Muppets* video clip drew their attention to the monitor. "Attention-getters" were presented at the four corners or center of the screen to elicit eye movements. Between 3 and 8 points were registered in the software to calibrate the eye-tracker (a minimum of 3 are required).

After calibration, random attention-getters were presented across visual space to assess the quality of the calibration. The experimenter repeated the calibration procedure if the calibration was off by more than ~2°. Every infant that wore the tracker was successfully calibrated, and none required more than two calibration attempts. The eye-tracker was previously determined to have a spatial accuracy of 2°-3° with infants, and the sampling frequency of the eye-tracker was 30 Hz (the temporal resolution of the recorded video). The gaze video used in offline coding contained an inset image of the observer's eye (Figure 2, bottom panel), allowing coders to continually monitor how effectively the algorithm tracked the observer's pupil. Although the system's resolution is lower than standard desk-mounted systems, in natural settings the resolution is sufficient to determine the target of each fixation, and the slight decrease in accuracy is outweighed by the advantages of tracking infants during spontaneous play.

3.3 Participants and Procedure

Six 14-month-old walking infants (± 1 week) and their mothers contributed data to the final sample. Families were recruited through commercially available mailing lists and from hospitals in the New York Metropolitan area.

Infants played with their mothers in a large (6.3 m × 8.6 m) playroom filled with colorful toys (balls, dolls, etc.) to encourage infants to explore the room and manually explore different objects. Additionally, obstacles were placed around the room to challenge locomotion. Some obstacles were low enough for infants to walk onto or over (4 cm to 9 cm), and others were large (> 15 cm), forcing infants to crawl and climb. Mothers' instructions were simply to play naturally with their infants. They did not know that we were interested in locomotion, manipulation, or social interaction. An assistant followed infants around the room and recorded their actions on a handheld camera. A third, stationary camera mounted on a wall recorded the entire room. The video streams of infants' behavior were synchronized and mixed with the gaze video in Final Cut Pro.

4 Data Reduction and Coding

4.1 Exploratory Data Analysis

Video records of eye gaze and the accompanying locomotor, manual, and social interactions yield a huge amount of data. One drawback of head-mounted eye-tracking in an unconstrained natural environment is that automatic data coding is not feasible: The field of view is constantly in flux, and there is no limit on the number and type of objects to detect. The alternative, scoring every video frame by hand, is laborious and prohibitively time consuming. For example, the first 10 minutes of the 6 infants' sessions generated 108,000 unique video frames of behaviors. Thus, we conducted an initial, exploratory, sequential data analysis [Sanderson et al. 1994] on a subset of the data to determine what behaviors could be profitably scored in a full analysis.

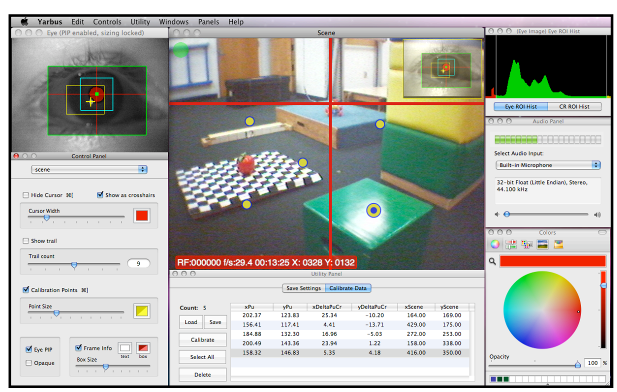

Figure 3 *Yarbus software layout in LiveCapture mode*

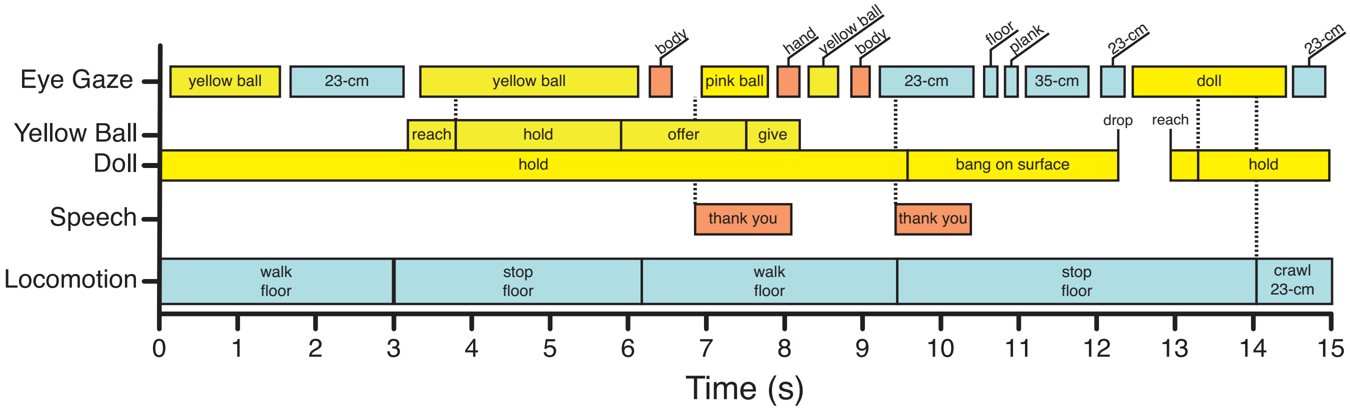

Figure 4 *Timeline illustrating 15 s of one infant's interactions with her mother. The top row shows the sequence of fixations—yellow bars are fixations of objects, blue bars are fixations of obstacles, and orange bars are fixations of the mother. The second and third rows indicate the infants' manual interactions with two different objects. The fourth row shows the mother's infant-directed vocalizations. The fifth row displays the infant's locomotor activity and the ground surface on which the infant is moving (floor or a 23-cm high obstacle). Vertical dashed lines mark the times when obstacle, manual, and social encounters were scored.*

We coded 60 s frame by frame of one infant's eye gaze, manual behavior, locomotion, and social interaction. The timeline shown in Figure 4 demonstrates the frequent and overlapping behaviors present in 15 s of activity. While holding a small doll in her hand, the infant walked over to a yellow ball and stopped to pick it up with her other hand. She walked over to her mother, held out the ball to offer it to her. The mother immediately responded with "Thank you, thank you." The mother took the ball, and the infant walked over to an obstacle and banged the doll on the obstacle's surface. She dropped the doll but reclaimed it immediately, then crawled onto the large (23-cm) obstacle while holding the doll in her hand.

Our exploratory analysis revealed that fixations fell neatly into three divisions: obstacles, objects, and people. Similar to previous studies with adults [Hayhoe et al. 2003; Land et al. 1999], eye gaze paralleled the ever-shifting task dynamics. The infant fixated objects before reaching for them and obstacles before navigating them. Mother's infant-directed vocalizations sometimes captured the infant's attention and elicited an eye movement toward her after the utterance. Although visual inspection of the timeline points to several potential links between gaze and behavior, a formal coding system was needed to objectively determine the role of eye movements in spontaneous interactions.

4.2 Event-Based Coding Scheme

We developed an event-based coding scheme to score if and when fixations occurred in relation to a set of predefined behaviors. The benefit of this coding system was to reduce the total number of frames of the eye gaze video that required manual coding. In brief, coders first scanned through the tapes to find key encounters of interest. Then, in a second pass, coders scored eye movements that were related to each type of encounter. Based on the initial scoring of encounters, MacSHAPA coding software [www.openshapa.org] allowed coders to automatically advance the video file to each encounter for subsequent coding of eye movements, thereby increasing coding efficiency. A reliability coder independently scored ≥ 25% of all behaviors. Agreement for categorical values ranged from 90% to 100% (kappas ranged from .79 to 1). Correlations for duration variables scored by the two coders ranged from r = .90 to .99, $p < .05$. All disagreements were resolved through discussion.

Specifically, the exploratory data analysis suggested that three types of encounters and visual fixations were of special interest: the times when (1) infants walked or crawled up, down, or over a surface of a different height; (2) infants' hands touched an object; (3) mothers spoke to the infants. We scored obstacle encounters at the moment that the leading limb (the foot when walking or crawling backwards, the hand for forward crawling) contacted the new surface. We scored manual encounters when infants' hands contacted objects or toys that could be lifted from the floor (not large objects like furniture or immovable objects affixed to the walls or floor). We only counted the first object touch during repetitive bouts during which touches of the same object occurred within 2 s of each other. We defined social encounters as any speech sound from mothers (laughing was not counted) directed toward infants separated by at least .5 s from the previous vocalization.

All three types of encounters were easy to detect while playing the video at full or nearly full speed, and these encounters set the initial framework for later coding. The 5 vertical dashed lines in Figure 4 indicate each of these key encounters.

The next step in coding was to score visual fixations. Coders identified fixations to obstacles and objects in the 5 s prior to obstacle and object encounters and to mothers in the 5 s following mothers' vocalizations. We counted an obstacle fixation if the gaze crosshair rested stably on the obstacle for 3 or more consecutive frames (100 ms). To avoid excluding any possible fixations of obstacles, we scored any fixation within a step's length of where infants actually placed their feet. If the infant fixated the surface multiple times in the 5 s period, we only counted the fixation that occurred closest to the moment of the encounter, as this was most likely to provide information relevant to locomotor guidance. Fixation initiation was scored from the start of that fixation until the moment of the encounter, and fixation termination was scored from the last frame of that fixation until the moment of the encounter. We scored infants' visual exploration of objects using a similar coding scheme: For each manual encounter, we scored object fixations in the 5 s prior to contacting the object with the hand. Because objects might be in motion (in mothers' moving hands) before infants reached for them, we included both fixations and smooth pursuit of objects, provided gaze was stable on the target for 100 ms. Smooth pursuits, however, were rare, and we will continue to refer to all of the coded visual behaviors as "fixations." As with obstacles, we counted only the last fixation before the manual encounter in the event of multiple fixations or smooth pursuits. We coded each time that infants fixated their mothers in the 5 s following the start of each vocalization. If infants fixated their mothers, we classified the location of each fixation as directed toward her face, hands, or body.

This coding scheme allowed us to address specific questions about infants' first person experiences without laboriously coding every video frame, reducing the data set by more than half: Coders only needed to score 52,471 of the total 108,000 frames.

5 Results

Because infants chose where to move in the room, what to play with, and whether to interact with mothers, all encounters were spontaneously produced. Fixations preceding and following encounters were—both in principle and in practice—not required. Figure 5 shows fixations relative to encounters for each of the 6 infants.

5.1 Visual Guidance of Obstacle Navigation

As infants walked and crawled through the room, they frequently encountered obstacles. Infants logged an average of 31.8 (SD = 13.3) obstacle encounters during the 10-minute play session. They readily switched between walking and crawling to navigate the various obstacles: They walked unsupported during 47.7% of encounters, walked holding onto a support (handrail, mother) 15.9% of the time, crawled hands-first 21.2% of the time, and crawled feet-first (backing or scooting) during 15.2%. Infants typically attempted to walk unsupported when confronting smaller obstacles (4 cm to 9 cm), reverting to crawling or supported walking when obstacles were large (> 15 cm), χ^2 (1, N = 151) = 15.37, p < .005; they walked on only 14.3% of large obstacles compared to 55.3% of small obstacles.

Circular points on Figure 5A show that each of the six infants occasionally navigated obstacles without fixating it in the prior 5 s (26% of obstacle encounters). Fixation rate differed depending on which of the 4 types of locomotor methods infants employed, χ^2 (3, N = 151) = 8.04, p < .05. Infants fixated 90.3% of obstacles when crawling hands-first, 75.0% of obstacles when walking unsupported, 62.5% of obstacles when walking with support, and 60.9% of obstacles when crawling feet-first. Most likely, the difference between feet-first and hand-first crawling depends on the position of the head relative to the obstacle: Feet-first crawling encounters most often occurred when infants crawled backwards down from a high surface.

Pooled across all locomotor methods, infants fixated obstacles before 74.0% of encounters. To put this number into perspective, our previous work showed that adults fixate obstacles before only 31.8% of encounters and 4- to 8-year-old children fixate obstacles before only 58.9% of obstacles in a similar free-locomotion task in the same playroom [Franchak et al. 2009]. Possibly, less experienced walkers rely more heavily on foveal vision, and learn to guide locomotion from peripheral vision as they become more adept.

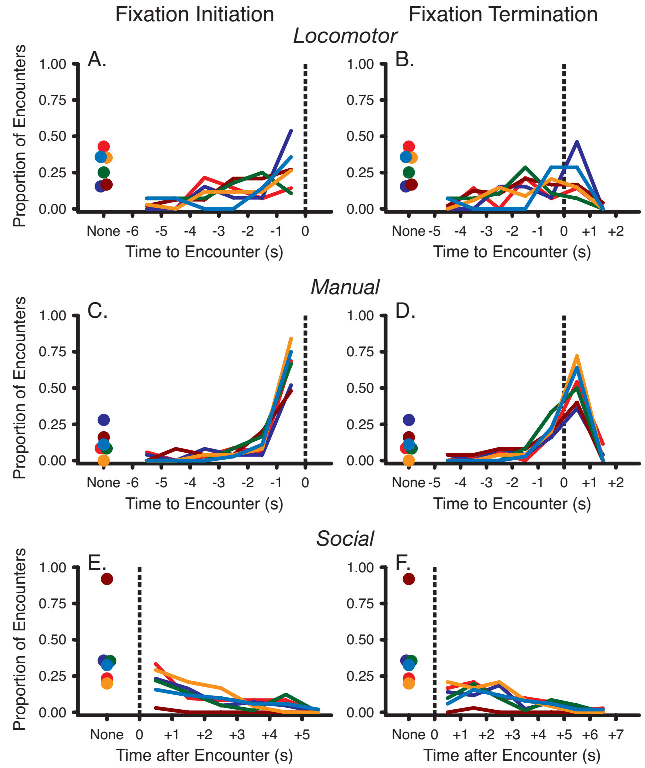

Figure 5 *Individual histograms for the initiation and termination times for each of the 6 infants' fixations for locomotor, manual, and social encounters. "None" refers to the proportion of encounters that infants did not fixate the target. Vertical dashed lines indicate the moment that defined each encounter.*

The 6 curves on Figure 5A show the time when each of the 6 infants initiated obstacle fixations prior to the encounter. On average, infants initiated obstacle fixations M = 1.9 s (SD = 1.4) in advance. However, the individual curves are relatively flat, revealing a wide range in timing between visual information of the obstacle and contact of the obstacle. Figure 5B shows when infants terminated obstacle fixations: Fixations lasted M = 0.62 s (SD = 0.62), and the average fixation ended M = 1.3 s (SD = 1.5) before limb contact. However, 25.9% of fixations ended after the limb landed on the surface. These fixations indicate that infants often use online visual guidance to guide their limbs to the surface—that is, they watched their foot step over the obstacle—in contrast to adults and children who always break fixation of obstacles at least one step in advance [Franchak et al. 2009; Patla and Vickers 1997].

5.2 Eye Movements during Manual Exploration of Objects

While exploring the room, infants found many attractive objects to pick up and manipulate, averaging 31.3 (SD = 5.3) object encounters in 10 minutes. Of the 182 total encounters, 51.1% of the time infants reached for and grasped objects, holding them in their hands. During the remaining 48.9% of encounters, infants touched objects without picking them up.

Overall, infants fixated 88.5% of objects before manual encounters, a significantly greater proportion than they did before obstacle encounters (74.0%), χ^2 (1, N = 332) = 11.6, p < .001. The circular points on Figure 5C show the proportion of encounters that each infant did not foveate objects. Reaching and grasping encounters were preceded by foveal vision more frequently (93.5%) than encounters when they simply touched objects (83.1%) without grasping them, χ^2 (1, N = 182) = 4.821, p < .05. Grasping an object requires precise motor control, so infants relied more often on visual information from the fovea when reaching to an object to pick it up.

The 6 curves on Figure 5C depict the distribution of each infants' fixation initiations. Infants fixated objects M = 0.88 s (SD = 0.32) before the hand made contact, significantly closer in time to the encounter compared to obstacle fixations, t(5) = 4.58, p < .01. In contrast to the inconsistent timing of obstacle fixations, all 6 infants' object fixation curves peak sharply at -1 s—76.4% of all fixations were made in the last second before the hand touched the object.

Figure 5D shows the distribution of times when infants terminated object fixations. Object fixations lasted M = 0.72 s (SD = 0.74), ending M = 0.16 s (SD = 1.05) after the hand touched the object. Similar to their fixation initiations, all 6 infants' fixation termination times showed a clear peak; 60.3% of fixations ended in the 1 s after contact. Infants' object fixations continued after the hand reached the object during 63.4% of encounters, a significantly greater proportion compared to obstacle encounters (25.9%), χ^2 (1, N = 273) = 33.14, p < .001 (compare the proportions of +1 s terminations in Figures 5B and 5D). This pattern of sustained visual guidance was more common for reaching and grasping movements (73.6%) compared to touching movements (51.4%), χ^2 (1, N = 182) = 8.50, p < .01, lending support to the idea grasping actions requires more visual guidance to execute successfully.

5.3 Infants' Visual Responses to Maternal Vocalizations

Infants decided when and how to encounter obstacles and objects in the environment, and actively gathered visual information in advance to plan and guide their actions. But many important sources of visual information about the world come from external sources: events that grab attention and prompt visual exploration. In particular, infants' looks may be elicited by social cues, such as mothers' infant-directed vocalizations. Mothers spoke to infants frequently: Infants heard M = 81.4 (SD = 27.5) utterances in 10 minutes for a total of 413 utterances.

We scored each time that infants fixated their mothers following an utterance. Infants were already looking at their mothers during 24.5% of their mother's utterances. We excluded these utterances from further analysis. Of the remaining 312 utterances, infants did not look at their mothers on 46.1% (circular points in Figure 5E)—a surprisingly large proportion given the emphasis in the social cognition literature on looking to mother to share reference of objects and events [e.g., Baldwin and Moses 1996; Moore and Corkum 1994]. Infants only fixated their mothers following 53.9% of their utterances. They rarely fixated their mothers' faces (16.2%). More often, infants looked at their mothers' hands (33.7%) or elsewhere on her body (50.0%). In contrast to headcam studies where infants "gazed" at mothers' hands and faces across the tabletop [Yu et al. 2008], when infants moved freely through the environment, fixations were primarily to mothers' bodies. Objects elicited fixations to mothers' hands: 72.5% of hand fixations occurred while mothers were holding objects. Infants' fixations to mothers were initiated M = 1.8 s (SD = 1.4) after mothers began vocalizing, suggesting that looks may merely indicate recognition of mothers' presence and location rather than a search for how they're feeling or the referent of their utterance. Indeed, many of mothers' utterances had no specific referent (e.g., "Good job," "Yeah, yeah," "Ooh"). However, response times ranged widely, as seen in Figure 5E. Fixations lasted M = 0.53 s (SD = 0.51), ending M = 2.3 s (SD = 1.5) after the vocalization onset (see Figure 5F).

6 Conclusion

We have presented a new method for studying infants' first person perspective using a wireless, head-mounted eye-tracker. The light and comfortable eye-tracker let infants crawl, walk, and play freely and naturally in a large room with their mothers. Our first look at mobile infants' eye movements revealed that infants frequently fixate obstacles and objects before encountering them. Unlike children and adults, infants occasionally watched their feet as they placed them on obstacles, relying on foveal vision online as they navigated obstacles. Infants most often guided manual actions using continual visual feedback, monitoring closely as their hands approached and contacted objects. Mothers spoke often to infants, but infants visually oriented towards their mothers following only half of the vocalizations. This first glimpse into infants' visual world—the real world of natural and unfettered interactions—provides an important first step in understanding visual guidance of action.

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