Head-mounted eye tracking

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Introduction

Infants' eye movements provide a rich source of information. Measuring real time *visual selection***,** where infants choose to look**,** can inform on skill level and psychological processes in perceptual, cognitive, social, and language tasks. The accumulation of *visual experiences* over development is also of psychological interest. How often infants see different visual stimuli may relate to rates of learning in a variety of domains. Many developmental studies employ remote eye trackers: High-speed cameras record infants' eye movements while they sit and watch stimuli displayed on a computer monitor (Aslin, 2011). Remote eye tracking is appropriate for studying visual selection in tasks that require precise control over the stimuli. However, studying eye movements in controlled, laboratory contexts cannot adequately inform on infants' visual selection in natural tasks or during their everyday visual experiences over development. In the real world, infants select what they see and they do so while mobile. Accordingly, understanding infants' vision in real world tasks requires measuring eye movements from infants' first-person view as they walk, crawl, reach, and play.

Head-mounted eye tracking addresses these concerns by measuring eye movements in a mobile observer. A long history of adult research using head-mounted eye tracking (see Hayhoe & Rothkopf, 2011; Land, 2009, for reviews) demonstrates that eye movements in real world tasks are driven by the observer's goals, not the visual properties of the scene. Observers fixate areas of the environment to support the requirements of ongoing actions and rarely look to task-irrelevant locations. They fixate curves in the road while driving, the teapot spout while filling a mug, and the future location of the ball while playing cricket.

Head-mounted eye tracking can provide similar insights about the characteristics of infants' eye movements in everyday tasks, but the method is new to developmental psychology.

This entry explains the basics of head-mounted eye tracking, highlights the unique challenges of infant studies, and discusses processing and analyzing eye tracking data.

Basics of head-mounted eye tracking

A head-mounted eye tracker records eye gaze using two miniature video cameras (Fig. 1A). As with remote eye trackers, infrared illumination of the eye is used to record a dark-pupil image and corneal reflection (*eye camera* in Fig. 1A). Whereas remote eye trackers record eye movements relative to stimuli on a computer display, head-mounted eye trackers employ a *scene camera* (Fig. 1A) to record the observer's first-person view. As observers move their bodies and heads, the scene camera captures the resulting changes to the observer's field of view. A calibration procedure linking pupil position from the eye camera to locations in the scene camera yields a record of observers' point of gaze within their first-person view (cross hair in Fig. 1A).

Head-mounted eye tracking with infants

Using head-mounted eye trackers with infants presents several methodological challenges. Until recently, commercially-available eye trackers were designed to be worn by only adults. Most models house the eye and scene cameras in rigid glasses frames or goggles that fit on adults' heads. Infants' heads are much smaller, so adult-sized headgears do not fit comfortably. Whereas a young child may be coaxed into wearing an adult eye tracker, infants cannot be reasoned with, nor do they respond well to physical discomfort. Calibration procedures are also more difficult to implement with infants because they do not respond to instruction. Attempts to use an adult eye tracker with infants have resulted in high subject attrition (64%), because infants did not tolerate wearing the equipment or comply with calibration procedures (Corbetta, Guan, & Williams, 2012).

These challenges have been overcome in a head-mounted eye tracking methodology adapted for infants (Franchak, Kretch, Soska, & Adolph, 2011). The first studies using this methodology reported relatively low attrition rates, ranging from 20% to 33% (Franchak *et al*., 2011; Kretch & Adolph, in press; Kretch, Franchak, & Adolph, 2014; Yu & Smith, 2013), demonstrating a marked improvement over using adult eye trackers with infants. The Positive Science system (www.positivescience.com) houses the eye and scene cameras on a flexible band that conforms to the size and shape of infants' heads instead of using rigid glasses frames (Fig. 1A). The headband attaches to a snugly fitting spandex hat with Velcro strips. The hat and headband, weighing only 46 g, are not too cumbersome. To prevent infants from grabbing the headgear during setup, an assistant distracts the infant with toys to keep the hands occupied while the experimenter places the equipment and adjusts the cameras. After setup, the experimenter conducts a short calibration procedure to link pupil positions to gaze locations in the scene camera view. As with remote eye tracking, attention-getting targets are shown at pre-specified locations to elicit infants' eye movements. Figure 1B shows a simple calibration apparatus: An assistant presents an attractive, sounding toy in each of the 'windows' to draw the infants' eye gaze. The calibration procedure takes less than a minute and can be repeated throughout a session to ensure data quality.

Researchers have successfully adapted the method to work in a variety of contexts. In mobile studies, such as free play, an experimenter wears a backpack with a recording laptop and follows the infant (Fig. 1C), allowing the infant to walk, crawl, and explore (Franchak *et al*., 2011). The experimenter holds straps attached to a harness to ensure that the infant does not fall and become injured while wearing the equipment. When locomotion is undesirable, such as in face-to-face play, infants sit and the eye tracking cables attach to a desktop computer (Yu &

Smith, 2013). Across contexts, eye movement time series can be synchronized with other data sources, such as third-person video of the infant's behavior, motion trackers (Franchak & Yu, 2015) and eye trackers worn by social partners (Kretch & Adolph, in press; Yu & Smith, 2013).

Data quality and processing

With any eye tracking methodology, researchers must pay careful attention to data quality. Eye tracking accuracy (viz., how closely the measured gaze location matches the observers' true gaze location) depends on a variety of factors. For infant head-mounted eye tracking, calibration quality and parallax error are of particular concern. First, infants do not always look at the calibration targets, and when they do look, they may fail to fixate them accurately. The resulting noise in calibration leads to less accurate eye tracking data for infants compared to adults, as with remote eye tracking. With compliant adults, head-mounted eye trackers can achieve accuracy of .5º to 1.0º, but accuracy in infants might vary from 1.0º to 3.0º. Consequently, researchers should design areas of interest (AOIs) with respect to eye tracking accuracy in infants (Aslin, 2011; Oakes, 2010).

Second, parallax errors affect the quality of head-mounted eye tracking data for any participant. The small offset between the location of the scene camera and the observer's eye creates a discrepancy in viewing angle to a target (Fig. 2). Calibration corrects for this discrepancy when targets are at the same distance as the calibration stimuli. However, parallax errors occur when viewing targets at other distances. The magnitude of error depends on the difference between target distance and calibration distance. Ideally, researchers should present calibration stimuli at the same distance as targets of interest. To study vision during manual behavior, calibration should be performed at arm's length, but to study parent-child interactions, calibration should be performed at the same distance as the parent. In a free-play context where observers may look at both near and far targets, calibrating at an intermediate distance (~4 feet) is an acceptable compromise.

Processing head-mounted eye tracking data raises additional complications, because observer head movements change the 'stimulus'. In contrast, the fixed displays used in remote eye tracking studies simplify data processing. For example, defining an AOI for a peanut-butter jar in a static photograph requires drawing a single rectangle (Fig. 3A). In a dynamic movie, the AOI must be defined for every video frame if the jar changes location. But for head-mounted eye tracking, the AOI must be defined for every frame *for each participant*. Each observer's unique sequence of head movements alters the location of the jar in the field of view (Fig. 3B). Data coding can be a time-consuming endeavor; using computer assisted coding software, such as Datavyu (www.datavyu.org) or GazeTag (www.positivescience.com), can speed up the process. In the future, computer vision techniques may automate AOI segmentation by using algorithms that can detect particular stimuli, such as hands and faces (Bambach, Franchak, Crandall, & Yu, 2014).

Analysis of head-mounted eye tracking data

For many applications, the unique analysis options afforded by head-mounted eye tracking outweigh the costs of intensive data coding. Crucially, recording gaze in mobile observers allows researchers to test whether eye movement results from screen-based tasks generalize to real world contexts. For example, remote eye-tracking studies show that by 6 months, infants spend over 50% of the time looking at faces while watching videos on a screen (Frank, Vul, & Johnson, 2009). However, infants fixate faces less frequently in real-world tasks. In so-called 'face-to-face play', 12-month-old infants spent only 11% of the time looking at their caregivers' face, but looked to objects 62% of the time (Yu & Smith, 2013). While exploring a room during free play, 14-month-olds only fixated their mothers' faces in response to 8% of the mothers' speech episodes (Franchak *et al*., 2011). Infants' short stature may contribute to low fixation rates to faces: Infants fixate their parent's face more often when the parent crouches or sits compared to when the parent stands upright. Indeed, face fixation rates become comparable to rates from screen-based tasks when infants are held up off the ground (Kretch & Adolph, in press).

In addition to analyzing the point of gaze, researchers can score scene camera videos to determine how often different types of stimuli occupy infants' field of view. Because head and body movements determine viewpoint, motor skills shape visual experiences. For example, faces are rarely in view when infants crawl, but are more often in view when infants sit or walk (Kretch *et al*., 2014). Moreover, researchers can link the presence or absence of stimuli in the field of view to gaze behavior: Infants fixate mothers more often when the mother is present in the infant's field of view at the onset of a speech episode (Franchak *et al*., 2011). Spatial regularities in where different stimuli reside in infants' view may predict looking behavior. During object play, parents' hands occupy a central location; whereas, parents' faces are squeezed at the top of infants' field of view (Bambach *et al*., 2014).

Conclusions

Head-mounted eye tracking is an emerging methodology for studying visual experiences generated by natural behavior. Three decades of research have revealed how optimally adults' eye movements are adapted to a wide range of everyday tasks. Now the onus rests on developmental psychologists to figure out how infants learn where to look to do the things they do. Moving beyond real-time behavior, head-mounted eye tracking is poised to allow researchers to measure the visual experiences in the natural environment that supports learning and development. Frequency of exposure to different types of visual stimuli may help to shape the developmental trajectories of cognitive, language, and social skills.

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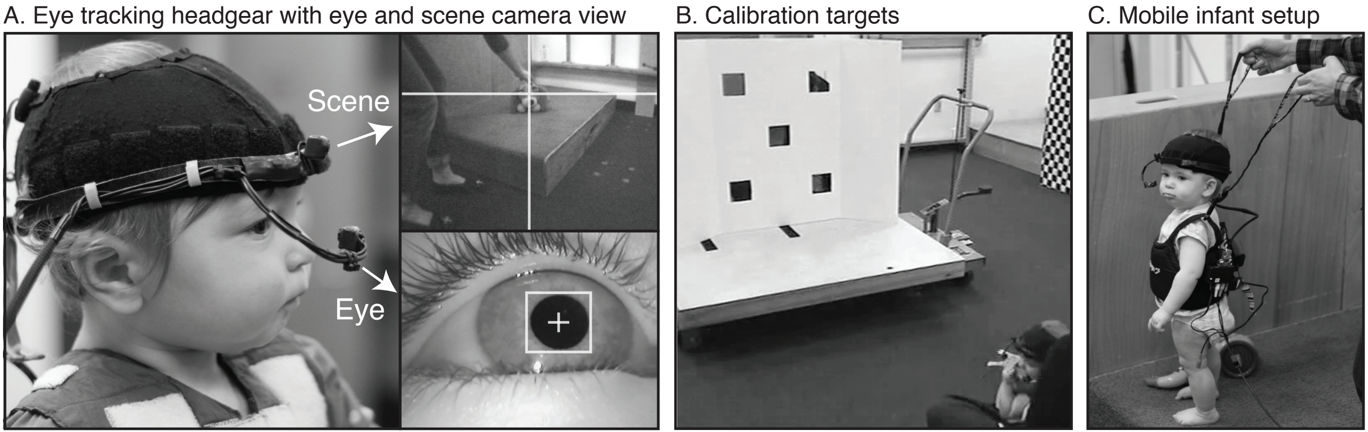
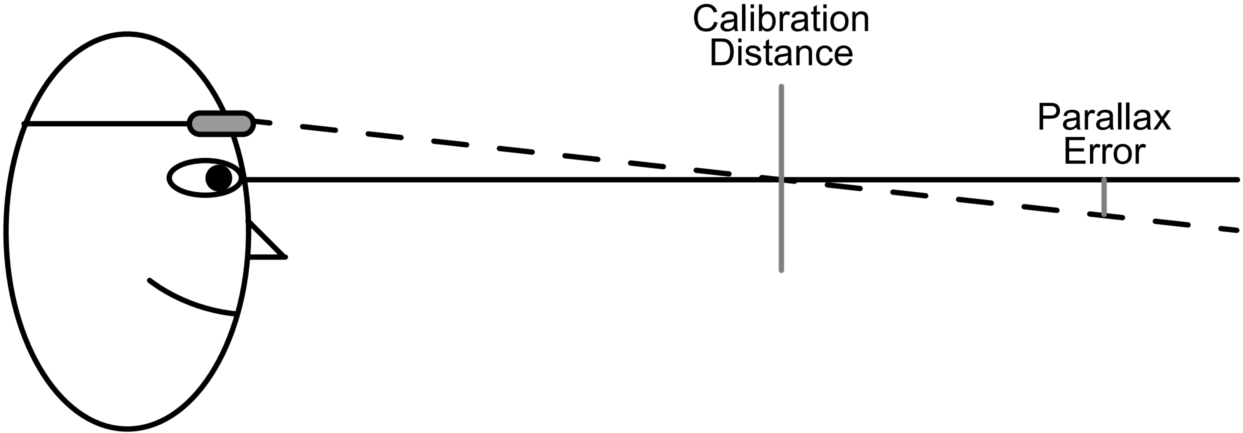
Figure Captions

Figure 1. Infant head-mounted eye tracking method. (A) Infant wearing hat and headgear. Headgear houses miniature eye and scene cameras. Scene camera view showing infant's first person perspective of a parent reaching for a toy (cross hair shows infant's point of gaze). Eye camera view showing detection of pupil (white rectangle). (B) Infant viewing calibration stimulus while an experimenter presents an attractive toy in different locations. (C) Mobile eye tracking setup with an experimenter following the infant with the recording laptop.

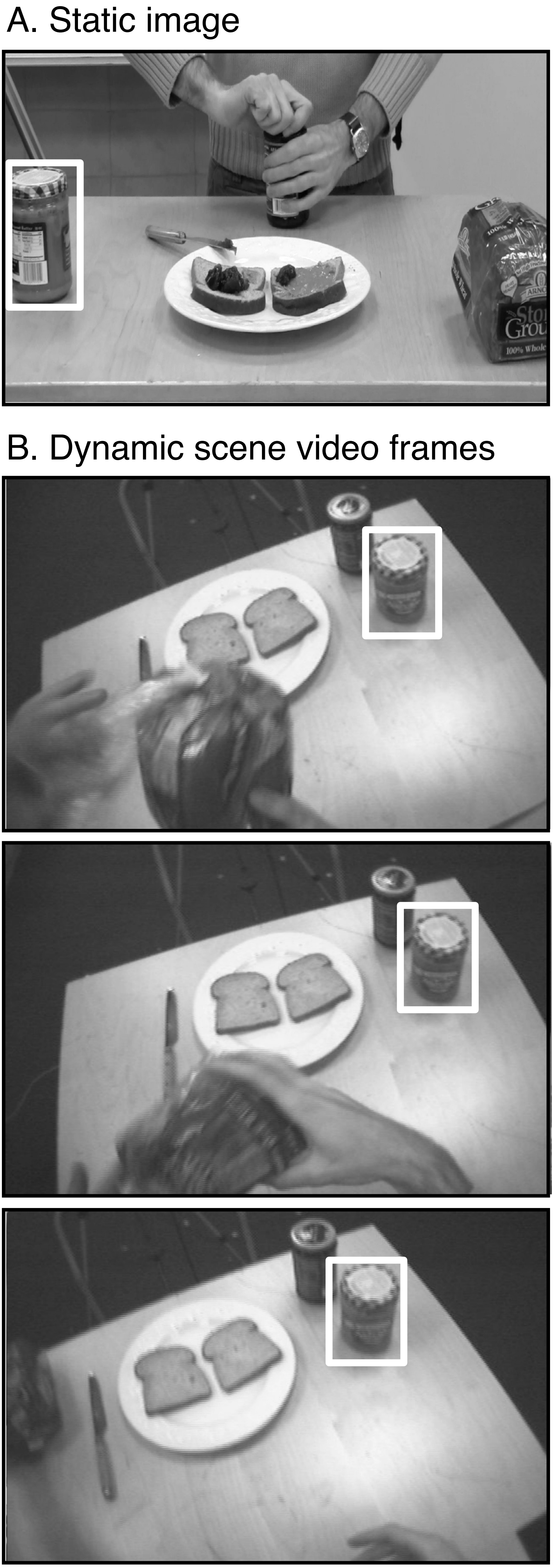
Figure 2. Parallax error in head-mounted eye tracking. The scene camera is vertically offset from the observer's eye. At the calibration distance there is no discrepancy between detected gaze and the observer's true gaze. At a different distance, a parallax error results.

Figure 3. (A) Defining an area of interest (AOI) for the peanut-butter jar in a static image requires drawing a single rectangle. (B) In dynamic scene video frames, the observer's head movements change the location of the jar, requiring AOIs to be defined for every frame for each participant.


A. Eye tracking headgear with eye and scene camera view
Scene
Eye
B. Calibration targets
C. Mobile infant setup



Calibration
Distance
Parallax
Error


A. Static image
B. Dynamic scene video frames