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Eye Tracking in Infancy Research

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The current review offers a unique introduction to the use of corneal reflection eye tracking in infancy research. We provide a detailed description of how to calibrate, collect, and analyze infants' gaze in a series of experimental paradigms, focusing specifically on the analysis of visual tracking, point of gaze, and the latency of gaze shifts (prediction and reactive gaze shifts). The article ends with a critical discussion about the pros and cons of corneal reflection eye tracking.

Looking is one of the very first behaviors to develop in the young infant. Even newborns direct gaze selectively at certain objects and events. They are attracted by moving objects and other people, especially their faces. Before language develops, looking is thus a major gateway to the infant's mind. Recent advances in corneal reflection (CR) eye tracking techniques have provided investigators of human development with a new tool that holds much promise. With this technique it becomes possible to measure how infants perceive the world with a high spatial and temporal accuracy. A recent special issue of the journal *Infancy* illustrates the broad applicability of state of the art eye tracking, reporting on infants' ability to categorize visual and auditory events (McMurray & Aslin, 2004), perceive object unity (Johnson, Slemmer, & Amso, 2004), represent temporarily occluded objects (Gredebäck & von Hofsten, 2004), and scan dynamic human faces (Hunnis & Geuze, 2004). While there are some descriptions of eye movement measures in adults and children from both normal and clinical populations (Karatekin, 2007; Luna, Velanova, & Geier, 2008; Trillenberg, Lencer, & Heide, 2004) no systematic attempts (besides the *Infancy* special issue) have been made to describe the use of eye tracking on infant populations. We believe that special attention is required in order to enhance the availability and ease of use of eye tracking technology in this pre-verbal population. Starting with a bit of history…

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While looking is one of the most basic human behaviors, until recently it has also been one of the most difficult ones to measure with high detail. The first attempts to measure gaze direction were associated with bulky and awkward contraptions that were mounted on the head or sometimes directly on the eye (Yarbus, 1967). More than 30 years ago Young and Sheena (1975) surveyed the state of the art of eye tracking methods. Several promising techniques were mentioned including electrooculography (EOG), the use of electrodes to measure change in potential as the eye (a strong dipole) rotates, and corneal reflection techniques (CR), the recording of the location of near infra-red light reflected of the cornea (the outer surface of the eyeball). These early off-the-shelf CR eye tracking devices, clearly, were not suitable for infancy research. CR devices such as the Polymetric Eye Movement Recorder were able to record gaze with fair accuracy (0.5 visual degrees), the downside being that participants' heads had to be fixated. Other CR solutions could be carried on the head (such as the Mobile Polymetic corneal reflection eye movement camera). This system held an accuracy of 2 visual degrees; however, it weighed almost 2 kilos. Over the years numerous solutions have been brought forward that minimize the weight of head-mounted systems and allow table-based CR solutions to accurately track gaze even during small head movements, allowing ever more accurate recording of infants gaze. However, the fundamental problems still stand. Much data are lost due to head movement and the use of head mounted trackers applicable to infants is still under development. The current methodological review aims to describe these difficulties, point to possible solutions, and discuss the pros and cons of using CR eye tracking to investigate the development of perception and cognition in young infants. At the same time we aim to provide an introductory tutorial to eye tracking methods by describing some of the most common analysis tools used.

CORNEAL REFLECTION EYE TRACKING

Corneal reflection methods for evaluating gaze movements were originally developed by Salapatek, Kessen, and Haith (see Haith, 1969; Salapatek & Kessen, 1966). The method relies on the fact that a light source reflected from the cornea will remain relatively stationary when the eye moves because of spherical properties of the eyeball. Therefore, if the positions of these light reflections are related to the center of the pupil it is possible to make an estimate of gaze direction. The lights directed toward the cornea need to be invisible to the subject; otherwise they will catch attention. Therefore they are in the infrared part of the spectrum. An early version of this method was based on filming infants' eyes with infrared film and analysing the positions of the reflections and the centre of the eyes frame-by-frame in the recording (Aslin & Salapatek, 1975).

Since then, eye tracking based on corneal reflection has been increasingly common. With improved computer capacities the laborious measurements of reflection positions have been made automatic and several different companies now market eye trackers that give gaze points directly. The common denominator is that all rely on picture processing algorithms to analyze the reflection of infrared light from the eyes. In order to obtain this reflection each system is equipped with infrared light sources (750 to 1,400 nm) and a camera that captures the light as it reflects on the cornea, sclera, iris, and retina.

Depending on the location of the light sources, the strength of these reflections varies. If the light source is located in front of the infant a large amount of light is reflected from the retina, creating a bright disc against the surrounding iris (similar to the red eyes observed during flash pho-

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tography). In addition, a small but bright reflection is created on the cornea, called the first Purkinje image. Eye tracking that relies on a light pupil and a bright reflection of the cornea is often refereed to as "bright pupil" corneal reflection (for an example see Figure 1).

An alternative technique is referred to as "dark pupil" eye tracking. In this case the light is shone from the sides, creating a dark pupil and bright reflections of the sclera and iris, in addition to the first Purkinje image caused by reflections on the cornea. The pupil remains dark since little light passes through the pupil and reflects of the retina. These techniques are optimized for slightly different populations. The bright pupil technique is better suited for participants that have a highly reflective retina (this is common in people with blue eyes and young infants) and the dark pupil technique is better suited for older participants and participants with dark eyes. The image of the pupil and corneal reflections are recorded with a camera and processed by computerized algorithms. Regardless of technique (dark or light pupil) the algorithms calculate gaze location based on the reflections on the first Purkinje image relative to the center of the pupil. These coordinates will vary depending on the shape of the eye and the angular relationship between the eye, the light source, and the eye tracking camera. In order to compensate for these differences infants must undergo a calibration procedure.

The calibration ensures that the eye tracking algorithms are tuned to each infant's eye. But more importantly, the calibration serves as a means to relate these coordinates to the external world (in most cases a monitor or a live stage in front of the infant). During calibration infants' attention is cued to a series of locations at the same time as the eye tracking camera records the coordinates of the pupil center and the first Purkinje image. Most systems allow the user to set the number of calibration points required for a particular study, and the number typically varies from 2 to 9. Generally, a larger number of calibration points will result in a higher spatial accuracy than fewer calibration points. However, due to the low attention span of young infants it can sometimes be beneficial to reduce the number of calibration points. It is our experience that infants from 4 months upward can perform a good 5 or 6 point calibration whereas younger infants benefit from a 2 point calibration. Regardless of the number of calibration points included in the procedure it is important that the calibrated area corresponds to the actual location of the scene; this includes both distance from the infant and the eye tracker as well as the vertical and horizontal extension of the scene.

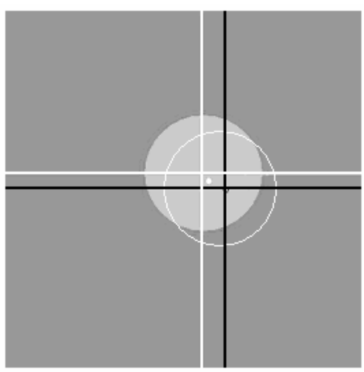

FIGURE 1 Reflection and center of the pupil (light gray disc and white cross) and first Purkinje image from the cornea (dark cross) collected with a bright pupil ASL 504 cornea reflection eye tracker.

To achieve a good calibration, the experimenter has to make sure that the infant is actually looking at the cued locations. This is often achieved through the use of motion. Figure 2 shows two examples of moving calibration stimuli. Figure 2A depicts a 2 point calibration performed on a monitor. In this example a spherical object looms in and out in each of the two calibrations locations (in reality, the two calibration points are shown one at a time). This stimulus combines movement with a fixed calibration location. The infant's attention is readily captured and gaze is usually directed at its center of the sphere. As the infant looks at it, the eye tracker records the coordinates of the pupil center and the first Purkinje image. With this method it is possible to provide infants with an interesting and accurate calibration procedure that rarely takes more than a minute or two to perform (depending on the number of calibration points).

When performing live calibration it is more difficult to rely on similar looming stimuli. A more direct way to perform calibrations is to have a small toy appear in a series of holes in a screen at the same time as the experimenter (hidden behind the screen) talks to the infants in order to cue their attention forward (Figure 2 B and C depict such an event). Motion is also a vital part of this calibration procedure; however, in this case the motion is mostly translational, as the experimenter shakes the toy to cue the calibration location. Such live calibrations are inherently less accurate than computer generated looming calibrations that rely on the same number of calibration points. This loss of precision is caused by the increased size of the calibration object (relative to the small shrunken sphere) and the variability added by shaking the toy.

It is critical for both calibration and subsequent recordings that the eye tracking camera capture the eye (or eyes) in a robust and reliable fashion. It can be difficult to find a procedure that ensures that the infant's head is located in the optimal recording area of the eye tracking camera throughout a session. Placing the infant in a car seat will ensure that the infants' movements are appropriately restricted. In addition, this prevents younger infants from leaning forward (which results in data loss due to insufficient visibility of the eye) and older infants from crawling away. If the car seat is placed in the parent's lap this will allow the parents to stay close to their child and allow them to monitor the infants throughout the session without inadvertently affecting their behavior.

Different eye tracking systems have solved the issue of head movement in slightly different manners. Some systems couples a lens (that records one eye) with a motor control system that allows the camera to compensate for head movements. The motors are operated with a remote con-

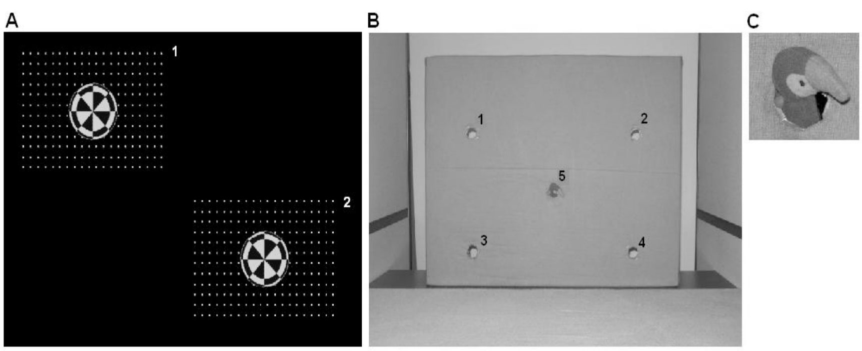

FIGURE 2 A 2-point calibration on a monitor (A) and a 5-point live calibration (B). A toy used to cue the infant's attention during live calibration is enlarged in (C).

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trol for large scale movements that place the eyes outside the camera view and an automatic correction algorithm that compensates for small head movements that offset the eye relative to the center of the camera view. This setup is somewhat cumbersome since a single operator must control the experiment, the eye tracking equipment, and move the camera with the remote control, all at the same time. However, some such systems can easily be integrated with a magnetic positioning system that allows automatic compensation for head movements. This integrated system has the added advantage of providing head coordinates in addition to the location of gaze. Combining these types of information is crucial for measuring smooth pursuit (a detailed description of these procedures can be found below). The downside is that the positioning system is sensitive to interference from metal and it requires a sensor to be placed on the participants' forehead using a cap or headband.

Other CR eye tracking products feature a wide angle camera that captures the participant's head and records the movement of both eyes. The advantage of such systems is that the wide angle camera will capture both eyes even following large scale head movements. These systems are often completely non-invasive since nothing is attached to the infants head.

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AN OVERVIEW OF EYE TRACKING ANALYSIS TOOLS

The procedure for recording and analyzing data obviously varies considerably depending on the eye tracking methods used, the recording context, and the dependent variables in a particular experiment. In the following section we will review a series of analysis tools that focus on temporal or spatial properties of an infant's gaze. The research questions addressed with these methods range from the developing oculomotor system to social cognition and cognitive functions. The examples introduced are selected to represent the diversity of experimental paradigms and analysis techniques available to eye tracking research but are not comprehensive.

OCULOMOTOR TRACKING

For decades, researchers have been relying to eye tracking technology to map the functions and organization of the oculomotor system (Collewijn & Tamminga, 1984; Katatekin, 2007; Leight & Zee, 1999). In general, infants are presented with objects that move back and forth on sinusoidal trajectories. The aim of these studies is to investigate how infants develop control over the oculomotor system and to understand how the different components of gaze (smooth pursuit, saccades, and head movements) are integrated (Phillips, Finoccio, Ong, & Fuchs, 1997; Richards & Holley, 1999; Rosander & von Hofsten, 2002; von Hofsten & Rosander, 1996; 1997). In brief, we know that newborn infants neither discriminate motion direction (Atkinson, 2000) nor track objects reliably with smooth pursuit. Newborns can, however, follow moving objects with a series of saccades (Aslin, 1988). The ability to smoothly track moving objects develops rapidly over the first few months of life. Infants can accurately track one-dimensional horizontally moving objects with smooth pursuit eye movements from 2 to 5 months of age (Aslin, 1981; Johnson, Davidow, Hall-Haro, & Frank, 2008; von Hofsten & Rosander, 1996, 1997). Direction discrimination and smooth pursuit develop in tandem in individual infants, implying a common developmental mechanism, perhaps maturation of cortical areas or networks that support motion perception

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(Johnson et al., 2008). Infants are much worse at tracking one-dimensional vertical trajectories and two-dimensional trajectories. In these cases normal development requires several additional months (Gredebäck, von Hofsten, Karlsson, & Aus, 2005; Grönqvist, Gredebäck, & von Hofsten, 2006). For comprehensive reviews of the oculomotor development see Luna, Valenova, and Geier (2008) and Rosander (2007). These reviews offer a detailed description of the progression of eye movement control; however, they focus less on the methodological aspects of performing oculomotor studies. The following section aims to make this process more transparent.

To map out oculomotor development it is important to know how the infant's gaze and the tracked object change over time, and this requires time locked information about the movement of the object and gaze. Figure 3 demonstrates how gaze and a moving object can be plotted over time. In this case a 6-month-old infant is tracking a small happy face moving on a circular trajectory at 0.4 Hz (one circle is completed in 2.5 seconds).

In order to separate gaze components and perform accurate analysis it is essential that non task related data (off-task fixations and sampling error) are removed. Off-task fixations are removed with linear interpolations (should not exceed 5% of the data set) and sampling error is corrected using median or mean filters (Grönqvist, Gredebäck, & von Hofsten, 2006).

Statistical analysis can be performed on the location or velocity of gaze, smooth pursuit, saccades, or head movements. Most corneal reflection eye trackers report gaze location so each subcomponent has to be reconstructed from the original gaze data. The saccadic contribution to gaze tracking can be evaluated by removing all data that are not comprised of high velocity gaze shifts (e.g., larger than twice the object's velocity). The residual data (after saccades have been removed) comprise head movements and smooth pursuit; these components can only be separated if head movements are recorded, most often using an external position tracking system (von Hofsten & Rosander, 1997).

In order to measure the timing of infants' visual tracking (whether they manage to keep up with the object or if they lag behind) it is common to perform a cross correlation analysis. This analysis calculates the overall phase shift between the moving object and gaze or its subcomponents (see Figure 4). It is done by (1) calculation of the correlation coefficient between the moving object and the eyes. The data are then (2) shifted back and forth while correlation coefficients are calculated for each step. The lead-lag is equivalent to the distance (in time) that data have to be shifted

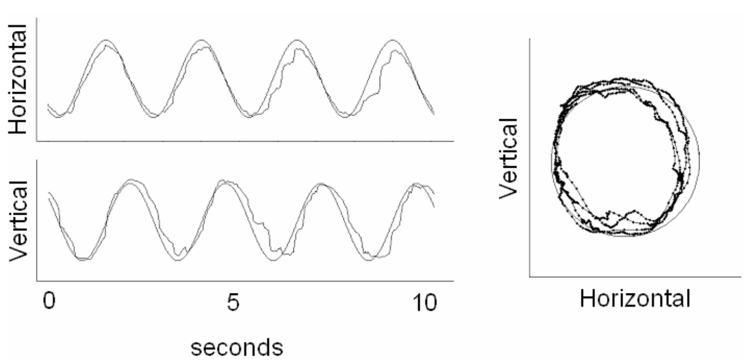

FIGURE 3 A 6-month-old infant tracking a circular trajectory for 10 sec. The figure is divided into two one-dimensional graphs depicting horizontal and vertical data plotted over time and a two-dimensional reconstruction of the same data.

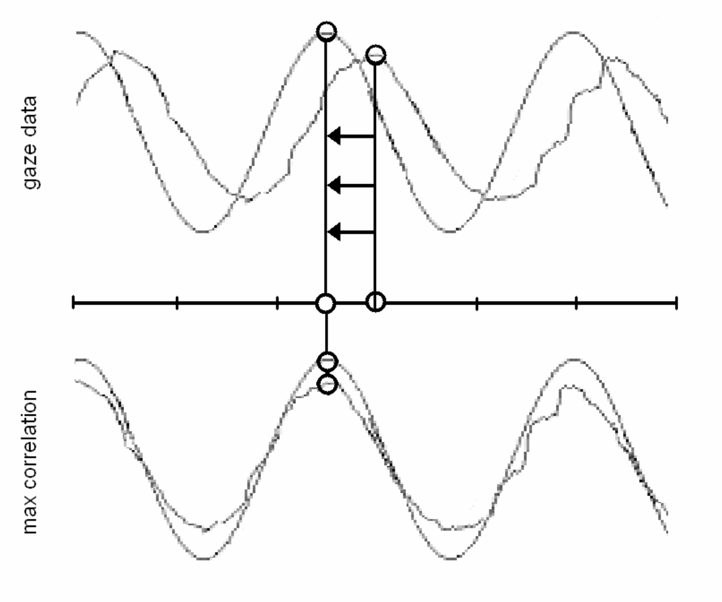

FIGURE 4 Original gaze data (top panel) and the maximum correlation phase shifted gaze data (bottom panel). The timing (lag) of this segment of data (from a 6-month-old infant) is equal to the amount of phase shift required to obtain the maximum correlation (defined by the horizontal arrows in the gaze data). The presented data extends over 6 sec (each mark on the horizontal line equals 1 sec). In this case the infant is lagging behind the target by approximately 500 msec.

to achieve the maximum correlation. If this cross correlation is based on position changes, then the measure is referred to as *timing* (Gredebäck et al., 2005); if the operation is based on velocity than the common unit for this measure is *phase* (von Hofsten & Rosander, 1997).

A complementary analysis relies on Fast Fourier Transformations (FFT) to calculate the gain of gaze (or its subcomponents). Gain reports the relative amplitude of eye movements and the target's trajectory in the target's fundamental frequency. In the example shown in Figure 4 the object completes a circular lap in 2.5 sec; this is equivalent to 0.4 Hz. The purpose of this measure is to evaluate whether infants track the full extension of the trajectory or if they only track a sub-portion of the trajectory. In brief, the FFT calculates a frequency over power distribution and extracts the amplitude of the power at the fundamental frequency (in our example 0.4 Hz) for both the target and the relevant components of gaze. Gain reports a simple ratio that addresses whether infants track the full extension of the target (Gain = 1) or if the smooth pursuit system is engaged yet the point of gaze (POG) fails to keep up with the target (Gain < 1). It is also possible to find a Gain that is higher than 1, if infants overshoot the target and track the object with a larger amplitude than the actual movement of the target.

Both timing and gain evaluate infants' continuous tracking performance and relate this to the movement of the target. It is, however, also common to report the number of saccades elicited during an event and the mean distance between the target and gaze (referred to as RMS). The latter measure gives an indication of whether infants on average maintain gaze on the target or not, and

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it can also be used to calculate learning effects during visual tracking. All of these measures are reported by Grönqvist et al. (2006).

WHERE DO INFANTS LOOK?

The aforementioned analyses have been (and continue to be) important for advancing our understanding of the organization and development of the oculomotor system. In addition, these studies form a basis from which further analysis tools have evolved. These tools are more suitable for analyzing how infants distribute their attention, focusing on where infants look (scanning patterns) and when infants shift gaze from one location to another (saccade latencies). Both of these analyses will be reviewed next, including descriptions of the methods and paradigms used.

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Scanning Patterns

Looking at how infants scan different images or dynamic events provides us with valuable information about the distribution of interest and (overt) attention. However, because attention can be influenced by various high (for example, statistical regularities) and low (such as light intensity) level stimulus properties it becomes important to control for unwanted co-variations. This need for experimental control is not unique to eye tracking; however, the requirements are heightened due to the high spatial-temporal accuracy of CR eye tracking techniques. The ability to record the POG every 17 to 20 msec (with a standard 60 Hz or 50 Hz CR eye tracker, respectively) necessitates precise control of both spatial and temporal properties of one's stimulus material.

Of the three analysis tools presented in this methodological review the analysis of scanning patterns represents the most accessible route to analyzing gaze data. Analyses that focus on how much time infants spend fixating one of several Areas of Interest (AOIs) can easily be obtained through the software packages provided by most CR eye tracking manufacturers. Additional analyses can be performed with any standard computer video player that allows the user to analyze each frame successively. In this case, analysis is performed on a video including both the stimulus material and infants' gaze, superimposed on the stimulus as a moving crosshair or dot. Such exports are also available from most eye tracking control programs.

Perceptual completion. Objects are often partly hidden by other objects that are closer to the observer, and a critical visual skill is the recognition of objects as wholes and not merely in terms of their directly visible constituent surfaces. Perception of coherent objects, rather than surface fragments, is known as perceptual completion, and a large literature supports the notion that very young infants do not perceive completion in displays that depict moving, center-occluded objects (reviewed in Johnson, 2004). That is, until 2–4 months of age, infants seem to perceive such objects only in terms of what is directly visible, and do not make the perceptual "inference" characteristic of adults when they view such displays. A key developmental question is what processes and mechanisms underlie the emergence of perceptual completion in the first several months after birth.

Recent experiments highlight a role for eye movements in the development of perceptual completion. Amso and Johnson (2006) and Johnson et al. (2004, 2008) investigated perception of unity of rod parts that were aligned above and below an occluder, and moved horizontally in tan-

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dem, back and forth, as the infant watched. Perceptual completion was assessed with looking times, and the authors obtained evidence for individual differences in completion in a group of 2–3-month-old infants. The infants' eye movements were also recorded with an eye tracker. Infants who perceived object unity in the display tended to direct their gaze more often toward "relevant" parts of the stimulus—specifically, the visible surfaces, their points of intersection, and their motions—unlike infants who did not seem to perceive unity, who tended to look more at less informative parts of the stimulus, such as the occluder or background (see Figure 5).

In these studies, separate AOIs were defined for visible rod parts, the occluding box, and the background. The AOIs for the rod parts moved as the rod parts did. AOIs were drawn slightly larger than the rod parts and box, about 1° visual angle on all sides, to accommodate any slight inaccuracies in calibration, and the small inaccuracies inherent in any eye tracking system (<0.5 visual degrees in most modern CR eye trackers). AOIs in this case were derived from the program, written in Macromedia Director (Adobe), which generated the events. The relations of gaze patterns to AOIs were then derived from the output of the eye tracker, a text file containing the x/y coordinates of POG as a function of time, using Matlab (Mathworks). Through this process measures of fixation duration (or dwell times) in each AOI (summed across fixations) was obtained, as well as other global measures—"local" versus "global" scanning (within vs. across AOIs, respectively), frequency of saccades per unit of time, and tracking the rod parts' motion.

These studies clearly illustrate that infants' attention might be related to how they perceive the world. By time-locking gaze with the experimental events (through the use of moving AOIs) we were able to demonstrate that young infants understand that partly occluded objects persist as a solid entity even in the absence of direct visual input.

Social cognition. Measuring infants' gaze as they view others engage in meaningful and goal directed actions provides a unique insight into emerging social understanding. With this technique it becomes possible to investigate how infants scan social events and manual actions performed by others. In a recent study Falck-Ytter, Gredebäck, and von Hofsten (2006) demonstrated that both 12-month-old infants and adults fixate the goal of an ongoing manual action. In this case an actor placed objects in a bucket. Six-month-olds did not fixate the goal of these ac-

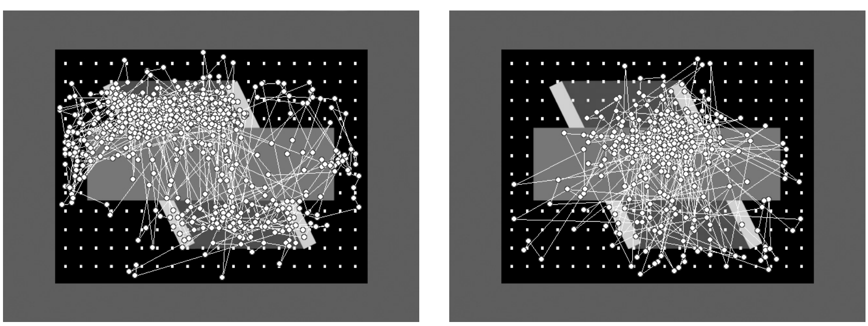

FIGURE 5 Eye movement records from two 3-month-olds who participated in a perceptual completion task. The full horizontal extent of rod motion is depicted; each white dot represents a single fixation, and each line represents a saccade. Left: this infant provided evidence for perceptual completion in an independent habituation task. Note how the infant fixates the rod parts (especially the upper part) and the range of motion. Right: this infant apparently did not perceive unity; and seems to have spent the bulk of the time looking at the occluder rather than the rod parts.

tions. When the objects moved on their own to the bucket without interference from the human actor, both adults and 12-month-olds performed much like the 6-month-olds in the action condition: They tracked the moving hand rather than fixating the goal. These findings are consistent with the mirror neuron system hypothesis and its assumption that action understanding is mediated by one's own motor representation for similar actions (Rizzolatti & Craighero, 2004).

Analyzing gaze data from developmental social cognition studies often relies on a comparison between when an actor performs certain actions and how infants scan these events. These analyses are frequently based on AOIs that define spatial locations in events being presented. Figure 6 depicts a snapshot of the stimuli used by Falck-Ytter et al. (2006) and AOIs covering the initial position of the objects, the goal area (the bucket), and the trajectory of the objects as they move toward the goal. In this study looking times to the goal AOI, the movement path of the objects, and the object's initial position were calculated, separately for each manual action. The data were then normalized (looking time to each location/total looking time to all three AOIs) separately for each manual action, prior to statistical analysis. This normalization is important since infants often vary in the amount of time they spend looking at the stimuli.

Other analyses of scanning patterns are often appropriate. In a recent study Senju and Csibra (2008) presented infants with videos of an actor who turned toward one of two objects placed on a table in front of her. Six-month-olds followed the model's gaze (fixating the same toy as the model) only if the gaze shift was preceded by either direct eye contact (toward the camera) or infant directed speech. The authors interpreted this finding as an indication that gaze following, even in young infants, is mediated by a social context (see also Gredebäck, Theuring, Hauf, & Kenward, 2008; von Hofsten, Dahlström, & Fredriksson, 2005). These studies rely on a frame-by-frame analysis of infants' gaze shifts. The number of gaze shifts from the model's face to the attended toy was compared to the number of gaze shifts from the model's face to other distracter toys. By dividing the number of accurate gaze shifts from the total number of gaze shifts, a difference score was calculated, providing an indication of whether infants shifted their gaze more often to the attended toy than to other potentially interesting locations. Each of these three locations were defined through rectangular AOIs that incorporated the object of interest and some additional space surrounding them to account for fixations on the object edges and sampling errors.

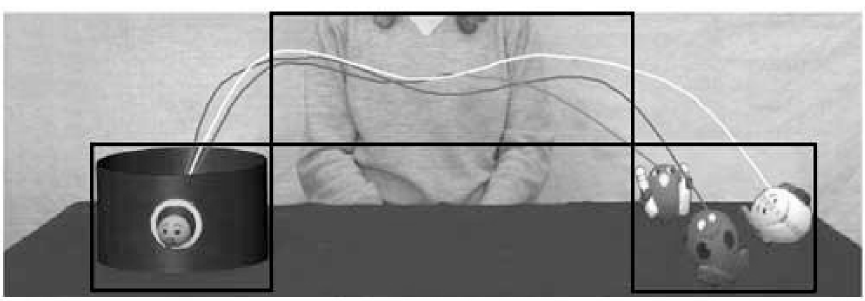

FIGURE 6 Snapshot of the stimuli used by Falck-Ytter, Gredebäck, and von Hofsten (2006). The black squares demonstrate the location of the three Areas of Interest (AOIs) used to analyze gaze data and the colored lines represent the trajectory of the moving objects.

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Saccade Latencies

In addition to analyzing scanning patterns it is often desirable to report saccade latencies, focusing on when infants shift their gaze between two locations. If gaze reliably and systematically reaches an area before something interesting happens, then that gaze shift is labeled predictive. In this case, infants look at a location in anticipation of future events. If infants, on the other hand, shift gaze to an interesting location only after an event occurred such events are labeled reactive. In this case, infants are assumed to react to peripheral stimuli by orienting their attention to that location due to a change in some relevant stimulus property. The examples that follow include studies that investigate either predictive gaze shifts, reactive gaze shifts, or the distribution of reactive and predictive gaze shifts between conditions. All of these analyses are performed by comparing when gaze enters the area of interest relative to the observed events. This analysis can be performed with computer video players that support frame by frame analysis. However, the spatial and temporal complexity of these analysis (gaze has to be in a particular area at a given time) is best handled by plotting the location of gaze over time in a stand alone programming environment (e.g., Matlab). Such analyses offer a better visualization of the relationship between gaze, AOIs, and important time stamps in the stimulus material. Another advantage of working in a programming environment is added freedom. Data points can be extracted manually or automatically and plotted as descriptive statistics or 3D histograms.

Regardless of how these analyses are performed, separating reactive and predictive saccades is not straightforward because it can be unclear what temporal threshold should separate these two kinds of eye movement. The most common method is to set the thresholds for prediction relative to the processing time of the oculomotor system. This threshold has been estimated to 150 msec in some studies (Johnson, Amso, & Slemmer, 2003) and 200 msec in others (Rosander & von Hofsten, 2002). The first of these criteria is based on infants' saccade latencies to the sequential reappearance of pictures (Canfield, Smith, Berzsnyak, & Snow, 1997) and the latter criterion is based on infants' (Gredebäck, Örnkloo, & von Hofsten, 2006) and adults' (Engel, Anderson, & Soechting, 1999) reactive saccade latency to abruptly turning trajectories. Common for both thresholds is that they are grounded in the functional importance of overcoming the internal processing lag of the oculomotor system, ensuring that gaze shifts are performed before the infant reacts to the appearance of, or change in, relevant events.

Neither of these thresholds ensures that infants actually look at the correct location before the event actually occurs. To make sure that infants' gaze precedes the relevant change, some studies have disregarded the internal processing time and instead related infants gaze to the time when events actual occur (Falck-Ytter, et al., 2006). In this case prediction is directed more toward external events than to the internal processing lag of the system. This latter approach represents a more conservative estimate of prediction that inherently will report more reactive gaze shifts then what would be true if accounting for the processing lag. Examples of both are provided below.

Revisiting social cognition. In the aforementioned study by Falck-Ytter et al. (2006) analysis of scanning patterns during observation of manual actions were supplemented with measures of saccade latencies. In this study the time when gaze fixated the goal area (the bucket) was compared to the time when the objects first reached the goal area. If gaze fixated the goal AOI before the object reached the same AOI, this event was categorized as predictive. Such proactive gaze shifts are consistently performed by adults both when performing manual actions (Johansson,

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Westling, Bäckström, & Flanagan, 2001) and when observing others engage in goal directed and meaningful actions that we can perform ourselves (Falck-Ytter et al., 2006; Flanagan & Johansson, 2003). As a consequence, consistent predictions by a group of infants are assumed to reflect an understanding of perceived events. In the study by Falck-Ytter et al., participants demonstrated a high degree of correspondence between scanning patterns and the degree to which they were able to predict the action goal. Adults and 12-month-olds were able to predict the goal of manual action, but failed to anticipate similar events in the absence of a human actor (i.e., when the objects moved by themselves). Six-month-olds did not anticipate any of the object movements.

This study represents a good example of the added value provided by analyzing saccade latencies. Because this was the first study that relied on eye tracking to examine social cognition and action understanding in infancy, the more conservative prediction threshold (disregarding the processing time of the oculomotor system) was used. More recent studies that elaborate on infant's action understanding have taken this delay into account, relying on the 200 msec threshold defined earlier (Gredebäck, Stasiewicz, Falck-Ytter, Rosander, & von Hofsten, 2009; von Hofsten, Uhlig, Adell, & Kochukhova, 2009).

Object representations. A large amount of research has focused on how infants come to represent temporarily non visible (or occluded) objects. Much of this work has been carried out using preferential looking techniques (Baillargeon, 2004; Spelke, Katz, Purcell, Ehrlich, & Breinlinger, 1994). Recently a series of published eye tracking studies report on infants' abilities to predict the reappearance of occluded objects (for a review see Gredebäck & Von Hofsten, 2007). With this paradigm it is possible to provide a detailed description of how infants' actions are directed to ongoing occlusion events, providing the opportunity to evaluate representations of occluded objects and measure infants' expectations of when and where an occluded object will reappear.

In brief, we know that infants as young as 4 months old can predict the reappearance of occluded objects (Johnson, Amso, & Slemmer, 2003; Rosander & von Hofsten, 2004). von Hofsten, Kochukhova, and Rosander (2007) found that 4-month-old infants timed their gaze shifts over the occluder such that gaze ended up at the reappearing side just before the object reappeared. This behavior was consistent over numerous occlusion durations. At this age, however, infants' representations have not yet matured and 4-month-olds do not always make accurate predictions from the first occlusion event. In certain situations infants may require prior experience that strengthen representations and enable predictions. This experience might involve prior occlusion events in the same session (Rosander & von Hofsten, 2004). Four-month-olds also benefit from "training," that is, prior presentations of non occluded objects that move on similar trajectories as the occluded objects (Johnson et al., 2003). Effects of training are rather transient, and decay after 30 min, but can be reinstated by a brief "reminder" trial (Johnson & Shuwairi, 2009).

At 6 months of age infants' representations have matured substantially (Gredebäck & von Hofsten, 2004; Johnson et al., 2003). At this age infants have expectations of the direction of object movement during occlusion. Infants initially expect occluded objects to move on linear trajectories but they quickly adjust to events that violate this initial assumption. If 6-month-olds are presented with trajectories that change the direction of motion behind the occluder, they accurately predict the reappearance location after only 2 trials. These new expectations are maintained for at least 24 h (Kochukhova & Gredebäck, 2007).

Investigating infants' object representations with an eye tracking paradigm is dependent on the fact that smooth pursuit requires a visible moving object (Leight & Zee, 1999). When the object moves behind the occluder, smooth tracking is disrupted. In order to continue tracking the object infants have to move across the occluder with a saccade. In Figure 7 a 9-month-old infant tracks an object with smooth pursuit prior to occlusion, crosses the occluder with a saccade, and continues smooth tracking of the moving object once it becomes visible again.

The timing of this saccade provides information about when the infant expects the object to reappear. If the saccade occurred before the infant perceived the reappearing object, the eye movement is classified as predictive; that is, the infant anticipated the reappearing object (exemplified in Figure 7B). Later gaze shifts, which are initiated by the sight of the reappearing object, are classified as reactive.

Inclusion of a particular occlusion event typically requires that (1) infants track the object prior to occlusion (or fixate the object as it disappears), that they (2) make a saccadic gaze shift across the occluder and fixate the reappearance location (during predictive trials) or track the object as it moves away from the occluder (during reactive trials). These criteria are defined to make sure that infants are attentive both prior to, and following, the occlusion event. Whether infants predict the reappearance of an occluded object or not is often of primary interest to eye tracking studies of object representations. However, this measure is sometimes supplemented with measures of spatial accuracy; that is, whether infant look at the actual reappearance location of the object or not (Kochukhova & Gredebäck, 2007).

Categorization. Another fruitful approach involves quantifying infants' predictions in paradigms that do not provide the opportunity to perform reactive saccades. Such a prediction task was developed by McMurray and Aslin (2004). They presented 6-month-old infants with a training session in which one of two objects disappeared behind a T-shaped occluder and reappeared in one of two locations (on either side of the vertical line). The reappearance location was dependent on the identity of the moving object. After a training phase, infants were presented with a series of

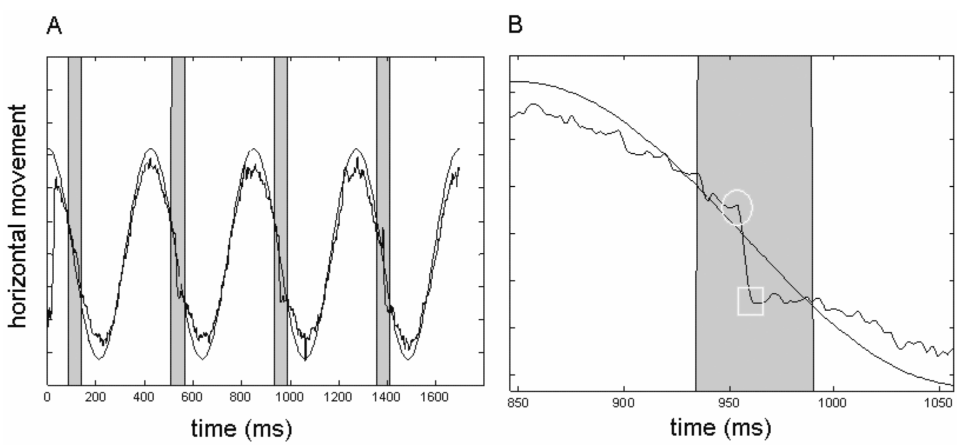

FIGURE 7 (A) An object moving with constant velocity on a circular trajectory that is partly occluded (dark grey areas). (B) Enlargement of a single occlusion passage. The circle represents when the saccade is initiated and the square represents the termination of the saccade. Only horizontal eye movements are displayed.

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generalization trials in which a novel stimulus (an altered version of the original stimuli) disappeared behind the occluder, never to come out on the other side. The question was how infants categorized these new stimuli. If they categorized the altered stimuli as belonging to the same category as one of the originals then infants were assumed to make similar predictions as learned during training. If they did not categorize the new stimuli as belonging to either of the trained categories then their response would be randomly distributed between the two reappearance locations. The study indicates that 6-month-old infants spontaneously categorize different exemplars along various dimensions (including color, shape, and orientation).

Visual attention. In a similar manner, it is often fruitful to focus on reactions alone, analyzing the latency of reactive saccades without interference from prediction. Amso and Johnson (2005, 2009) examined changes in the efficiency of infants' visual selection with a "spatial negative priming" paradigm. Each trial consisted of a *prime* and a *probe* presentation, separated by a 67, 200, or 550 msec interstimulus interval (ISI), to test the efficiency of selection as a function of processing time. In the prime, a target (an attractive toy that moved in synchrony with a rhythmic sound) was accompanied by a relatively uninteresting distracter (see Figure 8). In the probe, the target appeared either in the location formerly occupied by the distracter (shown in Figure 8) or in one of the other two locations. In this task, when a previously ignored location becomes the target to be selected, responses to it are impaired, providing a measure of visual inhibition.

At the slowest ISI, adults' and 9-month-olds' saccade latencies to the target were delayed when the target appeared where the distracter had been, implying that the distracter had been attended to covertly, and eye movements to the cued location were inhibited. The effect was not very pronounced at faster ISIs in 9-month-olds, although they were preserved in adults, suggesting that visual selection was not as efficient in infants (Amso & Johnson, 2005). The effect was not observed at any ISI in 3- and 6-month-olds; instead, latencies were facilitated, as predicted by a model of visual attention positing a time course for the onset and decay of excitation and inhibition of target locations (Amso & Johnson, 2009).

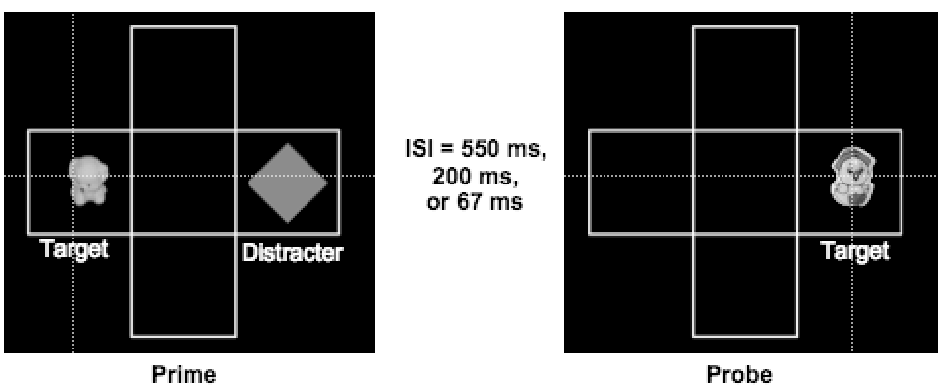

FIGURE 8 Displays used in studies of infants' visual selection. A target and distracter are presented simultaneously (left), and after a brief interval, a new target appears (right), either in the place formerly occupied by the distracter (shown at right) or in one of the other two places. If latency to fixate the second target is delayed when it appears in the distracter position, this implies that the distracter, while not fixated, nevertheless was processed covertly and inhibited an eye movement to that place.

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A NOTE ON FIXATIONS

With the exception of analysis of oculomotor development, the unit of analysis in all these studies is the *fixation*, maintaining the POG at a single location in space for a specified duration. The need to reduce scanning patterns to fixation points is based on the fact that sampling error is an integral part of all eye tracking measures. As mentioned earlier, a calibration procedure is performed to reduce the size of this error; however, it can never remove the error entirely. A second important reason why gaze routinely is recalculated as fixations is that most CR eye trackers are too slow to fully capture the rich dynamics of eye movements, in particular the velocity and absolute starting (and end) point of saccades. The fact that most systems capture gaze every 17 or 20 msec means that we have little information about what happens between samples. Both of these problems add uncertainty about the actual location of individual data points. By aggregating a series of data points we reduce the sampling error (which theoretically will even out over many samples), minimize the influence of "in flight" saccadic data points and produce a more accurate estimate of gaze location. Calculating fixations is most often automatically performed by the CR eye tracking control programs. Most often these systems apply a spatio-temporal filter that aggregates successive data points that fall within one visual degree for more than 200 msec and replace data with the mean gaze location for this interval. If gaze is not stable within one visual degree for 200 msec no output is provided (missing data). Exporting data in raw format (without fixations) to free standing analysis environments (e.g., Matlab) allows researchers to work more freely with defining their fixation filters. This can help to increase the signal to noise ratio, but the ability to work outside the eye tracker control program depends in part on the task and the quality of the data.

PROS AND CONS OF EYE TRACKING

The pioneering work of Robert Fantz in the 1950s and 1960s established the fact that infants show systematic preferences for some stimuli over others (e.g., Fantz, 1961). Since that time thousands of studies have been devoted to the study of infants' selective attention, habituation of looking at displays of various kinds, and dishabituation of looking when these displays have been altered in some way or another. These studies have revealed a great deal about detection, discrimination, categorization, expectations, and learning for a myriad of visual stimuli. Despite the widespread use of infant looking time paradigms, nevertheless, it can be difficult to relate looking time data to underlying processes (Aslin, 2007). There might be several different mechanisms, working at different levels (sensory, motor, perceptual, cognitive, and cortical), that result in changing looking patterns. This same basic problem applies to CR eye tracking studies. Accuracy is improved relative to observer judgments of looking behaviors, but the challenge of establishing concrete relations between infants' gaze and underlying processes remains.

However, two properties of eye tracking help to reduce the gap between observable behavior and underlying processes. First, eye tracking data can be assessed over time, allowing researchers to examine learning functions and changes in attention over a stimulus set. This can help researchers to assess the assumptions that infants have when entering the lab and what aspects of the experiment they pick up over successive presentations. The ability to time-lock gaze to events (down to every 17–20 msec) and the ability to measure where infants fixate (assumed to reflect which information infants have attended to) provide researchers with a better understanding of the exact representations and percepts that influence infants scanning patterns or gaze shifts.

Second, with respect to underlying mechanisms, measures of prediction become particularly important. The forward looking properties of prediction minimize the possibility that predictive gaze shifts are guided by arbitrary visual properties of the critical events, because, by definition, they have yet not occurred. The ability to anticipate the future state of affairs is by no means a simple process, and it can operate at various levels of the brain. For example, predictive smooth pursuit (as reviewed in the section oculomotor tracking above) is organized within the visual motor circuits and incorporates little cognition (Leight & Zee, 1999). However, saccadic predictions are controlled by several prefrontal areas that facilitate voluntary control (Techovnik, Sommer, Chu, Slocum, & Schiller, 2000) including the frontal eye fields (FEF) and supplementary eye fields (SEF). The detailed understanding that we have of the underlying neural substrate of various eye movement mechanisms are invaluable when discussing the networks responsible for a particular pattern of eye movements.

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Data Analysis and *Coding*

The data yielded by CR eye tracking paradigms are at once rich and daunting: If an infant looks at a stimulus set for, say, 5 min, and data are collected at 60 Hz, there may be as many as 18,000 data points. Managing these data presents unique challenges. Commercial eye trackers provide analysis tools that allow the researcher to examine specific locations (AOIs) in a stimulus set to which attention is directed, and these tools are very useful in understanding how the point of gaze changes with respect to specific stimuli over time. Yet for many paradigms a simple analysis of attention within AOIs is insufficient to address the questions of interest. One important example was discussed previously: that of predictive saccades, an oculomotor behavior that by definition involves relations of the POG and stimulus locations over both time and space. To our knowledge there are no off-the-shelf analysis tools that support such analyses, and for this reason some researchers have turned to offline analysis from video recordings (e.g., Johnson et al., 2003; Johnson & Shuwairi, 2009). Analyzing from video recordings can be useful for the researcher in visualizing both the broad pattern of oculomotor behavior in a particular study and individual differences in these behaviors, and thereby guide hypothesis generation. It is, however, quite laborious.

Because of the limitations inherent in simple AOI analyses, many researchers now prefer to set up their experiments outside the programming environment provided by the CR eye tracker. Programs such as E-prime (Psychology Software Tools) and Matlab can be used to generate stimuli, control the experiment, and collect data, all at the same time if desired. These programs can also be used for data analysis, or to facilitate analysis by collating eye movement data for export to statistical analysis packages. Most commercially available eye trackers provide software to integrate programs and platforms.

Financial Considerations

A final concern worth noting is the cost of CR eye tracking systems. Most commercially available eye trackers are expensive, costing in the tens of thousands of dollars (or euros). Relative to other technologies common in psychology research, such as brain imaging, this is inexpensive, and the data provided by eye tracking are invaluable in revealing important new insights into infant development, as noted previously. Still, for many laboratories, the cost-benefit analysis may determine that eye tracking does not necessarily offer increased information that can justify its cost, relative to traditional low-tech looking time methods. Traditional methods are easy to implement and virtually free for many researchers who have access to undergraduate assistants. We would suggest, nevertheless, that the field should move in the direction of increased accuracy and objectivity. Eye movement data are rich, precise, and impartial—free from bias, even if unintentional.

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FUTURE DIRECTIONS

In this review we have focused on published results and well-established eye tracking paradigms. There are, however, numerous exciting and innovative new frontiers in eye tracking research, including the increasing use of real world displays featuring real objects and real social interactions, gaze contingent displays in which infants control the stimulus progression, the use of pupil size as an evaluation of surprise, and a series of integrative approaches with simultaneous recordings of infants gaze, electroencephalogram, and/or heart rate. All of these approaches will surely continue enhancing our understanding of infants' perceptual, cognitive, and social abilities as eye trackers become increasingly more available.

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