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TOOLS OF THE TRADE

Eye Tracking: A Brief Guide for Developmental Researchers

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Eye tracking offers a powerful research tool for developmental scientists. In this brief article, the author introduces the methodology and issues associated with its applications in developmental research, beginning with an overview of eye movements and eye-tracking technologies, followed by examples of how it is used to study the developing mind and discussions of the eye–mind relationship. The author also addresses a number of practical issues involved in starting eye-tracking research and provides resources for further reading.

There are times when the eyes can speak louder than the voice, or even than actions. Eye tracking can be a powerful tool to study the development of the mind; chances are you need little convincing of that. But the first step into eye tracking may seem like a big leap: It is easy to get lost in dazzling demos and confusing spec sheets, leaving some of the fundamental questions unasked. This short article is aimed at developmental researchers who want to incorporate eye tracking into their existing research. I begin with a number of conceptual issues in eye movements and developmental research, and move toward more practical aspects of eye tracking. Space limitations do not permit in-depth technical discussion, but resources are listed in the last section of this article to help you get started.

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EYE MOVEMENTS AND EYE TRACKING

We move our eyes constantly because only a small area of the retina (i.e., the fovea) gives us high-resolution vision (Carpenter, 1988; Leigh & Zee, 2006). There are several different types of eye movements, some of which help to maintain a stable vision while others bring in new information. Saccadic eye movements, which are rapid ballistic movements that bring the line of gaze from one place to another, are the primary means of acquiring new visual information. In between saccades are fixations, in which the eyes stay relatively still to allow for visual perception. Most eye trackers on the market are designed to detect saccades and fixations. Other types of eye movements such as the smooth-pursuit (for tracking slow-moving visual targets), the vestibulo-ocular reflex (for compensating head movements), and the vergence (in response to depth cues), also occur frequently. Not all eye-tracking devices can correctly measure and identify these types of eye movements, in which case they must be properly controlled in experiments.

Eye tracking involves two basic challenges: measuring the movement of the eye and mapping the gaze to the real-world. Attempts to objectively measure eye movements go back over 100 years (see Huey, 1908; Wade & Tatler, 2005). Some of the early techniques, while ingenuous, were not user-friendly to say the least. Not only was the method of tracking invasive, the data analysis was labor intensive, often involving frame-by-frame analysis of films or videos. That was then. In the past decade or so, the advancement of video and computer technologies has revolutionized eye movement research (Duchowski, 2003). Today, a typical eye-tracking system uses one or more cameras to capture images of the eye at a sampling rate of 30 to over 1,000 frames per second. To measure the movement of the eye, video processing software—some high-end devices use dedicated hardware—tracks certain features of the eye within the video frame. A prominent feature to track is the pupil; most eye trackers use infrared or near-infrared light to increase the contrast between the pupil and the iris in order to facilitate tracking. However, the pupil location is particularly sensitive to head movements. One solution, thanks to modern video technologies, is to track both the pupil center and the location of the corneal reflection (the bright "gleam"). The relative position of the two signifies the eye location with respect to the camera, but is insensitive to modest head or body movements (Aslin & McMurray, 2004; Duchowski, 2003; Gredeback, Johnson, & von Hofsten, 2010). The use of the pupil-center-corneal-reflection and other techniques has greatly reduced the need for bite bars, chin rests, and other head-stabilization devices formerly required.

The second part of the problem is to identify where or at what the viewer is looking. The mapping between the eye position and the real world is achieved through a calibration. Before (sometimes during or after) a study, the participant is asked to look at several predetermined positions. These points define a grid by which all subsequent gaze positions are interpolated. It is hard to overstate the importance of a good calibration—it is the sole basis for determining which part of the stimulus the viewer is looking at. Although more calibration points allow for a more accurate estimation of gaze positions, this advantage must be balanced against the subject population's attention span and level of oculomotor control. Whereas preschool-aged and older children typically can complete 9 or 16-point calibrations (e.g., Feng & Guo, under review), infancy researchers often have to settle with 5-point or even 2-point calibrations (Gredeback et al., 2010). This is less of an issue given young infants' poor oculomotor control in general, and is often accommodated for by using large visual stimuli. It is important to note that the quality of the calibration can change during a study because of drifts, brightness of the stimulus, or changes in the arousal state, among many other factors. One should always monitor the quality of the data throughout the experiment, and repeat calibrations as necessary.

EYE MOVEMENTS AND THE DEVELOPING MIND

Eye movements offer a number of unique advantages to developmental researchers. Appearing early in fetal development (Birnholz, 1981; Prechtl & Nijhuis, 1983) and functional at birth, eye movements are among the few behavioral responses newborns exhibit (M. H. Johnson, Dziurawiec, Ellis, & Morton, 1991). As motor responses, eye movements are faster and metabolically more efficient than head and other movements; unlike traditional paradigms, they can be used to study younger infants (McMurray & Aslin, 2004). However, the unique appeal of eye tracking is the capacity to determine where and how children look. One of the most intriguing fields of developmental eye-tracking research investigates how newborns and infants scan human faces (Hainline, 1978; Haith, 1969; M. H. Johnson et al., 1991). Important discoveries such as the developmental changes in face scanning patterns in the first weeks of life would not have been possible without the methodology.

Children are not passive perceivers. They make predictions about the world, and their anticipatory eye movements reveal their knowledge structure. For example, McMurray and Aslin (2004) familiarized 6-month-old infants with two types of objects moving in different trajectories behind an occluder—those objects being a red square that always came out on the right side and a yellow cross that emerged on the left. In the test trials infants saw a red cross or a yellow square moving under the occluder, and the critical questions were whether they could anticipate the path of the object and whether their prediction would be based on color or shape. The authors reported that 6-month-old infants were able to make predictions and their anticipatory eye movements showed a color-bias in this artificial categorization task. Also using anticipatory eye movements, Southgate and colleagues (Southgate, Senju, & Csibra, 2007) examined toddlers' understanding of beliefs and intentions. In their study, 25-month-old children saw an adult who intended to retrieve an object from one location but did not know that the object had been moved. Just before she returned to retrieve the object, the scene was paused and the two alternative locations were highlighted. Most 2-year-olds in this study moved their eyes to the side where the object was originally stored, suggesting that they expected the adult to behave based on what she knew, not on the basis of where the object actually was located. Using the same paradigm, Senju et al. (Senju et al., 2010; Senju, Southgate, White, & Frit, 2009) showed that autistic children and adults fail to spontaneously anticipate actions involving false beliefs.

As an "on-line" measure, eye movements also provide rich information about the time course of cognitive processes. For example, the meaning of the sentence "Put the frog on the napkin in the box" is temporarily ambiguous. "To put the frog on the napkin" is the most likely interpretation until one hears "in the box," at which point the sentence has to be reanalyzed. Most adults can revise their interpretations quickly. The question here is whether young children are also able to. Using the "visual world" paradigm originally developed for adults (Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995), Trueswell et al. (Trueswell, Sekerina, Hill, & Logrip, 1999) showed 5-year-olds four things on a table—i.e., a toy frog, a napkin, another toy frog on a napkin, and a empty box—and asked them to move things according to the instruction. They measured the likelihood of looking at each object as the sentence unfolded over time. The data indicated that children had a hard time deciding which frog was the intended target. This so-called "kindergarten-path" effect has inspired numerous eye-tracking studies of children's language comprehension (e.g., Choi & Trueswell, 2010; Snedeker & Trueswell, 2004; see Trueswell, 2008).

Eye movements can also be part of the stimulus rather than merely responses. The gaze-contingent display is a technique in which the stimulus changes in real-time depending on where the viewer looks (Duchowski, Cournia, & Murphy, 2004; McConkie & Rayner, 1975; Rayner, 1975). This technique is used extensively in research on reading (see Rayner, 1998) and human-computer interaction (Duchowski et al., 2004). It can also be a powerful tool for developmental research. In a series of recent studies on parent-child shared storybook reading (Feng & Guo, 2011, under review), we found that prereading children often do not know whether adults read from pictures or texts; meanwhile, many parents are unaware of where on the page their children attend to and are therefore ineffective in regulating joint attention. We then showed children a moving cursor indicating where parents were looking in real time. Seeing eye movements of adult readers significantly increased children's concept of print, attention to print, and word learning. Similarly, we showed parents children's eye gaze in real time, and observed significant improvements in their joint attention regulation. Gaze-contingent display techniques have a lot of potential in developmental sciences both as a research method and as an intervention tool.

FROM EYE GAZE TO COGNITION

The eye–mind relationship is often more complicated than meets the eye. To begin with, we cannot assume attention is on the spot reported by the eye tracker. Measurement errors are only part of the problem. We extract useful information from an area around the line of gaze. This region—known as the *perceptual span* in the reading literature (Rayner, 1998)—varies with tasks, participants, and processing load. For example, skilled adult readers' perceptual span extends approximately 15 letter spaces, whereas beginning readers have a much smaller span (Rayner, 1986); the perceptual span also shrinks as reading becomes difficult (see Rayner, 1998). The size of the fovea is not a reliable estimate of the perceptual span because information processing may occur simultaneously in the fovea and in the parafovea (Engbert, Nuthmann, Richter, & Kliegl, 2005; Findlay & Walker, 1999). For example, an infant may attend to fine features of the focal stimulus while also extracting gross features and motion information from a larger region. This requires more sophisticated theories and data analyses than we have today.

Another source of errors is our imperfect oculomotor control. Our eyes do not always end up where we intended. We frequently overshoot or undershoot the target, and eye movement records cannot tell them apart. In addition, saccadic eye movements take time to plan and execute. The saccadic delay, though often cited as around 150 msec, varies greatly from trial to trial (Carpenter, 1999), making it difficult to infer when a cognitive decision is made (Feng, 2009). Most importantly, the voluntary control of eye movements continues to develop throughout childhood (Klein & Foerster, 2001). Johnson (1990) suggested that saccadic eye movements are mostly reflexive in the first couple of months postnatally because the primary visual cortex and other cortical structures to control voluntary eye movements are immature at birth. The ability to suppress reflexive saccades and plan cognitively-driven eye movements does not reach adult levels until adolescence (Kramer, de Sather, & Cassavaugh, 2005). This has important implications for developmental research. For example, the "kindergarten-path" effect (Trueswell et al., 1999) was originally explained in term of children's biases toward certain syntactic structures. However, the failure to suppress eye movements toward an incorrect target occurs at an age when children have great difficulty suppressing automatically-generated saccades in general (Luna, Velanova, & Geier, 2008; Munoz, Armstrong, & Coe, 2007). This realization has turned into a general account of language acquisition emphasizing the development of inhibitory control in children (Novick, Trueswell, & Thompson-Schill, 2005; Trueswell, 2008).

Where children look—and by implication where they do not look—has important developmental consequences. For example, Johnson and colleagues (Johnson, Slemmer, & Amso, 2004) eye tracked 3-month-old infants in a study on children's object perception when part of a moving object was occluded. They found in the test phase that some children appeared to have perceived the object as a whole ("perceivers") and others did not ("non-perceivers"). When they looked at how the perceivers and non-perceivers observed the scene during earlier habituation trials, the perceivers spent more time scanning the non-occluded parts of the object and tracking its motion, compared to the non-perceivers. The authors suggested that where infants look limits the information input and hence influences the development of object concepts. This is further elaborated in a theory of perceptual development that highlights the contribution of oculomotor system (Johnson, Davidow, Hall-Haro, & Frank, 2008).

Like any other measures of behavior, eye movements bear a complex relationship with the underlying psychological constructs. We must make simplification assumptions—both technical and theoretical—and it is crucial that these assumptions be made explicitly. Trueswell (2008) presented a nice example in which he articulated how the eye gaze indicates attention, how visual attention is driven by processing decisions, and how these decisions reflect the underlying linguistic processing. Each of these "linking hypotheses" may be open to alternatives, but it is the clarity of the conceptual analysis that distinguishes high-quality studies from superficial ones.

MORE QUESTIONS ABOUT EYE-TRACKING

I now turn to more practical issues on conducting developmental eye-tracking studies. The most frequently asked questions are perhaps: "Should I do an eye-tracking study?" and "Which eye-tracker should I buy?" With some of the conceptual issues cleared away, I will try to provide my perspectives on these questions.

When Should I Use Eye-Tracking?

This is always a tough question to answer, in part because the payoff depends on the research question. One successful strategy to begin eye-tracking research is to add eye-gaze measures to existing protocols, as did Johnson et al. (2004) and Southgate et al. (2007). It is also helpful to borrow protocols from other fields or populations (e.g., Trueswell et al., 1999). There are numerous success stories in the literature in which eye-movement research not only enriched our understanding of a particular phenomenon but also reshaped how we think about development. That is the ultimate appeal of the methodology.

On the cost side, the initial investment is relatively easy to quantify in monetary terms, and the cost of maintaining an eye tracker is generally minimal. There are, however, other costs to consider. One needs to budget sufficient time and resources, as eye tracking can be technically involved. While many equipment venders advertise turn-key systems with integrated experiment design and data-analysis software, at some point one will graduate from these "canned" functions. Someone in the lab will need to develop new paradigms and/or data analysis methods. Another potential downside of eye tracking has to do with attrition. It is not uncommon that a small percentage of children cannot be tracked for various reasons, although eye trackers continue to improve in this aspect. Calibration can be boring or frustrating for some children, particularly in infant studies. And finally, depending on the age of the participants, the task, and the equipment, missing data can be a significant issue because of excessive head movements, loss of interest, or other problems. In deciding whether or not to use eye tracking, one should carefully weigh the costs and benefits. Perhaps the best advice in this case is to talk with colleagues.

Which Eye-Tracker Should I Buy?

For someone new to eye tracking, the best advice, again, often comes from colleagues (see Gredeback et al., 2010; Trueswell, 2008). Most developmental researchers will probably get one of two types of eye trackers. A head-mounted system uses a light-weight helmet or an eye-glasses frame to fix the camera relative to the head. There is often another scene camera to capture the point of view from the participant, on which the eye gaze can be overlaid. High-end mobile systems allow free movement of the viewer by recording images of the eyes and the scene to a digital recorder for later off-line analysis. They offer enticing possibilities to study development in the real world. On the other hand, head-mounted eye trackers may not be suitable for infants and very young children. And due to the free head movement, frame-by-frame coding is often required to know what the viewer is looking at.

Remote eye trackers, in contrast, use a stationary camera to acquire the image of the eye. Due to limitations of the camera's field of view and resolution, a remote tracker requires the eyes to be within a certain position from the camera. Some popular remote eye-trackers are integrated with LCD monitors, although others can be configured to work with real-world objects or scenes. Because weight is less of a concern, high-end remote trackers often offer better spatial and temporal resolution than head-mounted systems. They are a natural choice if stimulus presentation is primarily on the screen; they also prove to be indispensible in infancy research (Aslin & McMurray, 2004; Gredeback et al., 2010).

A number of techniques—e.g., the dark pupil and the bright pupil methods—have been used to track the eyes (Duchowski, 2003). High-end systems often use a combination of technologies to ensure high tractability across individuals and lighting conditions. Tractability has not been a major issue in our research, although we do find that systems differ in the amount of head and body movements they tolerate. Be sure to test the eye-tracker with the target population of your research before making a purchasing decision.

Over time, technical and software support become more and more important. Creative researchers will push the limit of the system, particularly the stimulus presentation and data analysis software. Check to see if the company provides a stable, up-to-date software development kit. Talk to their technical staff to get a sense whether you (or your student) will receive help developing a new paradigm or a new data analysis.

Where Can I Go for Further Information?

There are many other resources to consult. Duchowski (2003) provides an excellent introduction to eye tracking. You can receive great (occasionally contradicting) advice by posting your questions to the eye-movement mailing list at https://www.jiscmail.ac.uk/cgi-bin/webadmin?A0=eye-movement. The wiki page at http://www.cogain.org/wiki/Eye_Trackers is also a good resource for researching various eye trackers, not all of which are suitable for research. Visit vendors at conference exhibits and they can often recommend a researcher in your area with whom to speak. Some manufacturers have academic discounts. And if cost is a limiting factor, some companies have rental programs. Your best bet, though, is to collaborate with a colleague with expertise in eye tracking. You will be in a much better position to decide which eye tracker best suits your research needs.

In summary, the rapid advancement of eye-tracking technology continues to lower the cost of entry. Meanwhile more and more developmental researchers transform their area of research with innovative uses of eye-gaze analyses. Interested readers should consult Gredeback et al. (2010) and

Aslin and McMurray (2004) for in-depth discussions of infant eye-tracking research. Trueswell (2008) provides an overview of developmental psycholinguistic research. Rommelse, Van der Stigchel, and Sergeant (2008) is an authoritative review of eye-movement research in childhood and adolescent psychiatric populations. Readers interested in the development of oculomotor control and its neurological underpinning should find Luna et al. (2008) and Munoz et al. (2007) helpful.

There are always costs associated with adopting a new method, and I do not mean to suggest that eye tracking is any different. But if you are with me thus far, chances are you are weighing the potential benefit of eye tracking. I, for one, will be happy to answer any questions you have. And should I not be able to provide you with an answer, rest assured that there is an ever-growing community of developmental eye trackers, ensuring that someone *will* be able to.

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