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Advances in Relating Eye Movements and Cognition

Mary M. Hayhoe
Department of Brain and Cognitive Sciences
University of Rochester

Measurement of eye movements is a powerful tool for investigating perceptual and cognitive function in both infants and adults. Straightforwardly, eye movements provide a multifaceted measure of performance. For example, the location of fixations, their duration, time of occurrence, and accuracy all are potentially revealing and often allow stronger inferences than measures such as percentage correct or reaction time. Another advantage is that eye movements are an implicit measure of performance and do not necessarily involve conscious processes. Indeed, they are often a more revealing measure than conscious report (Hayhoe, Bensinger, & Ballard, 1998). Although the mere presence of gaze at a particular location in the visual field does not reveal the variety of brain computations that might be operating at that moment, the experimental context within which the fixation occurs often provides critical information that allows powerful inferences. The articles in this thematic collection are excellent examples of this.

EYE MOVEMENTS AND COGNITIVE PROCESSES: THE GENERAL PROBLEM

As Aslin and McMurray (2004/this issue) point out in their introduction, there is a long history of attempts to use eye movements to infer cognitive processes in adults. Despite the tradition of work on saccadic eye movements in which they are treated as more or less reflexive, saccades are quintessentially voluntary movements (Kowler, 1990). It is well established that saccades are preceded by an attentional shift to the target location (Gottleib, Kusunoki, & Goldberg, 1998;

Requests for reprints should be sent to Mary M. Hayhoe, Department of Brain and Cognitive Sciences, University of Rochester, Rochester, NY 14627. E-mail: mary@cvs.rochester.edu

Kowler, Anderson, Dosher, & Blaser, 1995) and a variety of psychophysical and imaging studies support the idea that the shifts in attention made by the observer are usually reflected in the fixations (Corbetta, 1998). In addition, spatial memory, planning, and sensitivity to target probability and reward are all fundamental aspects of the saccadic system (Kowler, 1990; Platt & Glimcher, 1999; Stuphorn, Taylor, & Schall, 2000). Eye movements in reading have long been a focus of research because of the regularity of fixation patterns and the tight link between fixations and comprehension (Rayner, 1998). In the investigation of more general visual processes, perhaps the most influential work was that of Yarbus (1967), who showed that the fixation patterns on a picture were fundamentally different when observers were trying to answer different questions about the picture. The significance of this finding was that it revealed in a particularly compelling way that "seeing" is not a unitary process and is inextricably linked to the observer's cognitive goals. For example, the instruction to remember the position of the objects and people in the room might easily be taken as the job of vision. The fact that other instructions produced strikingly different patterns means that the role of vision is much more complex.

This study reveals both the strengths and limitations of using eye movements to infer perceptual and cognitive processes. On the one hand, it reveals the importance of the task in determining where participants look, a point that is discussed extensively later. On the other hand, the particular fixations do not reveal much more than that the observer attended to these locations. The attempt to understand pattern perception by examination of scan paths (Noton & Stark, 1971) has not been particularly revealing, despite the existence of some regularity in the fixation patterns. Viviani (1990) discussed other similar examples of failure to find a relation between fixation patterns and cognitive operations. In these kinds of passive viewing situations it seems likely that the central limitation is that the experimenter has little control of, and does not know, what the observer is doing, and consequently inferences are limited. Thus, although a given cognitive event might reliably lead to a particular fixation, the fixation itself does not uniquely specify the cognitive event.

STUDIES IN ADULTS: THE IMPORTANCE OF TASK

In adults, the most revealing situations have been those in which the task structure is clear and those that provide an external referent for the internal computations. An example of this is a study by Ballard, Hayhoe, and Pelz (1995). They had observers copy simple colored block patterns on a computer screen by picking up blocks with the mouse and moving them to make a copy, as shown in Figure 1. Observers demonstrated regular, stereotyped fixation patterns. In the course of copying a single block, the most common sequence was to fixate a block of a particular color, then fixate a corresponding block to pick it up. Observers then refixate the

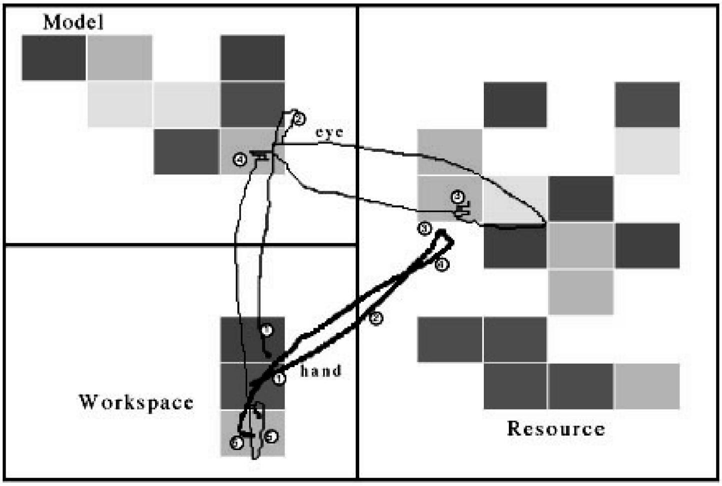

FIGURE 1 Block copying task used by Ballard, Hayhoe, and Pelz (1995). Blocks in the area on the right are moved using the mouse to copy the model pattern on the top left. The thin trace shows eye position; the thick trace shows hand cursor position. From "Task Constraints in Visual Working Memory," by M. Hayhoe, D. Bensinger, and D. Ballard, 1998, *Vision Research, 38,* 125–137. Used by permission.

block in the model, followed by a fixation on the location in the copy for placement. The sequence is then repeated. Given the requirements of the task, it seems natural to suppose that block color is acquired during the first fixation, the next fixation is for guiding the mouse movement for pickup, the third fixation is to acquire block location, and the fourth is to guide block placement. Although this is only a rudimentary description of the ongoing computations, the basic structure of the task allows one to link the visual operations fairly closely in time with the occurrence of eye and hand movements. Ballard et al. called this a "just-in-time" strategy, where observers acquire the specific information they need just at the point at which it is required in the task. The paradigm can then be used to ask more detailed questions about task performance, such as the extent of memory use (e.g., Hayhoe et al., 1998).

Because of the importance of task structure in interpreting the eye movements, a variety of successful investigations in adults have involved observers engaged in everyday tasks, such as tapping a sequence of targets on a table (Epelboim et al., 1995), driving (Land & Lee, 1994), table tennis (Land & Furneaux, 1997), cricket (Land & McLeod, 2000), tea making (Land, Mennie, & Rusted, 1999), and sandwich making (Hayhoe, Shrivastrava, Myruczek, & Pelz, 2003). The central result of all these investigations is that fixations are tightly linked in time to the evolution of the task, in a similar manner to that described in the block copying task. When making tea or sandwiches, very few fixations fall on objects that are irrelevant to the task (Hayhoe et al., 2003; Land et al., 1999). During the task, the fixations are tightly linked in time to the actions, such as grasping and moving objects and moving on to the next object when the needs of the current action have been met (Land et al., 1999).

Not only is the sequence of fixations tightly linked to the task, but in addition, many of the fixations appear to have the purpose of obtaining quite specific information. For example, in driving, Land and Lee (1994) showed that drivers reliably fixate the tangent point of the curve to control steering around the curve. The angle of gaze with respect to the body then gives the required steering angle. In cricket, players exhibit very precise fixation patterns, fixating the bounce point of the ball just ahead of its impact (Land & McLeod, 2000). Land and McLeod showed that the location and time of the bounce provided batters with the information that was needed to estimate the desired contact point with the bat.

The specificity of the information acquired in different fixations is indicated not only by the ongoing actions and the point in the task but also by the durations of the fixations, which vary over a wide range (Hayhoe et al., 2003). It appears that a large component of this variation depends on the particular information required for that point in the task, fixation being terminated when the particular information is acquired. In the block copying task, fixations for acquiring block location took about 75 msec longer than those for acquiring color (Hayhoe et al., 1998). Pelz et al. (2000) observed different distributions for three phases of a model building task: reading the instructions, searching for the pieces, and putting the pieces together. Each phase had a characteristic distribution of fixation durations. In any particular instance, the duration of a fixation will, of course, depend on a variety of factors, in addition to the time required to acquire the currently relevant information. However, the extent to which fixation durations vary moment by moment during task performance underscores the overriding control of visual operations by the internal agenda rather than the properties of the stimulus as well as the range of different kinds of visual information that can be extracted from the same visual stimulus. Indeed, many parameters of oculomotor behavior generally thought to be low level, such as the main sequence (the speed of movement as a function of its magnitude), have been found to depend on task factors (Epelboim et al., 1995; Epelboim et al., 1997).

THE CONTRIBUTION OF INFANT STUDIES

All the findings just discussed support the general enterprise of measuring eye movements and suggest that the interpretation of fixation patterns depends on a thorough understanding of the specific task demands. This presents a particular challenge for infant eye movement studies because infants are usually passive viewers, hand movements or locomotion are not involved, and it is not possible to instruct infants to do a particular task. These circumstances make the interpretation of eye movement measures more difficult. The articles in this thematic collection have met this challenge in a variety of interesting ways.

One particularly creative use of eye movements is demonstrated by McMurray and Aslin (2004/this issue). They used anticipatory fixations to signal how 6-month-old infants categorize objects. The infants were trained to associate the location of a reinforcer with a particular shape. After training, the infants anticipate the occurrence of the reinforcing event by directing gaze at its expected location, contingent on the shape just presented. By making changes to the stimuli on which the infants were trained, the investigators were able to determine how the infants generalized across different stimuli, by seeing where they expected the reward to appear. Because the fixation in the reinforced location precedes the reinforcing event, this is a particularly compelling indication that the shape has been classified in a particular way. As McMurray and Aslin discuss, this method has an advantage over habituation and similar paradigms because it is less susceptible to criterion effects.

Anticipation was used in a similarly compelling way in the experiment by Gredebäck and von Hofsten (2004/this issue). They tracked the development of 6- to 12-month-old infants' ability to predict the reappearance of a circularly moving object from behind an occluder. Even at 6 months, infants show an ability to predict the location and time of reappearance of the object, and this ability steadily improves over the following 6 months. Fixations on the location where the object reappears occur later in time, when the object is moving more slowly. Together with the fact that the path is circular, this suggests that 6- to 12-month-olds have the ability to model complex dynamic properties of the world. As with the McMurray and Aslin (2004/this issue) study, these fixations can only be driven by the infant's internal predictions of the state of the world.

There has been less use of anticipation in adult studies of vision, which are typically observational. (Indeed, in many traditional paradigms in adult eye movement research, considerable effort is taken to prevent prediction.) In Land and McLeod's (2000) investigation of cricket, batsmen anticipated the bounce point of the ball, and more skilled batsmen arrived at the bounce point about 100 msec earlier than less skilled players. These saccades were always preceded by a fixation on the ball as it left the bowler's hand, showing that batsmen use current sensory data in combination with learned models of the ball's motion to predict the location of the bounce. Other evidence of anticipation in the adult literature comes from the occurrence of "look-ahead" fixations, where observers often glance at an item a second or two before they are about to use it (Hayhoe et al., 2003; Pelz & Canosa, 2001). The common occurrence of these look-aheads suggests that prediction is an intrinsic aspect of normal cognitive and perceptual function. Thus it may be fruitful for studies of adult eye movements to take advantage of techniques that use anticipation that were developed for infants. Both the McMurray and Aslin

(2004/this issue) and the Gredebäck and von Hofsten (2004/this issue) techniques could be useful for a range of ages and have distinct advantages over verbal report.

The article by Johnson, Slemmer, and Amso (2004/this issue) also shows that eye movements can reveal information about internal representations. They address the issue of interpolation in space, rather than time. They showed that infants who perceptually complete a partially occluded rod, as measured in a habituation paradigm, also reveal different fixation patterns. They tend to make more scanning movements along the length of the rod and follow it as it moves behind the occluder. This result is important in that it validates the use of eye movements as a measure of perceptual completion and provides more extensive data than paradigms such as habituation. Although the interpretation of individual fixations is still limited, in the sense that we do not really know what processes are occurring when an infant makes a fixation from one part of the rod to another, the occurrence of reliably different patterns can be used as an index of pattern completion across different stimuli and ages. This technique, too, could be very usefully extended to studies of adult visual perception and to nonhuman primates.

As mentioned earlier, viewing static pictures is one of the more difficult situations for making inferences about perceptual and cognitive mechanisms. The attempt to link fixations to "informative" regions in pictures (see Viviani, 1990, for a discussion) is limited by the fact that informativeness is not a general visual property and can only be defined with respect to a particular task. Hunnius and Geuze (2004/this issue) add a new element by using dynamic pictures of faces, stimuli that are more ecologically relevant than static pictures or line drawings of faces. Interestingly, this turns out to be important. Infants spend more time looking at the mouth than with less realistic stimuli, and much less time looking at the edge of the face. Note that studies of faces using reverse correlation methods have identified the corners of the mouth as a primary locus of emotional content in faces (Kontsevich & Tyler, 2004). Given that the eye and mouth regions contain the information needed in social interactions, this is again consistent with the active, information-seeking role for eye movements described earlier. Infants scanning patterns showed a clear developmental progression between 6 and 26 weeks of age, with scanning patterns stabilizing around 18 weeks, slightly later than with static stimuli.

FUTURE DIRECTIONS

All the articles in this thematic collection reveal the importance of the development of cognitive and perceptual skills in determining fixation patterns. This is not a process that is confined to young infants. Adult studies (e.g., sports and driving) reveal that fixation patterns reflect that observers have learned the particular fixation patterns required by the task (Chapman & Underwood, 1998; Land & Lee, 1994; Land & McLeod, 2000; Shinoda, Hayhoe, & Shrivastava, 2001). In more controlled experiments, it has been demonstrated that saccade targeting is quite sensitive to the probabilistic and reward structure of experiments (He & Kowler, 1989; Platt & Glimcher, 1999; Stuphorn et al., 2000). Thus, matching eye movement patterns to the dynamic properties of the world is an ongoing process. This suggests that there is a tremendous opportunity for the investigation of eye movements over a wider range of ages and perceptual domains.

CONCLUSIONS

The last decade has seen a burgeoning of studies on eye movements, largely made possible by the development of eye trackers that can be used fairly easily, without interfering with ongoing behavior. In addition to the infant studies described in this thematic collection and the investigation of natural behavior in adults, eye movements have also become an important measure in spoken language comprehension (e.g., Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995, and subsequent work). Despite the intrinsic difficulty of making inferences about cognitive processes from eye movements and the special challenges of infant research, the focus on active information acquisition in all these domains has allowed a variety of interesting discoveries. The potential of eye movements as a performance measure is far from exhausted and is likely to be an increasingly important tool in research on visual perception and motor coordination.

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