Part 1

Eye-Tracking: Characteristics and Methods

Part 2

Eye-Tracking: Research Areas and Applications

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Eye-Tracking: Characteristics and Methods

Introduction

Eye movements are arguably the most frequent of all human movements (Bridgeman, 1992). Large ballistic scanning movements called saccades typically occur 3-4 times every second. As one early researcher put it, "there seems to be an almost ceaseless twitching, as if rest for more than an instant were the one thing not to be endured" (Stratton, 1906). Indeed, virtually all animals with developed visual systems actively control their gaze using eye or head movements (Land, 1995). This frenetic movement is a consequence of the enormous amount of visual information that is available to an organism. Rather than devote resources to processing it all in detail, evolution appears to have selected a solution whereby small portions of the visual world are inspected in a rapid sequence (Treue, 2001). Consequently, the human eye monitors a visual field of about 200º, but receives detailed information from only 2º (Levi, Klein, & Aitsebaomo, 1985). This region, about the size of a thumbnail at arm's length, is called the fovea, and is jerked around at speeds of up to 500º a second, during which its sensitivity drops to near blindness levels (Matin, 1974; Thiele, Henning, Kubischik, & Hoffmann, 2002). During the 200-300 milliseconds it is at rest, however, over 30,000 densely packed photoreceptors in the fovea provide high acuity color vision.

Eye movements, therefore, are fundamental to the operation of the visual system. 'Eye movement research' relates to a patchwork of fields more diverse than the study of perceptual systems, however. Due to their close relation to attentional mechanisms, saccades can provide insight into cognitive processes such as language comprehension, memory, mental imagery and decision making. Eye movement research is of great interest in the study of neuroscience and psychiatry, as well as ergonomics, advertising and design. Since eye movements can be controlled volitionally, to some degree, and tracked by modern technology with great speed and precision, they can now be used as a powerful input device, and have many practical applications in human-computer interactions.

History & Methods

The first data regarding eye movements were obtained either through introspection or by the experimenter observing a subject's eye using a mirror, telescope or peep hole. These methods were dubious, of course, since any feature of the eye being studied could be obscured by the eye doing the studying. The first significant advance, therefore, was the invention of mechanical devices that would translate the eye's movements into permanent, objective records of its motion. (Taylor, 1971)

At the end of the nineteenth century, eye movement research served a pressing theoretical need. As Delabarre wrote, "[m]any problems suggest themselves to the psychologist whose solution would be greatly furthered by an accurate method of recording the movements of the eye" (Delabarre, 1898). Phenomena such as visual illusions and aesthetic preferences were commonly explained away in terms of eye movements, and yet there was little data beyond introspection to support these hypotheses. In some of the first empirical studies, Javal (1879) used mirrors to observe the eye movements of subjects while reading, and was the first to note that the eyes moved in a series of 'jerks'. These fixations were counted by placing a microphone on a closed eyelid while the subject read monocularly. Each time the bulge of the moving cornea bumped the microphone, a saccade could be counted (Lamare & Javal reported in Tinker, 1928). An approximate measure of the location of these fixations could be obtained by inducing an afterimage in the subject's eye with a bright light, and then asking them to report the location of the afterimage as they read (Erdmann & Dodge, 1898).

Such observational methods, however, were limited by the accuracy and memory of the person making the observations (Dodge, 1906). An objective record of the motion of the eyes was required. Since "plaster of Paris will attach itself firmly and immovably to any moist surface", Delabarre (1898) was able to fix a small moulded cap to a sufficiently "cocainized eye". A wire ran from the cap to a lever, which drew the horizontal movements of the eye on the smoked surface of a kymograph cylinder. With his lids propped open, the subject (usually Delabarre himself) could read text through a hole drilled in the cap. It was reported that the cap "will not detach itself until it becomes thoroughly soaked with tears". "As to whether there is any danger to the eye to be feared from using it in this manner," Delabarre writes, "I cannot say with assurance". He reports that he was able to record his own eye movements for up to an hour, and suffered no ill effects after a week's recuperation.

Huey (1898) simultaneously developed a similar mechanical method to study the behaviour of subjects reading an article in the magazine *Cosmopolitan*. By varying the distance between the subject and the text, he found that ‘the number of jerks was shown to be a function of the matter read rather than of the arc described by the eye’s rotation’. Although the temporal resolution of his apparatus was too poor to measure the speed of the eye movements, he conjectured that they maybe so fast that “ we really do not see foveally what we read except at the few points on the ordinary line where the eye pauses.”

Huey and Delabarre were able to gain valuable first insights into the function and characteristics of eye movements, yet their mechanical devices were criticised for impeding motion and straining the eye. To overcome these flaws Dodge and Cline (1901) invented a device to produce “a group of what we may justly claim to be the first accurate measurements of the angle of velocity of the eye movements under normal conditions.” Dodge’s method, as it became known, used photography to record the movements of the eye accurately and non-invasively, and the same basic technique continued to be used into the 1970s (Taylor, 1971).

If the eye were a perfect sphere and rotated about its center, a light ray would be reflected at a constant angle despite rotations. Given that the eye has neither of these characteristics, however, the reflection of a ray of light bouncing off the bulge of the cornea will move as the eyes move. In Dodge’s first device, a vertical line of light was bounced off the cornea and fell on a horizontal slit. Behind this slit was a photographic plate that moved vertically, regulated by the escape of air from a cylinder. When developed, this plate showed time on the y-axis and horizontal motion of the eye on the x-axis.

Further developments in the 1920s in labs at Chicago and Stanford allowed two photographical recordings to be made simultaneously. In this way, head position could be recorded by reflecting a light off a bead on a pair of spectacles (Miles & Shen, 1925), or the horizontal eye movements of one eye could be recorded with the vertical movements of another, producing the first two dimensional eye movement records (Gilliland, 1921). Later technology allowed the reflection beam from a single eye to be split, its vertical and horizontal components measured and recombined in the form of a fixation dot recorded on a film reel. This methodology allowed researchers such as Buswell (1935) to produce some of the first two-dimensional scan paths of subjects inspecting images. Whilst a thread of research continued for a couple of decades investigating the relationship between mental imagery and eye movements (H. Clark, 1916; Goldthwait, 1933; Perky, 1910; Stoy, 1930; Totten, 1935) the vast bulk of eye movement research in the first half of the century investigated the processes, habits, and individual and cultural differences involved in reading (Jacobson & Dodwell, 1979; Stone, 1941; Tinker, 1928, 1946; Walker, 1933).

The 1960s saw a renaissance of turn-of-the-century, invasive techniques of Delabarre (1898) and Huey (1898) for recording eye movements. Researchers found that rather than using sticky plaster of Paris, a device could be tightly clamped to the eye using suction. Yarbus (1965) used a tiny valve to withdraw fluid from under a contact lens; Fender (Fender, 1964) found that sodium bicarbonate would osmose through the tissue of the eye and create negative pressure. A tiny plane mirror could be attached to the surface of the contact lens, and its reflection could be recorded much as a corneal reflection. To avoid a tear film clouding the lens, researchers also mounted the mirrors on stalks that protruded out from the eye (Fender, 1964). As well as reflecting with mirrors, these stalks could produce their own light source if fitted with small lamps (Byford, 1962) or glowing radioactive tritrium (Nayrac, Milbled, Parquet, Leclerco, & Dhedin, 1969). Finally, a non-optical method employed a scleral search coil: a contact lens embedded with two orthogonal wire coils that would perturb a magnetic field surrounding the subject's head (D. A. Robinson, 1963). Due to the discomfort produced by these contact lens methods, all but the last have dropped out of use, and that is primarily used in animal research.

In the early 1970s, a host of techniques were developed in which the eye was scanned with a television camera, and certain distinct features were electronically detected and localised. These methods are most sensitive to high contrast, and so one technique scanned the image of the eye for the limbus, the boundary between the white sclera and the coloured iris. If small electronic photoreceptors are aligned near the limbus, their output will vary according to the amount of white sclera exposed. This method will give a very rapid measure of horizontal eye movement (Young, 1970). Unfortunately, the iris is large and often obscured by the eye lid, and vertical eye movements in particular are difficult to track with this method. An alternative is to scan for the lack of reflectance from the pupil ("dark-pupil" tracking), although there can be low contrast between this black circle and dark-brown irises. If the pupil is lit directly from the front, the light will bounce off the back of the retina and appear very bright ("bright-pupil" tracking), as it does in poorly taken flash photographs. This bright circle can then be more easily detected by a scanning technique (Merchant, Morrissette, & Porterfield, 1974).

All the methods described so far for recording eye movements are more precisely stated as methods for recording movements of the eye in relation to the head. In order to infer where the subject was looking in the world, researchers needed to ensure that the head was absolutely stationary and employ severe methods of restraint. These draconian means were obviated by the innovation in the 1970s of simultaneously measuring two optical characteristics of the moving eye. Since these features behaved differently under head movement and eye rotation, their differential could be used to calculate the ‘point of regard’, the place in the world where the subjects was actually looking (see Figure 1). Whilst such devices still needed to restrain the head with a bite bar or chin rest, they allowed slight movements of the head to be deconfounded from eye movements, and so produced more accurate gaze tracking.

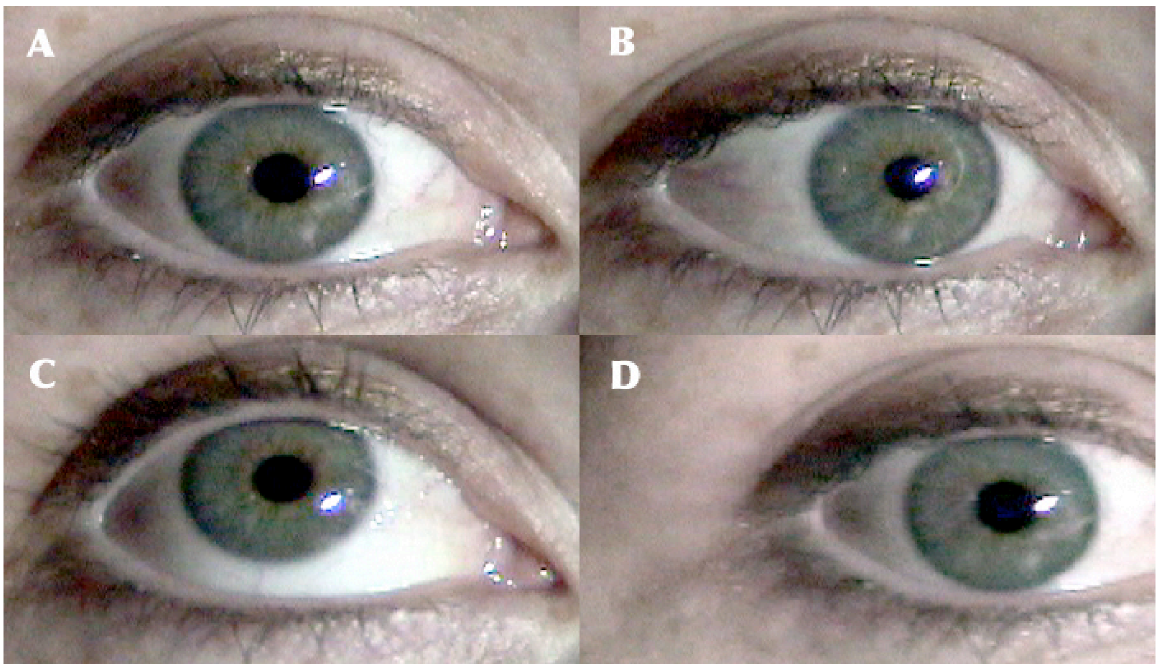

Figure 1. The corneal reflections produced by different eye-head positions. The corneal reflection appears as a bright white dot, just to the right of the pupil (A). The relative positions of the pupil and the corneal reflection change when the eye rotates around its vertical (B) and horizontal (C) axes. This relationship does not change, however, when the head moves and the eye is stable (D).

As described above, Merchant and Morrisette (*34*) employed a scanning method to detect the center of a brightly lit pupil. The same technique was also used to find the smaller, brighter corneal reflection. Since the position of the corneal reflection in relation to the center of the pupil remains constant during head translation, but moves with eye rotation, point of regard can be extrapolated. Like contemporary systems (Lambert, Monty, & Hall, 1974) the Honeywell oculometer was able to calculate what location on a screen was being fixated, whilst being so non-invasive that the subject was often not aware of its presence in the room.

A similar logic lay behind the development of the dual Purkinje image eye tracker (Cornsweet & Crane, 1973). Light bouncing off the eye produces a series of reflections. The first, and the brightest, is the corneal reflection. A second image is reflected off the rear surface of the cornea, and another two by the front and rear of the lens. The four Purkinje images all have different motions in relation to eye rotation. The dual Purkinje image eye tracker measures the disparity between the first and the fourth images by adjusting a series of mirrors with servomotors until the two images are superimposed upon electronic photoreceptors. The degree to which the mirrors had to be moved is directly related to eye rotation and is independent of head translation, although the head still must be held in place with a chin rest or bite bar so that the eye can be detected by the equipment. The advantage of the Purkinje eye tracker is that since it is only limited by the speed of the servomotors, it is remarkably fast and accurate. The continuous, analogue signal was sampled at a rate of 300Hz in initial incarnations, and modern computers can sample at up to 1000Hz.

The balance between obtaining a high-precision record of an observer's point-of-regard and allowing natural head- and body-movements is where much of the technological advancement in eye-tracking takes place in the current state of the art. While systems like the Dual Purkinje eyetrackers require that a subject's head be immobilized by a chinrest or bitebar, new headband-mounted eyetrackers point an additional "scene camera" at the subject's field of view from the subject's perspective, thus allowing point-of-regard to be superimposed on the scene camera's image regardless of where or how the subject moves (Ballard, Hayhoe, & Pelz, 1995; Land & Lee, 1994; Tanenhaus, Spivey Knowlton, Eberhard, & Sedivy, 1995) (see Figure 2). Recent table-mounted remote optical eyetrackers have also been developed that allow some natural head movement while sitting in front of a computer screen for two-dimensional stimulus presentation.

Figure 2. A subject wearing a light, head-mounted eye tracker. The eye monitor, with cross hairs on the pupil and corneal reflection is shown in the top right. The view from the scene camera, with the subject's point of gaze superimposed, can be seen in the bottom right.

One particularly important, and frequently used, method in eyetracking concerns not just the eyetracker itself but the yoking of the eye-position signal with real-time stimulus presentation: gaze-contingent display paradigms. The visual system receives highly detailed information from the small part of the visual field that the eye is fixating at that moment; and yet the target for each detailed fixation is planned on the basis of information gathered from low-resolution peripheral vision. This relationship between peripheral information and saccades has intrigued researchers. Its influence could only be assessed, however, if subjects were instructed to hold their eyes still, or if stimuli were presented tachistoscopically before an eye movement could occur. The next advance in eye movement research came when a cluster of researchers in the 1970s were able to overcome these limitations by coupling the system that was measuring eye movements with the system that was presenting stimuli to the subjects (McConkie & Rayner, 1975; Rayner, 1975; Reder, 1973). During the 30-50 milliseconds that the eyes take to saccade to a new location, the visual system's sensitivity is greatly reduced. To trigger a change in the visual stimulus during that brief period, the saccade must be detected within a few milliseconds of onset, the appropriate stimulus change calculated by the computer, and the screen display refreshed. Using a limbus reflection system that sampled eye position every millisecond, McConkie and colleagues (McConkie & Rayner, 1975; McConkie, Zola, Wolverton, & Burns, 1978) were able to produce 'saccade-contingent display control'. In such experiments, the characters of a line of text could be changed while a subject was reading, and hence the amount of information that a subject detected peripherally could be assessed.

The advent of gaze-contingent paradigms are a highly significant advance in eye movement research. It has had a far greater impact, perhaps, in its practical applications. The technology provides not merely a device for a scientist to study a subject's eye-movement behavior, but also a way for the subject's eye-movement behavior to manipulate a device.

Conclusion

Dodge and Cline's (Dodge & Cline, 1901) revolutionary invention allowed researchers, for the very first time, to make a permanent, objective record of a subject's eye movements using a non-invasive method. Although eye tracking techniques were refined in the following decades, there were no comparable breakthroughs until the advent of digital technology and image processing in the 1970s. Such advances have placed fewer constraints on experimental subjects, such that modern researchers are able to record the eye movements of freely moving subjects carrying out everyday tasks. We speculate that further developments will produce smaller, cheaper eye trackers, that may well populate a range of human-computer interfaces. The potential ubiquity of such devices underscores the need for a solid understanding of the cognitive and perceptual processes that govern human eye movements.

Eye-Tracking: Research Areas and Applications

Introduction

In this brief review of the research fields and practical applications of eye-movement technology, we will begin by considering studies of the relationship between eye movements and attentional mechanisms. Typically, in such experimental paradigms, a subject is required to fixate one location and direct their attention to another whilst psychophysical and neuropsychological measures are taken. We will then examine how the relationship plays out as observers view more complex, natural scenes. The relationship between visual perception and language has historically interested researchers, and we will review studies of eye movements during spoken language comprehension and production, as well as during the more specialized case of reading. In addition to perceptual demands, language processing is a cognitive task, and we shall see how eye movements are also implicated in cognitive processes such as memory, imagination, reasoning and decision-making. Perhaps as a result of this tight integration with a spectrum of perceptual and cognitive processes, eye movements are richly intertwined with behaviour in a variety of task domains, from social interaction to jet plane navigation. Moreover, differences between the eye movements of individuals can reveal differences in aptitude, expertise, and even pathology.

Spatial Attention And Scene Perception

Attending to a location in space aids processing of a stimuli at that location (Posner, 1980), and has neural correlates such as modulating the activity and sensitivity of neurons across the visual cortex (Treue, 2001). The link between attending to a location and launching a saccade to it is intuitive, yet it is equally clear that while fixing the eyes on one location, spatial attention can be directed to other locations. This spotlight of covert attention (Posner, 1980) was thought to be a mechanism behaviourally and neurally dissociable from eye movement control. However, it is highly likely that spatial attention and saccade planning are closely coupled during natural unconstrained eye movement (Findlay & Gilchrist, 1998). There is behavioural evidence that covert attention directed in one direction can lead to deviations in orthogonal saccades (Sheliga, Riggio, Craighero, & Rizzolatti, 1995), and neuropsychological evidence from single cell recordings suggesting that they utilize overlapping neural systems (Corbetta, 1998). Moreover, planning a saccade toward a location improves processing at that location, regardless of whether or not the saccade is launched (Hoffman & Subramaniam, 1995; Sheliga, Riggio, & Rizzolatti, 1994; Shepherd, Findlay, & Hockey, 1986), and indeed, evidence shows that microstimulation of neurons in the frontal eye fields can cause both a saccade to a certain location (D. A. Robinson & Fuchs, 1969), and, with a lower level of simulation, an absence of eye movement, but improved stimulus detection at that location (Moore & Armstrong, 2003; Moore & Fallah, 2001).

How are these coupled mechanisms of attention and eye movement deployed when a scene is viewed? Early eye movement recordings showed that a subject's fixations would center on interesting or informative areas of the image, leaving blank or uniform regions uninspected (Buswell, 1935). These findings have been recently replicated on a large scale. Wooding and colleagues installed an autonomous eye tracker in a public museum in London, and collected data from over 5000 subjects looking at works from the National Gallery (Wooding, 2002; Wooding, Muggelstone, Purdy, & Gale, 2002). They too found that only a small set of regions in a work of art were reliably fixated by viewers. Contemporary research aims to quantify what determines such regions of interest, and has identified two main components (Henderson, 2003). Firstly, statistical properties of the image such as high spatial frequency (Mannan, Ruddock, & Wooding, 1996; Mannan, Ruddock, & Wooding, 1997) and local contrast (Reinagel & Zador, 1999) have been found to be closely correlated with fixation likelihood. These "bottom-up" properties can be analysed to produce a 'salience map' of any given image, which may correspond to a neural representation in visual cortex (Itti & Koch, 2000; Li, 2002).

A second influence on scene perception comes "top-down," from knowledge, memories, beliefs or goals that the viewer may bring to the image. In an early demonstration of this effect, Yarbus (1965) presented various subjects with Ilya Repin's painting "An Unexpected Visitor", and asked them different questions, such as "What are the ages of the people in the painting?", "What had the family been doing before the visitor arrived?", and "How long had the visitor been away?" The scanpaths differed dramatically according to the question. The semantic content of the scene itself can also attract attention. If there are out-of-place objects in a scene, such as a farmyard animal in a hospital, these anomalies are frequently fixated (Loftus & Mackworth, 1978).

In order to scan a scene efficiently, some form of short-term memory for saccade location must be retained (Leek, Reppa, & Tipper, 2003; Posner, Rafal, Choate, & Vaughan, 1985). It is not clear exactly what kind of memory representation is constructed from these successive fixations (Henderson & Hollingworth, 2003; Irwin, 1991, 1996; Peterson, Kramer, Wang, Irwin, & McCarley, 2001). Although observers are surprisingly poor at detecting large changes across scenes under some circumstances (Bridgeman, Hendry, & Stark, 1975; O'Regan, Deubel, Clark, & Rensink, 2000; O'Regan, Rensink, & Clark, 1999; Rensink, O'Regan, & Clark, 1995; Simons & Levin, 1997), there is evidence that eye-fixation patterns are related to this form of scene recognition (Henderson & Hollingworth, 1999; Hollingworth, Schrock, & Henderson, 2001; Nelson & Loftus, 1980).

Eye movements have contributed to our understanding of the functioning of the visual system and attentional mechanisms. They have also provided insight into abnormal brain functioning. In the early years of eye movements research, Diefendorf and Dodge (1908) observed a deficit in smooth pursuit eye movements in patients with 'praecox dementia'. The relationship between this disorder, now known as schizophrenia, and eye movements was rediscovered in the 1970s (Holzman, Proctor, & Hughes, 1973; Holzman et al., 1974). During a saccade the eye moves in a rapid ballistic motion, but the human eye can also rotate slowly and smoothly when tracking a moving object. Schizophrenic patients, however, find it difficult to maintain these smooth pursuit movements, and launch more predictive, saccade eye movements than control subjects. On tasks that demand such predictive eye movements, however, schizophrenic subjects perform faster than controls (Karoumi, Ventre Dominey, & Dalery, 1998; McDowell, Clementz, & Wixted, 1996). In an 'antisaccade' task, subjects must inhibit an eye movement towards a suddenly appearing stimulus, and make a saccade in the opposite direction, something that schizophrenics find relatively difficult (Fukushima et al., 1988; Gooding, 1999; Sereno & Holzman, 1995). Lastly, schizophrenics also show different exploratory eye movements and scan paths when viewing faces and stimuli with emotional valence (Shimizu et al., 2000; Williams, Loughland, Green, Harris, & Gordon, 2003). These eye-movement differences are of great interest to researchers attempting to relate schizophrenia to dysfunction in specific brain mechanisms (Radant, Claypoole, Wingerson, Cowley, & Roy Byrne, 1997), and to clinicians diagnosing and treating the disorder. For example, abnormalities in eye movements can be seen in children susceptible to schizophrenia by the age of six, more than ten years before the highest risk for onset of psychosis (Ross, 2003).

Reading

The general characteristics of eye movements during perception have been studied in great depth during the process of reading (Rayner, 1978, 1998). In general, eye fixations during reading last approximately 200-250 milliseconds (Pollatsek, Rayner, & Collins, 1984). Reading saccades span on average about 2 degrees of visual angle, although this can be better expressed here in terms of a span of 7 to 9 letter spaces, since the number of letters covered remains largely invariant despite differences in text size or distance (Morrison & Rayner, 1981). The chances of an individual word being fixated vary according to whether it is a content word (85%) or a function word (35%) (Carpenter &

Just, 1983), and in relationship to the length of the word, with 2-3 letter words being skipped 75% or the time, but 8 letter words fixated almost always (Rayner & McConkie, 1976). Eye movements also vary as a function of the legibility of the text (Kolers, Duchnicky, & Ferguson, 1981; Morrison & Inhoff, 1981; Tinker, 1927), syntactic difficulty of the text (Ferreira & Clifton, 1986; Rayner, Carlson, & Frazier, 1983; Trueswell, Tanenhaus, & Kello, 1993), conceptual difficulty of the text (Jacobson & Dodwell, 1979; Rayner, Sereno, Morris, Schmauder, & et al., 1989; Tinker, 1928), and whether it is being read silently or out loud (Levy Schoen, 1981).

Saccades typically land between the beginning and middle of a word (Morris, Rayner, & Pollatsek, 1990). A reader will gather information from text at and around this fixation point. The size of this 'perceptual span' has been investigated using a gaze contingent paradigm (McConkie & Rayner, 1975). The text appears normal at the reader's fixation point and within a window of a certain character length, but beyond that the text is garbled. With a small window, reading is impaired. Reading is unaffected, however, when the window extends 3-4 letters to the left of fixation and 14-15 letters to the right, suggesting that there is a perceptual span of around 18 characters centered asymmetrically around the fixation point (McConkie & Rayner, 1976; Rayner, McConkie, & Zola, 1980). This asymmetry in the perceptual span is reversed for languages that are printed left to right (Pollatsek, Bolozky, Well, & Rayner, 1981), and rotated for those that run vertically (Osaka & Oda, 1991). Although readers typically move their eyes forward when reading, approximately 10-15% of saccades move backward, fixating previous letters or words. These regressive saccades are thought to be related to difficulties in processing an individual word, or difficulties in processing the meaning or structure of a sentence; in these cases, readers can accurately re-fixate the part of the text that generated confusion (Kennedy & Murray, 1987; Murray & Kennedy, 1988).

These features of eye movements during reading - gaze durations, saccade lengths, and occurrence of regressions - can be used to infer moment-by-moment cognitive processing of a text by the reader (Just & Carpenter, 1980). Details of the cognitive processes of pronoun resolution and co-reference, word frequency, lexical ambiguity, syntactic ambiguity, and discourse factors can all by gleaned from analyses of eye-movement patterns (for a review, see Rayner, 1998). As well as being an important data source about language processing, for this reason, eye movements can reveal significant differences between individuals. Differences in eye-movement patterns can be distinguished between fourth- and fifth-graders, successful and unsuccessful third-grader and undergraduates, dyslexics and non-dyslexics, and even graduate students and professors (Dixon, 1948; Eurich, 1933a, 1933b; Miles & Bell, 1929; F. P. Robinson, 1932). As a consequence, the study of eye movements while reading has considerable practical applications in education psychology (McKane, Maples, Sellars, & McNeil, 2001).

Language In A Visual And Social Context

Language use, more often than not, occurs within rich visual contexts, and the interplay between linguistic processes and visual perception is of increasing interest to psycholinguists and vision researchers (Henderson & Ferreira, 2004). Eye movement research provided some of the first compelling demonstrations of the real-time interdependence between spoken language processing and visual perception (Tanenhaus et al., 1995). In these paradigms, a subject wears a headband-mounted eyetracker and typically follows spoken instructions to move objects around on a table or on a computer screen. One of the important finding with this paradigm demonstrated how spoken word recognition is an incremental process, at the timescale of milliseconds, that is profoundly influenced by the visual context. For example, when facing a display containing a bag of candy, a candle, an envelope, and a spoon, and being instructed to "Pick up the candy," subjects occasionally look first at the candle (because of the overlap in the first few phonemes between "candy" and "candle") and then at the bag of candy to pick it up (Allopenna, Magnuson, & Tanenhaus, 1998). When the object with the phonologically competing name, candle, is not present in the display, subjects look more accurately and more quickly to the bag of candy. (The same results are found with a wide variety of objects and object names, e.g., penny and pencil, towel and tower.) The timing of the eye movements suggests that, in a sufficiently constrained visual context, spoken word recognition can be achieved in the listener before the word is even finished being spoken. This kind of real-time interaction between visual and linguistic processing is also seen in eye-movement patterns during syntactic processing (Spivey, Tanenhaus, Eberhard, & Sedivy, 2002), spoken language production (Griffin & Bock, 2000), and even natural unscripted conversation (Brown-Schmidt, Campana, & Tanenhaus, 2004).

Eye movements also reveal social characteristics and processes of face-to-face communication. Humans are remarkably sensitive to changes in where others are looking. Gibson and Pick (1963) demonstrated that a subject can detect a millimeter displacement of a viewer’s gaze away from the bridge of the subject’s nose, which is at the limit of the visual acuity of the eye. The gaze direction of others is a powerful attentional cue, yet is only beginning to be studied empirically (Kingstone, Smilek, Ristic, Friesen, & Eastwood, 2003). In analysis of face-to-face communication, however, research has mainly focused on one variable – eye contact between a speaker and listener. Mutual gaze has two consequences. Firstly, it correlates with many interpersonal factors, such as attractiveness, authority, and perceived sincerity (Argyle, 1976). Secondly, the timing of mutual gaze is used to coordinate dialogue. Bavelas and colleagues (Bavelas & Chovil, 2000; Bavelas, Coates, & Johnson, 2002) found that, typically, a listener will look more at the speaker than vice versa. The speaker will periodically cast looks at the listener, creating a period of mutual gaze. At this point, the listener is likely to respond with a nod or 'mhm', prompting the speaker to continue. In this way, eye movements are employed as part of the composite signal used in the collaborative act of conversation (H. H. Clark, 1996).

Memory, Imagery, and Dreaming

Due to their selective and rapid sampling of the visual world, eye movements must recruit memory processes in order to build up some representation of the visual world (Irwin, Zacks, & Brown, 1990). Conversely, it has also been found that memory processes often recruit eye movements (Spivey & Geng, 2001). Richardson and Spivey (2000) demonstrated that subjects will systematically fixate particular empty spaces when questioned about the semantic content of a linguistic event that had previously taken place at that location. Subjects were presented with video clips of four people relating short pieces of factual information. The clips appeared in each of four regions of a grid. While viewing an empty grid, subjects answered a question about one of those facts. The location which had previously been associated with that information received significantly more fixations. This result holds even when the locations move around before the question period, and parallel behaviour has been shown in infants as young as six months of age (Richardson & Kirkham, 2004). These results suggest that the location of cross-modal events is spatially indexed by the brain, such that relevant locations can be re-fixated when a memory of the event is activated.

Contemporary neuroscience suggests that to some degree memory representations recapitulate perceptual processes (Barsalou, 1999; Kan, Barsalou, Solomon, Minor, & Thompson-Schill, in press; Kosslyn, Behrmann, & Jeannerod, 1995; A. Martin, 2001). Researchers have long been intrigued by the relationship between eye movements during a perceptual experience, and eye movements that occur when one remembers, imagines, or dreams about that experience. Early empirical investigations found that the frequency of eye movements increases during mental imagery, particularly that of a spatial nature (H. Clark, 1916; Goldthwait, 1933; Perky, 1910; Stoy, 1930; Totten, 1935); and an increase in rapid fluttering of the eyes while sleeping correlates with vividness of dreams (Antrobus & Antrobus, 1969; Goodenough, Shapiro, Holden, & Steinschriber, 1959; Roffwarg, Dement, Muzio, & Fisher, 1962). A specific account of this relation during picture recognition, 'scanpath theory' (Noton & Stark, 1971) held that a mental representation of a given perceptual experience is comprised of a sequence of sensory and motor activities. A picture is recognised partially by replaying the memory of this sequence of eye movements and visual stimulation and comparing it the present stimulus. The predictions of this model were borne out by the finding that scanpaths of subjects inspecting an abstract pattern bore a strong similarity to scanpaths of subjects looking at a blank display and recalling the pattern (S. A. Brandt & Stark, 1997).

Recent work suggests that not only are eye movements engaged by a memory of a specific perceptual experience, but also cognitive acts of imagination. Spivey and colleagues (Spivey & Geng, 2001; Spivey, Tyler, Richardson, & Young, 2000) asked subjects to listen to short narratives describing events extending either horizontally or vertically (for example, a story about a train pulling out of the station and a story about the apartments in a forty-story building). Subjects eye movements were recorded while they looked at a blank white screen, or while their eyes were closed. The directionality of saccades corresponded to the directionality of the narratives, suggesting that 'lower-level' motor actions such as eye movements can accompany 'higher-level' cognitive processes because, rather than being separate functions that are triggered by a mental state, motor actions may be fundamental components of the mental state.

The notion of a systematic relationship between eye movements and mental activity has percolated into a wider realm, where it has devolved into a series of popular myths and dubious therapeutic techniques. Bandler and Grinder (1975) proposed the theory of ‘neurolinguistic programming’. They observed that when patients were visualising they tended to look up, when they remembered sounds they looked horizontally, and when they looked downward and to the left they were ‘accessing their feelings’. NLP stated that these eye movements to particular locations corresponded to areas of the brain that were being used. Although Bandler and Grinder’s observations, theories and grasp of neuroanatomy have been discredited (Elich, Thompson, & Miller, 1985; Farmer, Rooney, & Cunningham, 1985; Gumm, Walker, & Day, 1982; Jupp, 1989; Poffel & Cross, 1985; Salas, de Groot, & Spanos, 1989), NLP is still the basis of a large therapeutic industry.

There have also been claims that eye movements can be used to help alleviate the symptoms of post-traumatic stress syndrome. Shapiro (1995; 2002) developed the technique of ‘eye movement desensitization and reprocessing’, whereby patients recalled a traumatic episode whilst following a moving stimulus (such as the therapists hands) with their eyes. The claim is that this looking behaviour would disrupt the eye movement pattern associated with the traumatic memory, diminishing the visual aspect of the memory and desensitising the patient to the memory. It is hotly contested whether such methods produce objective improvements (Acierno, Hersen, Van Hasselt, Tremont, &

Meuser, 1994; Oswalt, Anderson, Hagstrom, & Berkowitz, 1993). Whilst they have been empirically shown to help some patients (Forbes, Creamer, & Rycroft, 1994; Silver, Brooks, & Obenchain, 1995; Wilson, Becker, & Tinker, 1995), it could be the case that this is due to the general therapeutic practices employed, rather than the specific effect of eye movement manipulation (Hyer & Brandsma, 1997).

Eye Movements In The Service Of Complex Tasks

The research we have discussed so far investigates relatively passive acts of perception and information processing. But eye-movement research can inform the study of more complex behaviors, such as selecting a commercial product, playing cricket or flying a jet plane. In these cases, eye-tracking technology can reveal what different sources of information the subject is using, how frequently they are sampled, and how they affect decisions.

Consumer behavior rests on an interplay between immediate perceptual factors and decision-making processes that can be seen in eye-movement behavior. It was soon realized that eye-movement technology could use used to identify factors that determine the amount of attention allocated to different advertisements (H. F. Brandt, 1944; Karslake, 1940; Macnamara, 1941); indeed, when they are placed next to vital traffic signs, their over-effectiveness can also be seen in eye movements (Boersema & Zwaga, 1990). Such measures have predictive value, since it is the case that gaze durations to competing advertisements correlate with later product choice (Lohse, 1997; Treistman & Gregg, 1979).

Good visual design is important in a wide range of activities. The eye movements of radar operators (Gerathewohl, 1952; Wallis & Samuel, 1961), gunners (Brues & Damon, 1946) and pilots (Kamyshov & Lazarev, 1969; Milton, 1952) have been recorded and used to evaluate operator skill and equipment design. Similarly, a range of studies employed eye-tracking to study the effectiveness of different instrumentation panels (Haider, Luczak, & Rohmert, 1982; Kolers et al., 1981; Leermakers & Boschman, 1984; Moray & Rotenberg, 1989; Steinke, 1980; Swanston & Walley, 1984), and later, different computer user interfaces (Deffner, 1995; MacGregor & Lee, 1987; Menozzi, 2000; Yamamoto & Kuto, 1992). Such research has even been used to investigate the ways in which people experience Japanese formal gardens (Ohno, Hata, & Kondo, 1997).

Clear instrumentation, efficient perception, and rapid decision-making are crucial while driving or piloting a vehicle. Early research indicated that eye movements away from the direction of heading were related to steering errors of pilots (G. Martin, 1940), and saccade frequency was employed as a measure of fatigue in long-distance truck drivers (Specht, 1941). Finer analyses investigated what information sources people use, and how frequently they were sampled during different driving conditions (Kito, Haraguchi, Funatsu, Sato, & Kondo, 1989; Mourant & Rockwell, 1970, 1972; G. H. Robinson, Erickson, Thurston, & Clark, 1972) . Particularly difficult perceptual-motor tasks, such as cornering, have come under close scrutiny. One or two seconds before normal car drivers enter a curve, they direct their gaze to the tangent point on the inside of each bend, and leave it there for approximately three seconds (Land & Lee, 1994). The direction of the tangent point relative to the car heading is a good predictor of the curvature of the road. While this anticipatory behaviour is not present in novice drivers (Dishart & Land, 1998; Underwood, Chapman, Brocklehurst, Underwood, & Crundall, 2003), in professional race-car drivers it is advanced to the point that the head is rotated proportionally to the estimated car rotation speed, such that it is brought in line with the expected tangent points (Land & Tatler, 2001).

Differences in oculomotor responses can been seen between professional and amateur athletes (Harbin, Durst, & Harbin, 1989; Lenoir, Crevits, Goethals, Wildenbeest, & Musch, 2000), and saccadic performance was claimed to correlate with batting averages in little-leaguers (Trachtman, 1973). More specific analyses have examined differences in scanpaths between novices and experts. For example, during putting, skilled golfers are less likely to look at the club, and more likely to look at the ball and the hole (Vickers, 1992). Land and McLeod (2000) studied the scanpaths of cricket batsmen, who have to judge the trajectory of a fast bowl with an unpredictable bounce and spin on the basis of half a second viewing time. The batsmen fixated the ball at its time of release and then made a saccade to where they anticipated the bounce. The better batsmen were faster at making this predictive eye movement.

Eye movements do not only reveal the strategies of highly trained sportsmen. They can also reveal the more mundane strategies we employ while carrying out everyday tasks, such as making a sandwich. Land and Hayhoe (2001) found that eye movements are tightly linked with moment-to-moment goals and sub-tasks. This is in contrast to the passive perception of a static scene or picture, when eye movements may be drawn by areas of high contrast or spatial frequency (Henderson, 2003). Such task related fixations have been examined in detail using the block-copying task developed by Ballard, Hayhoe and colleagues (Ballard et al., 1995; Ballard, Hayhoe, Pook, & Rao, 1997; Hayhoe, Bensinger, & Ballard, 1998).

In these eye-tracking experiments, subjects were given the job of constructing a pattern of colored blocks. The pattern was displayed in the “model area” of a board. Participants took blocks from the “resource area”, and copied the pattern in the “workspace area”. The participants’ hand actions were recorded, and a headband-mounted eye tracker recorded their eye movements to obtain a window on the strategy used in the task. One method participants could use is to look at the model area and memorize the pattern; each block in turn could be located in the resource area, and then placed in the workspace. A second method, which is a less memory-intensive option, would be to remember the color and location of one block from the model, collect it from the resource, place it in the workspace, and then consult the model again for the next block. The strategy used by participants, however, most often entailed the minimal possible memory demands. Participants would commonly fixate the model, then fixate and pickup a correctly colored block from the resource area, fixate the model again, and then place the block in the workspace. Thus two fixations per block were made on the model - one to extract color information, one to extract relative spatial location information (Ballard et al., 1995). This is a strategy of indexing, whereby just the location of an object is maintained in working memory, and other properties can be “looked up” as they are needed (Ballard et al., 1997). In a computerised, gaze-contingent version of the block-copying task, the colour of a block was changed during a subject’s saccade (Hayhoe et al., 1998). The subjects rarely noticed this property change, further demonstrating that subjects rely upon fixating external information rather than mentally storing it (Spivey, Richardson, & Fitneva, 2004).

Interactive applications

The relationship between eye movements and cognitive processing has been employed as a tool to improve ergonomic design and computer interfaces (Kramer & McCarley, 2003). The emergence of gaze contingent eye tracking has allowed eye movements to be further employed as means to interact with such systems (Duchowski, 2002). Since fixations indicate what parts of the visual world are salient to the user, eye movement information can be used to tailor visual displays. Regions that are not fixated can be rendered at a far lower level of detail (Ohshima, Yamamoto, & Tamura, 1996; Santella & DeCarlo, 2002; Watson, Walker, Hodges, & Worden, 1997), and hence eye tracking can be used to make valuable computation shortcuts. Given the speed and frequency of naturally occurring eye movements, and their close relation to perceptual and cognitive processing, they also have the potential to be a efficient and expressive input device

In the first applications of this technology, eye gaze replaced the hand operated mouse, allowing users to select icons and menus in a graphical user interface. It takes very little training for naïve users to employ their gaze as a means to control a computer (Stampe & Reingold, 1995). Whilst gaze is also faster than a mouse, there is no clear equivalent of a button press. Blinks were found to be unnatural for users, and so dwell times were used as a selection criteria. Initially, this led to the ‘Midas touch’ problem: users could not distinguish between items they wanted to visually inspect and items they wanted to select, and so everything they looked at would be chosen. If a long enough dwell time is used, typically 600-1000, this can be avoided. If the dwell time is very carefully calibrated to be just longer than a normal fixation, then users report an eerie sense that the system knows what they want to do before they do (Jacob, 1991).

This technology can be employed by users who are unable to operate standard input devices due to physical disability (Frey, White, & Hutchinson, 1990). One such application is ‘Eye-typing,’ in which users can enter characters by fixating on a the keys of a virtual keyboard (Majaranta & Raiha, 2002). There are currently limitations to such implementations. Accuracy issues limit the size of buttons on the screen, such that a whole alphabet cannot always be employed at once (Frey et al., 1990). It can take severely disabled users many months to learn this form of interaction (Gips, Dimattia, Curran, & Olivieri, 1996), since they have had little experience actively controlling devices. The speed of eye typing is typically a character a second (Kahn, Heynen, & Snuggs, 1999). In order to be a successful, real time communication tool, systems have been developed where the user selects a word or phrase from a hierarchical menu (Chapman, 1991).

Conclusion

Eye movements are driven both by properties of the visual world and processes in a person’s mind. Uniquely poised between perception and cognition, eye movements are an invaluable tool for psychologists. Compared to the single data point provided by a button-press reaction time, the eye movements of a subject can provide researchers with a rich, dynamic data source concerning the temporal dynamics and psychological processes that led up to the response. These properties are also of great value to designers and engineers, as they allow for detailed measurements of how a user is interacting with a device. Since the technology has become highly efficient, such information can now be fed back into devices in real time, and the movements of a user’s eyes can be used to issue commands or tailor computational processes. Although such applications are currently in their infancy, this most frequent of all human behaviours could turn out to provide the most fluid and expressive interface between humans and computers.

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