Eye movements in language and cognition

A brief introduction

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1. The role of eye movements in the visual system

The eye independently evolved over 40 times in nature (Fernald 1997), yet strikingly all animals with developed visual systems actively control their gaze using eye or head movements (Land 1995; Treue 2001). Indeed, it can be argued that the most frequent behaviour of human beings is movement of the eyes (Bridgeman 1992). This 'ceaseless twitching', as one early researcher described it (Stratton 1906), is the visual system's solution to the huge amount of available visual information and limited processing resources. The human eye covers a visual field of about 200°, but receives detailed information from only 2° (Levi, Klein, & Aitsebaomo 1985). This tiny high-resolution area of the retina, which receives input from an area of the visual field about the size of a thumbnail at arm's length, is called the fovea, and is jerked around at speeds of up to 500° 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 direct this information conduit to relevant portions of the world, and are therefore fundamental to the operation of the visual system.

There are several classes of eye movements. Of most interest to the cognitive psychologist – and arguably most common – are saccades, the rapid, ballistic movements that move the eye around the visual field roughly 3–4 times a second. Other classes of eye movements, such as smooth pursuit, vergence, optokinetic nystagmus, torsion, and micro-saccades, serve to maintain fixation despite head, body or object motion, changes in depth, and to correct for muscle drift and inaccuracy. They are explored for purposes of understanding the oculomotor system, in and of itself, but rarely as a measure of cognitive processing. Typically, experimental psychologists measure when saccades are launched, where they land, and how long the eye stays there. The pattern of locations that saccades visit is termed the scanpath, the duration between a stimulus onset and a saccade is called the 'saccade latency', and the amount of time spent looking at a particular location is called the fixation duration. In this chapter we will show how eye movement metrics such as these have yielded a rich skein of data relating to cognitive processes, and suggest ways that they can be further mined by experimental psychologists.

2. The value of eye movements to cognitive psychologists

Eye movements are uniquely poised between perception and cognition. They are central to the function of the visual system, but for such scanning to be efficient, it cannot be simply a random sample of the visual world. To be useful, eye movements must be related to an organism's memories, expectations and goals. Consequently, eye movements are driven equally by bottom-up perceptual properties of the world and top-down cognitive processes. This role in the perception-action cycle makes saccadic behaviour particularly informative for the experimental psychologist.

There are several specific characteristics of eye movements which also prove to be of great practical and theoretical benefit. Saccades occur roughly 3–4 times per second. During the response time of a typical experimental task then, eye-tracking data can provide a semi-continuous record of regions of the visual field that are briefly considered relevant for carrying out an experimental task. Crucially, this record provides data during the course of cognitive processing, not merely after processing is complete, as is often the case with more conventional measures. Eye-tracking data thus provide not only behavioral end products of our cognitive processes but also clues to the process through which they are achieved. Importantly, this sensitive semi-continuous measure of cognitive processing can also be used in ways that do not interrupt task processing with requests for metacognitive reports or other overt responses. Thus eye-tracking allows for a certain degree of ecological validity in task performance, as the responses it collects are ones that typically occur regardless of experimenters' instructions and participants' intent.

Moreover, eye movements exhibit a unique sensitivity to partially active representations that may not be detectable by most other experimental measures, or even result in any other overt behaviour. Since eye movements are extremely fast, quickly corrected, and metabolically cheap, compared to other motor movements, they have a much lower threshold for being triggered. Hence, briefly partially-active representations – that might never elicit reaching, speaking, or even internal monolog activity because they fade before reaching those thresholds – can nonetheless occasionally trigger an eye movement that betrays this otherwise-latent momentary consideration of that region of the visual display as being potentially relevant for interpretation and/or action. For example, in a classic experiment in psychology, two speech sounds that vary continuously between "ba" and "pa" are categorically perceived by participants, who report hearing *either* a "ba" or a "pa" and respond by pressing a corresponding button (Liberman, Harris, Hoffman, & Griffith 1957). However, McMurray and colleagues (McMurray, Tannenhaus, Aslin, & Spivey 2003) showed that eye movements between the two response buttons increased when the speech sound was near the ba/pa boundary. Thus, the graded nature of the perceptual process, which is lost in a categorical response, is revealed in the time course of eye movements.

Eye movements have a long and successful history as a window into perceptual and cognitive processing. The following sections present a subset of that research that would be of particular interest to cognitive linguists (for a broader review, see Richardson & Spivey 2004a, 2004b). First, we will briefly describe how eye movements reveal psychological processes in everyday tasks of perception and memory. Then we will show how very similar cognitive processes produce similar eye-movement patterns in more 'offline' situations, where relevant visual stimuli may not even be present. We shall then turn to the many ways in which eye movements reveal facts about language processing, from the mechanics of reading, to the integration of visual and verbal information, to the conceptual representation of narratives and metaphors. This chapter will conclude with a discussion of some of the practical methodological necessities involved in designing, conducting, and analyzing eyetracking experiments.

3. Perception and action

Visual attention is not always coincident with eye position. Posner, Snyder, and Davidson (Posner 1980) demonstrated that participants' covert visual attention can be dissociated from the fovea when they are explicitly instructed to not move their eyes. 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, Akbudak, Conturo, Snyder, Ollinger, & Drury 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 (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 eye movements and visual attention directed around a visual stimulus? In general, when viewing a static scene, the eyes appear to be driven by both visual properties of the stimulus and top-down effects of knowledge and expectations (Henderson 2003). For example, Buswell (1935) showed that a viewer will pay scant attention to solid regions of colour in a painting, and instead will tend to fixate regions of contrast and high spatial frequency; top-down effects will be seen in the viewers' saccades to semantically important regions of the painting, such as faces, and the ways in which a naïve viewer will inspect the painting differently from an art expert. 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.

We live a world more dynamic and interactive than an art gallery, however. How are eye movements integrated with action in the course of everyday tasks? With the advent of headband-mounted eye-tracking, which allows natural movement of the entire body, this real-time measure of perceptual and cognitive processing has been applied to a number of more richly interactive, and ecologically valid, experimental tasks and paradigms. Eye movements can even reveal the everyday strategies we employ while carrying out basic tasks, such as making a sandwich. For example, Land and Hayhoe (2001) found that eye movements are tightly linked with moment-to-moment goals and sub-tasks. Task-related fixations illuminating visual memory processes have been examined in detail using the block-copying task developed by Ballard, Hayhoe and colleagues (Ballard, Hayhoe, & Pelz 1995; Ballard, Hayhoe, Pook, & Rao 1997; Hayhoe, Bensinger, & Ballard 1998).

Ballard et al. (1995) recorded participants' eye movements during a block-pattern copying task, with a model pattern, a resource of blocks, and a workspace in which to copy the model. 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 could then be located in the resource area and placed in the workspace. A second, less memory-intensive, method 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 yet 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.

Eye movements thus reveal a cognitive process of "indexing," whereby the location of an object is maintained in working memory, and other properties can be "looked up" in the environment as they are needed, moment by moment, during a task (Ballard et al. 1997). For example, in a computerized, gaze-contingent version of the block-copying task, the color of a block was changed during a saccade (Hayhoe et al. 1998). The participants rarely noticed this property change, demonstrating that they had not encoded the information, but instead relied upon the fact that an eye movement could access it when required.

4. Cognition

A general case can be made that 'offline' cognitive processes such as remembering, imagining and reasoning may employ many of the same mechanisms as 'online' perceiving and acting in the world (Barsalou 1999; Damasio 1989; Kosslyn, Behrmann, & Jeannerod 1995; Martin 2001; Ryle 1949). Certainly, we will see here that eye movement patterns during cognitive activity bear a striking resemblance to those during the perception and manipulation of objects in the world. This continuity between perception and cognition can be exploited by psychologists, who can use overt eye-movement behaviour to investigate internal mental processes.

A clear example of this parallel exists between Ballard et al's (1995) task, where subjects moved blocks around, and a set of experiments where subjects remembered a series of verbally presented facts. Richardson and Spivey (2000) presented four talking heads in sequence, in the four quadrants of the screen, each reciting an arbitrary fact and then disappearing (e.g., "Shakespeare's first plays were historical dramas. His last play was The Tempest."). With the display completely blank except for the lines delineating the four empty quadrants, a voice from the computer delivered a statement concerning one of the four recited facts, and participants were instructed to verify the statement as true or false (e.g., "Shakespeare's first play was The Tempest.").

While formulating their answer, participants were twice as likely to fixate the quadrant that previously contained the talking head that had recited the relevant fact than any other quadrant. Despite the fact that the queried information was delivered auditorily, and therefore cannot possibly be visually accessed via a fixation, participants systematically fixated blank regions of space. This result was replicated when the talking heads were replaced by four identical spinning crosses.

Moreover, in a 'tracking' condition (Richardson & Kirkham 2004), participants viewed the grid through a virtual window in the center of the screen. Behind this mask, the grid moved, bringing a quadrant to the center of the screen for fact presentation. Then, during the question phase, the mask was removed. Even in this case, when the spinning crosses had all been viewed in the center of the computer screen, requiring no eye movements, and the relative locations of the quadrants implied by translation, participants continued to treat the quadrant associated with the queried fact as conspicuously worthy of overt attention. In fact, even if the crosses appear in empty squares which move around the screen following fact delivery, participants spontaneously fixate the square that was associated with the fact in its new location (Richardson & Kirkham 2004). The behaviour of associating events and information with a moving location, and re-fixating that location when the information is relevant has been termed 'spatial indexing'. Remarkably, there is evidence of spatial indexing behaviour in the eye movements of infants as young as 6 months of age (Richardson & Kirkham 2004).

When subjects listened to pieces of semantic information, they associated them with spatial indexes, just as the participants in Ballard and colleagues' block moving task did for the blocks they were manipulating (Richardson & Spivey 2000; Spivey, Richardson, & Fitneva 2004). As many researchers have argued (Ballard et al. 1997; O'Regan 1992; Pylyshyn 1989, 2001), deictic pointers can be used in visuomotor routines to conserve the use of working memory. In Brooks' (1991) words, the 'world can be used as its own best representation'. Instead of storing all the detailed properties of an object internally, one can simply store an address, or pointer, for the object's location in the environment, via a pattern of activation on an attentional/oculomotor salience map in parietal cortex (Duhamel, Colby, & Goldberg 1992), along with a spatial memory salience map in prefrontal cortex (Chafee & Goldman-Rakic 1998, 2000; Goldman-Rakic, Chafee, & Friedman 1993). If this spatial pointer is associated with some kind of coarse semantic information, e.g., a pattern of activation in one of the language cortices, or auditory cortex, or even visual cortex, then the spatial pointer can be triggered when sensory input activates that semantic information. Such pointers allow the organism to perceptually access relevant properties of the external world when they are needed.

It actually should not be surprising that an embodied working memory system using deictic pointers would attempt to index information from events that are over and done with. The pointer doesn't "know" that the sought-after information at its address is long gone precisely because it has offloaded that knowledge onto the environment – it wouldn't be a pointer otherwise. These eye movement findings demonstrate the robustness and automaticity with which spatial indices are relied upon in order to employ the body's environment as sort of noticeboard of 'virtual post-it notes' that complement our internal memory.

However, many complex tasks we face on a daily basis do not necessarily involve indexing of relevant objects in a task space. For example, producing/hearing descriptions of far away scenes or events, gossip about people who are absent, and discussions of abstract concepts, do not involve explicit reference to visible elements of the immediate situational context. An important question concerns the extent to which eye movements may be indicative of imagery processes when carrying out such tasks. How are eye movements implicated in visualizing a complex story or description? Will scanning of the visuo-spatial backdrop that is available to a listener be at all relevant during comprehension of language that refers to things that are not visually co-present with the speech?

In a headband-mounted eye-tracking experiment, Spivey and Geng (experiment 12001; see also Spivey, Tyler, Richardson, & Young 2000) recorded participants' eye movements while they listened to spoken descriptions of spatiotemporally dynamic scenes and faced a large white projection screen that took up most of their visual field. For example, "Imagine that you are standing across the street from a 40-story apartment building. At the bottom there is a doorman in blue. *On the 10th floor, a woman is hanging her laundry out the window. On the 29th floor, two kids are sitting on the fire escape smoking cigarettes. On the very top floor, two people are screaming.*" While listening to the italicized portion of this passage, participants made reliably more upward saccades than in any other direction. Corresponding biases in spontaneous saccade directions were also observed for a downward story, as well as for leftward and rightward stories. (A control story, describing a view through a telescope that zooms in closer and closer to a static scene, elicited about equal proportions of saccades in all directions). Thus, while looking at ostensibly nothing, listeners' eyes were doing something similar to what they would have done if the scene being described were actually right there in front of them. Instead of relying solely on an internal "visuospatial sketchpad" (Baddeley 1986) on which to illustrate their mental model of the scene being described, participants also recruited the external environment as an additional canvas on which to depict the spatial layout of the imagined scene.

Although eye movements may not be required for vivid imagery (Hale & Simpson 1971; Ruggieri 1999), it does appear that they often accompany it (Antrobus & Antrobus 1969; Brandt & Stark 1997; Demarais & Cohen 1998; Hebb 1968; Laeng & Teodorescu 2002; Neisser 1967). Early empirical investigations found that the frequency of eye movements increases during mental imagery, particularly that of a spatial nature (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). But what is it that the eyes are trying to do in these circumstances? Obviously, it is not the case that the eyes themselves can actually externally record this internal information. When the eyes move upward from the imagined 10th floor of the apartment building to the imagined 29th floor, no physical mark is left behind on the external location in the environment that was proxying for that 10th floor.

In the case of Spivey and Geng's (2001) eye movements during imagistic spoken narrative comprehension, a few pointers allocated on a blank projection screen will obviously not make reference to any external visual properties, but they can still provide perceptual-motor information about the relative spatial locations of the internal content associated with the pointers (see also Altmann & Kamide 2004). If one is initially thinking about x (e.g., the 10th floor) and then transitions to thinking about y (e.g., the 29th floor), then storing in working memory the relation *above* (y,x) may not be necessary if the eye movements, and their allocation of spatial indices, have embodied and externalized that spatial relationship in the environment already (cf. Pylyshyn 1989). In this way, a "low-level" motor process, such as eye movements, can actually do some of the work involved in the "high-level" cognitive act of representing spatial relations in visual imagery elicited by linguistic input. Eye movement data thus reveal a powerful demonstration of how language about things not co-present is interfaced with perceptual-motor systems that treat the linguistic referents as if they were co-present.

It seems clear from the evidence presented here that eye movements are a rich source of information about cognitive processing, even when the relevant items are not physically present, but are recalled from memory or merely described in memory. Although some researchers today argue on the basis of null results that eye movements are not really indicative of cognitive processes at all (Anderson, Bothell, & Douglass 2004), other researchers are demonstrating that eye movements can reveal not just which cognitive representation might be active, but how they are being manipulated. For example, eye movements appear to have a relationship to the reasoning process in mechanical problem solving (Hegarty 1992; Hegarty & Just 1993; Hodgson, Bajwa, Owen, & Kennard 2000; Rozenblit, Spivey, & Wojslawowicz 2002) and insight problem solving (Grant & Spivey 2003; Jones 2003; Knoblich, Ohlsson, & Raney 2001).

5. Language

Language processing encompasses a spectrum of phenomena, from the largely perceptual aspects of word identification, to the largely conceptual aspects of metaphor understanding. As one might imagine from the preceding sections, eye movements can provide insight at each of these levels. The most apparent, and most studied, link between eye movements and language is in the process of reading.

The general characteristics of eye movements during reading have been studied in great depth over the past quarter century (for thorough reviews, see Rayner 1978, 1998). This methodology has revealed a number of important facts about how people's eyes move when they read. For example, the eyes rest in fixation for approximately 200–250 milliseconds during reading. Saccades between fixations span an average about 2 degrees of visual angle, although this is 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 syntactic and conceptual difficulty of the text (Ferreira & Clifton 1986; Rayner, Sereno, Morris, Schmauder, & et al. 1989). 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 often accurately re-fixate the part of the text that generated confusion (Murray & Kennedy 1988).

These features of eye movements during reading – gaze durations, saccade lengths, occurrence of regressions, and a number of variations on these measures – can be used to infer moment-by-moment cognitive processing of a text by the reader (Just & Carpenter 1980; Rayner et al. 1989). Details of the cognitive processes of pronoun resolution and co-reference, word frequency, lexical ambiguity, syntactic ambiguity, as well as the influence of semantic and discourse context on these processes, can all by gleaned from analyses of eye-movement patterns (Rayner 1998; Tanenhaus & Trueswell 1995).

Light, headband mounted eye trackers have allowed researchers to extend the online measurement of language processing beyond reading, to the perception and understand of spoken language in a rich, naturalistic visual context. One field of research begins with the feature of eye movements, noted above, that participants will often look briefly at an object that is initially considered relevant for action, and then quickly re-fixate their eyes on another object that becomes the actual target of the action. This feature has been exploited to study many factors in the time course of speech processing and language understanding.

For example, Spivey and colleagues (Spivey-Knowlton, Tanenhaus, Eberhard, & Sedivy 1998) sat participants in front of a display of objects such as a candle, bag of candy, a pencil, and a spoon. The participants were then and instructed to "Pick up the candy,". About a third of the time participants fixated the candle for a couple hundred milliseconds before looking to and reaching for the candy. Participants typically denied looking to the candle at all, and yet their eye movements revealed a process substantially different from their conscious report and their manual action. This kind of brief interference between similar sounding object names occurs not just for cohorts but also for rhymes (Allopenna, Magnuson, & Tanenhaus 1998), as well as for novel words from an artificial lexicon (Magnuson, Tanenhaus, Aslin, & Dahan 2003), and even for words that sound similar across two different languages (Marian & Spivey 2003; Spivey & Marian 1999). It appears that the acoustic uptake of spoken input is continuously mapped onto visually relevant lexical representations, such that partial phonological matches to the names of multiple visual objects induces competition between partially active representations, in a system something like interactive processing in the TRACE connectionist model of spoken word recognition, (Elman & McClelland 1988; Magnuson, McMurray, Tanenhaus, & Aslin 2003; McClelland & Elman 1986).

A similar influence of visual context is observed with temporary ambiguities that arise across words, in the syntax of a sentence. When presented with a display containing an apple on a towel, another towel, and an empty box, and then instructed to "Put the apple on the towel in the box," participants often looked briefly at the irrelevant lone towel near the end of the spoken instruction before returning their gaze to the apple, grasping it, and then placing it inside the box (Spivey, Tanenhaus, Eberhard, & Sedivy 2002; Tanenhaus, Spivey Knowlton, Eberhard, & Sedivy 1995). (With unambiguous control sentences, such as "Put the apple that's on the towel in the box," they almost never looked at the irrelevant lone towel.) In this case, the syntax is ambiguous as to whether the prepositional phrase "on the towel" is attached to the verb "put" (as a movement destination) or to the noun "apple" (as a modifier). Given the actions afforded by the display, the latter syntactic structure is the correct one. However, people tend to have a bias toward interpreting an ambiguous prepositional phrase as attached to the verb (Rayner, Carlson, & Frazier 1983), at least when it is an action verb like "put" (Spivey-Knowlton & Sedivy 1995). Thus, the brief fixation of the irrelevant lone towel indicates a temporary partially-activated incorrect parse of the sentence. To demonstrate the influence of visual context on this syntactic ambiguity resolution process, the display was slightly altered to include a second apple (resting on a napkin). In this case, the visual co-presence of the two potential referents for the phrase "the apple" should encourage the listener to interpret the ambiguous prepositional phrase "on the towel" as a modifier (in order to determine which apple is being referred to) rather than as a movement destination (Altmann & Steedman 1988; Spivey & Tanenhaus 1998). And, indeed, with this display, participants rarely fixated the irrelevant lone towel, indicating that visual context had exerted an immediate influence on the incremental syntactic parsing of the spoken sentence (Knoeferle, Crocker, Scheepers, & Pickering 2005; Spivey et al. 2002; Tanenhaus et al. 1995).

The word-by-word interfacing between spoken language and visual perception is also evidenced by reference resolution with complex noun phrases. Eberhard, Spivey-Knowlton, Sedivy, and Tanenhaus (1995) presented participants with a display of blocks of various shapes, colors, and markings, and gave them instructions like "Touch the starred yellow square." When the display contained only one starred block, participants often fixated on the target block before the head noun of the noun phrase had even been spoken. Fixation of the target block was slightly later when the display contained another starred block that was not yellow, and later still when the display also contained a starred yellow block that was not a square. This result shows that even before hearing the noun that refers to the object being described, listeners are processing the pre-nominal adjectives as they are heard and mapping their meaning onto the options available in the visual context.

More recently, researchers have employed eye movement techniques to show that listeners are remarkably sensitive to subtle aspects of language, and employ that information in directing their gaze around a display. For example, Altmann and Kamide (2004) have demonstrated that participants will fixate a cake before hearing the word spoken in the sentence, 'The boy will eat the cake'. This anticipatory saccade will not occur when subjects hear, 'The boy will move the cake'. This evidence demonstrates participants are activating rich 'thematic role' knowledge (Ferretti, McRae, & Hatherell 2001) of the verb "eat", and fixating likely candidates for this action before the word is spoken.

Matlock and Richardson (2004) have provided further evidence of the nuances of language that drive eye movements around a scene. In previous reading time studies, Matlock (2004) found evidence that readers would mentally simulate motion when reading sentences such as 'the fence runs along the garden'. Such use of figurative language is termed 'fictive motion', since although the motion verb 'run' is used, no literal motion takes place. Matlock and Richardson (2004) showed that listeners would look longer along the relevant path when they heard 'the fence runs along the garden', compared to 'the fence is around the garden'. This suggests that fictive motion, far from being an example of a 'dead metaphor', elicits something like a perceptual simulation (e.g., Barsalou 1999) and influences how a listener directs their attention across a picture.

Eye movements thus reveal the incremental and interactive nature of spoken language comprehension. Subjects are gradually influenced by the incremental delivery of linguistic information, and eye movements exhibit the continuous, partially active representations that arise during processing. In addition, eye movements have permitted the observation of powerful interactive effects between language and vision. It seems that this incremental process of language comprehension can be strongly constrained by appropriate visual contexts, and that moment-by-moment visual perception can be driven by subtle aspects of language such as thematic roles and figurative motion.

6. Eye movement methodology

We hope that the reader is convinced by now that recording eye-movements does indeed provide a unique source of data for constraining one's theories about language and cognition. The ways in which the visual environment constrains, and is used by, various linguistic and cognitive processes are becoming better understood due to the insights afforded by many findings from eye-tracking experiments. However, there are a number of safeguards and practical tips that one accumulates over years of experience with eyetracking studies that are worth considering before a newcomer dives right into collecting a large mass of eye-movement data (for reviews, see Rayner 1998; Tanenhaus & Spivey-Knowlton 1996).

This section of the chapter is aimed at providing some concrete methodological preparation for students and researchers interested in tracking people's eye movements as a measure of cognitive processes. Of course, it would be naïve of us to think that a chapter, by itself, could prepare a reader to successfully and accurately track the eye movements of experimental participants. The only way to get good at eyetracking is to receive hands-on training from someone with years of experience, and then practice, practice, practice. That said, perhaps some of the following advice could speed up that learning process.

6.1 Choice of eyetracker

The first decision to make in considering eye movements as an experimental measure is what aspect of oculomotor behavior one thinks may be especially informative for the aspect of cognition being tapped. It is important to imagine in advance exactly what eye-movement analysis will be conducted and what the ideal results (and statistical analysis) will look like. This will often determine what kind of eyetracker is most appropriate for your experiment. Lucky for your experimental participants, the facility with which eye movements are tracked has improved considerably over many decades of developing technology. Devices attached directly to the eyeball (Delabarre 1898; Huey 1898; Yarbus 1965) gave way to photographic techniques (Diefendorf & Dodge 1908; Tinker 1928), which in the last few decades, have been replaced by electronic detection of the small differences among reflective properties of the eye (Cornsweet & Crane 1973; Merchant, Morrissette, & Porterfield 1974; Young 1970) that permit rapid and accurate calculation of gaze direction (for a review of the history of eye tracking methods, see Richardson & Spivey 2004a). There are also search coils (typically surgically implanted in monkeys) and electro-oculogram (EOG, for measuring movement latency, but not eye position), but those will not be discussed here as they are less practical for cognitive tasks with humans.

For the last few decades, uses of eyetracking in reading have tended to focus on durations of fixations on various words (and numerous permutations of this metric). When a sentence becomes syntactically or semantically complex, ambiguous, or misleading, fixations on the words that cause or resolve that confusion will often be longer than fixations on other words (of equal length and lexical frequency). The frequency of regressive saccades, back to earlier portions of a sentence, are also used as a measure of processing difficulty. Similar kinds of measures have been used for measuring cognitive processes during scene viewing. Two kinds of table-mounted eyetrackers have typically been used for these purposes. A dual-Purkinje eyetracker – rather expensive, but with extremely high spatial and temporal resolution – points infrared light into the eyeball and records the reflections off the front surface of the cornea (first Purkinje image) and the back surface of the lens (fourth Purkinje image). These two reflections allow for a calculation of the point-of-regard of the eye, mapping what part of the computer screen (on which the sentences are presented) is being foveated. Limbus tracking uses infrared emitter diodes and infrared detector diodes to record the position of the boundary between the iris and the sclera (white of the eye). Figure 1 shows an image of the Dr. Bouis limbus tracker. Limbus trackers are less expensive than dual-Purkinje eyetrackers, but also tend to have lower spatial and temporal resolution, as well as performing poorly along the vertical axis (as the eyelids can obscure the upper and lower portions of the iris-sclera boundary). Therefore, using limbus tracking for measuring reading often requires presenting only one sentence at a time, and it is rarely used for complex scene viewing.

While they both tend to have higher resolution than other eyetracking systems (fractions of a degree of visual angle, allowing one to know *which letter* is being fixated), two important limitations of dual-Purkinje and limbus trackers are that they are generally only used with computerized displays and with the head held motionless. In some cases, a chin and forehead rest are sufficient, but it is often necessary to also use a bitebar. A bitebar is

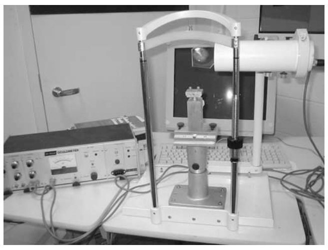

Figure 1. A Dr. Bouis limbus eyetracker, set up for recording movements of the right eye during reading. The metal pedestal in the middle is where the bitebar would be bolted in place. The glass eye piece above the pedestal is a silvered mirror that reflects the infrared light from the emitter diodes to the eye and back to the detector diodes, but allows normal visible light to pass, so that the participant can see through it.

Figure 2. An ISCAN, Inc. remote video-based eyetracker, set up for recording movements of one or the other eye during viewing of simple scenes on a computer screen. The cylinder in between the monitor and the camera lens is the infrared emitter. The mechanism immediately below the camera itself allows it to tilt up and down and pan left and right to accommodate small head movements.

made by heating dental wax in hot water until it is soft and malleable, shaping the wax around a horseshoe-shaped metal plate, re-warming the wax, and having the experimental participant bite down on the soft wax so that it makes a dental impression on top and underneath. (The third author once had a participant express reticence about this procedure, but when she was invited to quit the experiment, she said, “No, I’ll do it, but can you close the lab door? I don’t want any of my friends to walk by and see me doing this.”) When the wax cools again and hardens, the plate is bolted onto a post mounted on the table under the eyetracker’s infrared-emitting apparatus. While the participant is looking at the computer screen, and reading sentences or inspecting complex scenes that are typically extracted from any situational context, with the room lights off, they are biting down on the form-fitted bitebar so that their head does not move more than a millimeter or two. And the experimenter hopes to get data that are somehow ecologically valid.

Remote video-based eyetrackers (Figure 2) have an infrared emitter that bathes the participant’s face in low-intensity infrared light, and the eye camera zooms in to one of the eyes and sends the infrared image to a computer. The eye camera is on a swivel that allows it to re-orient its aim if the participant’s head moves slightly, either automatically or by remote control. The computer’s software performs some image processing on the

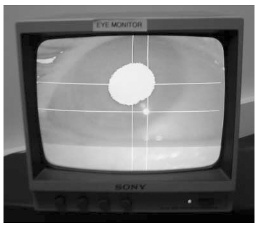

Figure 3. Image of the eye from a video-based eye camera, after the computer's image processing has placed crosshairs on the center of the pupil (upper left) and on the corneal reflection (lower right). (When these crosshairs are stable, and not jittery, the estimate of point-of-regard can be reliable and accurate.)

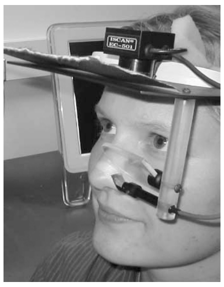

Figure 4. An ISCAN, Inc. headband-mounted eyetracker, set up for recording movement of the left eye during natural interactive task performance. Under the brim of the headband, an emitter sends infrared light down to the slivered mirror, which reflects it into the eye. Then the light bounces back and up to the eye camera, adjacent to the emitter, providing an image of the eye like that in Figure 3. The black cylinder underneath the silvered mirror is the scene camera whose image of the participant's field of view is reflected off the outside portion of the silvered mirror, off another mirror, and then into its lens.

eye camera's signal, finding the large disc of low reflectance (for "dark pupil trackers") or high reflectance (detecting light reflected back from the eye's tapetum, for "bright pupil trackers"). This disc is assumed to be the pupil, and crosshairs are placed at its center, as seen in Figure 3. The infrared emitter's reflection off the cornea is also identified in the image of the eye (Figure 3). With these two points on the eye's surface identified, and a generic model of the curvature of the eye, the software can estimate the direction of the eye relative to the head. With relatively minor head movement, one can calibrate these eye positions onto computer screen positions, interpolate between those calibrated points, and track where on the screen the participant is looking, with an accuracy better than one degree of visual angle.

Eyetrackers that are yoked with computer-screen stimulus presentation can often allow for automated data analysis (scan paths, fixation durations, etc.) either by adding an electromagnetic head-tracker that subtracts out head-movement in determining where in the field of view the eyes are pointed, or by using a head-mounted scene camera (Figure 4) and placing bright markers on the corners of the computer screen so that the calibration routine can re-normalize the eye-position estimate to wherever the computer screen's reference frame is in the scene camera's view. However, when the eyetracker is not yoked with computer-screen stimulus presentation, but instead eye movements are to be recorded during natural visuomotor tasks involving several 3-D objects, automated data analysis will often be infeasible because the locations of objects on the scene camera will move substantially during head and trunk movements. The eye-position estimate will still be accurate in terms of coordinates in the scene camera's reference frame, but having an automated algorithm that knows where the different objects are in that moving reference frame can prove difficult. Headband-mounted eyetrackers that allow this kind of natural head and body movement (Figure 4) often require hand-coded frame-by-frame data analysis of videotaped recordings of eye-position superimposed (as crosshairs) on the scene camera's view. This will usually require a digital VCR.

As their precision and accuracy are somewhat lower than the Purkinje-image eyetrackers or even the limbus eyetrackers, these video-based remote and head-mounted eyetrackers are less frequently used for studying reading, where *seconds of arc*, rather than degrees or minutes, are crucial. These kinds of eyetrackers (manufactured by a variety of companies, including ISCAN, Inc., SR Research, and Applied Science Laboratories) are more typically used for experiments where the visual display will be carved up into no more than a dozen or so regions of interest. For example, one could measure what critical objects in a participant's environment are fixated, for how long and in what order, while he/she is driving on a curvy road (Land & Lee 1994), following spoken instructions to move objects around (Eberhard, Spivey-Knowlton, Sedivy, & Tanenhaus 1995), making critical decisions in a chess game (Charness, Reingold, Pomplun, & Stampe 2001), selecting response buttons during a categorical speech perception task (McMurray, Tanenhaus, Aslin, & Spivey 2003), verbally describing a visual scene (Griffin & Bock 2000), attempting to solve a diagrammatic problem (Grant & Spivey 2003), following a pre-recorded baking recipe (Chambers, Tanenhaus, & Magnuson 2004), or even just preparing a peanut butter and jelly sandwich (Land & Hayhoe 2001).

6.2 Calibration

The first thing to get practiced at for actually conducting an eyetracking session is calibration. You need to make sure the eye camera (or the infrared diodes, for a limbus tracker) are evenly lined up on the eye such that when the participant looks at the edges of the main viewing field, the pupil (or iris, for a limbus tracker) is still in full view of the tracker. During calibration, several eye-position signals will be mapped onto particular regions of the participant's field of view (often the four corners, plus some others). To maintain a linear relationship between these positions, the participant's head must be is immobile as possible during the minute-or-two of the actual calibration routine. The faster you can go through asking them to fixate each calibration point on the screen, and collecting the eye-position signal belonging to that location (watch out for blinks!), the less time there will be for the head to drift, and the more linear your calibration points' relationships to one another will be. With a good set of evenly spaced calibration points, and a clean, stable eye-position signal associated with each of them, the software's interpolation for regions in between those calibration points should be reasonably accurate.

6.3 Display parameters

Perhaps the most important thing to keep in mind when designing an eye-tracking experiment with spoken linguistic input is to plan in advance exactly how the eye-position record will be coded. It is sometimes helpful to have an initial centralized fixation point where the subject is instructed to look at the beginning of each trial; and critical relevant objects should be equidistant from this initial fixation position. In order to reduce the likelihood of subjects inferring the experimental predictions due to repeated exposure to particular patterns or relationships in the stimuli, filler objects, as well as filler trials, are recommended. Highly complex displays, such as photographs that have objects partially occluding other objects in depth, or objects whose adjoined and abutting parts are important for separate analysis, can prove rather difficult for eye-position coding. Especially if data analysis is being performed by trained coders watching frame-by-frame videotape, but even when analysis is automated in x,y computer screen coordinates, just a small amount of noise or jitter in the eye position signal can introduce uncertainty in whether one abutting object/part or the other is actually being fixated. A common solution for this is to arrange the visual displays such that there is white space and/or a contour-based divider separating each relevant region or object by at least a couple degrees of visual angle.

6.4 "Blind" coding

If the eye-position record is being analyzed by human coders via frame-by-frame videotape, it is, of course, wise for the coders to be prevented from knowing the experimental conditions and predictions for each trial. If the critical experimental manipulation is in the auditory portion of the videotape, this can sometimes be solved by simply coding the silent video portion. However, in other circumstances, trained coders who are unaware of the experimental manipulation and the theoretical predictions may need to analyze each trial with a spreadsheet that uses coded labels for conditions. A more recent solution to this problem, is to store eye-position as x,y screen coordinates and map them onto the x,y coordinates of objects on the same screen. Current headband-mounted eye-tracking systems allow this automated data analysis as long as the visual display is presented on a computer screen and the subject makes rather minimal head and trunk movements in front of that screen.

6.5 Participant ease

Whether it is a bitebar on which the subject must make a form-fitting dental impression so that her head will be held in place during the experiment or a 3/4-pound headband that the subject is being asked to wear, eye-tracking equipment looks and feels intimidating to a newcomer. And experimental findings from uptight and uncomfortable participants may not generalize to how they behave in normal everyday settings. Therefore, a good tactic when the participant first enters the lab and begins filling out the consent form, is to chat with them a bit about the classes they're taking etc., and then describe the basics of how the eyetracker works, while demonstrating it on yourself. This way they get to see someone else wearing the equipment with ease. Also, wearing a headband-mounted eyetracker for more than half an hour can sometimes cause a headache. Experiments that last longer than 30 minutes should probably introduce a 10-minute intermission.

6.6 Practice

Every eye-tracking system has its own set of unique tricks and parameter settings that take time to learn. In particular, achieving an accurate calibration (usually a 5–10 minute process), such that the subject's actual eye position is correctly indicated for all regions of the display, is something that requires careful attention to parameters such as centering the eye in the eye camera's view, reducing distracting reflections on the sclera, as well as a certain amount of speed and fluidity in entering data for the calibration positions to minimize head-drift during calibration. The typical graduate student can expect to require a couple weeks of practice before being able to complete a good calibration for the majority of their experimental subjects. And there will always be some portion of experimental subjects, 5–10%, for whom three or even four attempts at calibration simply fail to produce an accurate record of eye-position. This can be due to a variety of things, such as very light or very dark irises (with some trackers), naturally droopy eyelids, downward-pointing eyelashes that obstruct the eye camera's view, the headband not fitting the person's head, or even incorrigible head motion during the calibration phase.

It could be said that the actual tracking of eye movements is more of an art than a science. And there are certainly dozens of minor tricks that a research team will learn and develop through practice with any given eyetracking apparatus and experimental set-up that cannot be anticipated in advance. However, the small handful of practical tips provided in this section are unlikely to be found anywhere else in the literature. We hope they prove helpful.

7. Conclusion

We contend that eye movements provide an index of real-time mental activity that most other methodologies do not (but cf. event-related potentials, Coulson, this volume, and continuous kinematic properties of manual responses, Abrams & Balota 1991; Coles, Gratton, Bashore, Eriksen, & Donchin 1985; Spivey, Grosjean, & Knoblich 2005). Eye movements provide a semi-continuous record of the time-course of partially-active representations competing for an overt skeletal motor response, and therefore offer rich insight into *how cognition happens* – not just the outcomes it produces. In Cognitive Linguistics' concern with the wide array of perceptual, cognitive, and motor faculties that underlie language use, it stands to gain considerably from eye movement techniques.

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