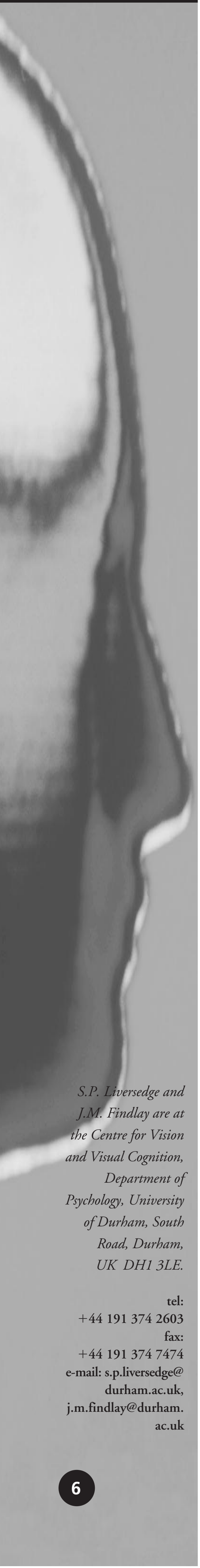
Saccadic eye movements and cognition

Simon P. Liversedge and John M. Findlay

Scanning of the visual scene is an important selective process in visual perception. In this article we argue that eye-movement data provide an excellent on-line indication of the cognitive processes underlying visual search and reading. We outline some recent advances from physiological investigations of saccadic eye-movement control before focusing on eye-movement behaviour in visual search and reading studies. We consider factors that can affect the duration of fixations and the choice of saccade targets, emphasising continuities between biological and cognitive descriptions. We discuss different ways of measuring cognitive processing time from an eye-movement record and the relationship between attention and eye movements.



S.P. Liversedge and J.M. Findlay are at the Centre for Vision and Visual Cognition, Department of Psychology, University of Durham, South Road, Durham, UK DH1 3LE.

tel: +44 191 374 2603
fax: +44 191 374 7474
e-mail: s.p.liversedge@durham.ac.uk, j.m.findlay@durham.ac.uk

The visual environment is an enormously rich source of information. Any approach to understanding visual perception must recognise that only a small part of this potential information is actually used. In this article we shall be concerned with one of the principal ways in which selection of information occurs. The visual axis of the eye is directed to a series of locations in the visual field, resulting in a continually changing sequence of images falling on the fovea. This sequence is the main, although not the only, way in which visual input is selected for cognitive visual tasks. We shall mainly consider recent work in two well-controlled cognitive situations, visual search and reading, to illustrate the progress that has been made in understanding this system of visual sampling and to flag some important unanswered questions.

The fundamental nature of this sampling is neatly illustrated by a recent case report of an individual with congenital ophthalmoplegia[1]. This individual has no functional eye muscles and her eyes are essentially fixed in her head. Her visual impairment is surprisingly small and she lives a normal life, currently as a university student. Examination shows that she makes scanning movements with her head which have very similar properties to the saccadic eye scanning seen in a normal individual. This shows that active saccadic scanning is a fundamental feature of vision. It is not so much dependent on the organisation of the oculomotor system as upon the organisation of the visual system. Saccades are necessitated by the rapid decline in resolution away from the fovea. It is often convenient to describe the fovea as occupying the central two degrees of the retina, flanked by the parafovea which extends out a further three degrees, beyond which the remaining area is termed the periphery[2]. As functional terms, however, these definitions are entirely arbitrary. Visual resolution declines steadily from a maximum in the very centre of the fovea.

Neural control of saccades

Considerable progress has been made in understanding the brain processes subserving saccade control[3]. The pattern of neural activity that results in a saccadic movement is shaped in the brainstem. Brainstem 'omnipause' cells are characterized by sustained activity except immediately before and during every saccade when the activity ceases. These cells trigger the movement but, as the name implies, they do not code the spatial characteristics. Spatial coding occurs in various 'burst' cells, located in neighbouring regions of the brainstem. Brainstem organisation therefore shows a separation between cells encoding the spatial characteristics of the saccadic movement ('where') and those concerned with triggering the movement ('when').

Both omnipause cells and burst cells receive signals from a higher centre intimately involved in eye-movement control, the superior colliculus (SC) of the midbrain. The SC receives visual input from several cortical regions (as well as a poorly understood direct input from the retina) and forms an important visuomotor centre, in which a retinotopically coded visual signal accesses a spatiotopic motor map that codes orienting movements of different sizes and directions. The rostral pole region of the SC is crucially involved in fixation and saccade triggering. The readiness with which a monkey will make an orienting saccade can be increased or decreased by injection into this region of GABA agonists or antagonists respectively[4]. Cells in the region are active during fixation and pause just prior to and during saccadic eye movements[5]. Their activity is quite similar to brainstem omnipause cells and anatomical connections between the respective regions in the colliculus and the brainstem have been traced[6]. Across the remainder of the colliculus, two types of cell, SC build-up cells and SC burst cells, are found, whose properties code the destination of saccadic movements[3]. This evidence can be interpreted in terms of a further where/when separation[7]. Saccade triggering is crucially dependent on events in the fixation centre, located in the rostral pole of the SC, whereas the choice of saccade destination is dependent on the pattern of activity throughout the build-up system, which may be likened to a salience map.

1364-6613/00/$ – see front matter © 2000 Elsevier Science Ltd. All rights reserved. PII: S1364-6613(99)01418-7

Box 1. Eye movements and attention

The sequences of eye fixations discussed in this review describe the way in which overt visual attention is deployed. It is well known that attention can be directed to locations in space without moving the eyes. How does this *covert* direction of attention interact with overt eye movements?

Could several covert shifts of attention occur during each eye fixation? Early estimates of the speed of covert attentional movements were as fast as 30 shifts of attention per second (Refs a,b). Such a rate would indeed allow several movements of the supposed mental spotlight during an eye fixation (about 250 ms). As discussed in the section on visual search of this article, alternative interpretations of the data are now common and direct estimates of the rate of deployment of covert visual attention give much slower rates (Refs c,d). Nevertheless, it appears to be possible for a peripheral cue to 'summon attention' during an eye fixation as indexed by enhanced discrimination at the cue location. The cue may achieve this without necessarily capturing the next eye movement, although such capture also occurs frequently (Ref. e).

Covert attention is indexed by the phenomena that peripheral visual targets to which attention is directed covertly are better discriminated and more rapidly processed. Such processing advantages are found with visual material at the location about to receive fixation with an eye movement (Ref. f). This may be interpreted as an indication that a covert attentional movement accompanies, and precedes, an overt eye movement. Such a close relationship between covert and overt attention is a feature of the 'premotor theory' of covert attention, which claims that covert attention is achieved by preparing but withholding execution of an overt eye movement (Ref. g).

Models of eye-movement control, particularly in the area of reading, have invoked covert attentional processes. Morrison proposed that, during each fixation, covert attention shifts from the word currently being processed to select the next location for the eye (Ref. h). The analogy of a rubber band is often made, a covert attentional shift occurring first and subsequently 'pulling' the eye along. Models of attention and eye movements have emphasised the capacity limitations of attention (Ref. ij), for example, arguing that when the fixated word is difficult to process, foveal attentional demands are high so that little attention can be allocated to parafoveal words. This would result in shallow parafoveal processing (however, see Ref. k for evidence against this suggestion). Another recent approach has been the model of the 'E–Z reader' of Reichle *et al.* (Ref. l), which maintains the emphasis on underlying shifts of covert attention but concentrates more on elaborating the processes involved in lexical access. There is no doubt that these models represent the most fully formulated attempts to predict eye-movement patterns in complex cognitive tasks. However, it is clear that covert attention is not well understood at present.

References

a Bergen J.R. and Julesz, B. (1983) Parallel versus serial visual processing in rapid pattern discrimination. *Nature* 343, 696–698

b Treisman, A. and Gelade, G. (1980) A feature integration theory of attention. *Cognit. Psychol.* 12, 97–136

c Duncan J. *et al.* (1994) Direct measurement of attention dwell time in human vision. *Nature* 369, 313–315

d Sperling G.S. and Weichselgartner, E. (1995) Episodic theory of the dynamics of spatial attention. *Psychol. Rev.* 102, 503–532

e Theeuwes J. *et al.* (1998) Our eyes do not always go where we want them to go. *Psychol. Sci.* 9, 379–385

f Deubel, H. and Schneider, W.X. (1996) Saccade target selection and object recognition: evidence for a common attentional mechanism. *Vis. Res.* 36, 1827–1837

g Rizzolatti G. *et al.* (1994) Space and selective attention. In *Attention and Performance Vol. XV* (Umilta, C. and Moscovitch, M., eds), pp. 231–265, MIT Press

h Morrison, R.E. (1984) Manipulation of stimulus onset delay in reading: evidence for parallel programming of saccades. *J. Exp. Psychol. Hum. Percept. Perform.* 10, 667–682

i Rayner, K. (1986) Eye movements and the perceptual span in beginning and skilled readers. *J. Exp. Child Psychol.* 41, 211–236

j Henderson, J.M. and Ferreira, F. (1990) Effects of foveal processing difficulty on the perceptual span in reading: implications for attention and eye movement control. *J. Exp. Psychol. Learn. Mem. Cognit.* 16, 417–429

k Rayner, K. *et al.* The effect of clause wrap-up on eye movements during reading. *Q. J. Exp. Psychol.* (in press)

l Reichle, E.D. *et al.* (1998) Toward a model of eye movement control in reading. *Psychol. Rev.* 105, 125–157

Because much work in visual cognition relies heavily on the duration of eye fixations, the precise details of the fixation region become of great importance. Gandhi and Keller[8] have reported cells showing 'fixation neuron' properties over a collicular region corresponding to the central 10 degrees of visual field and Krauzlis *et al.*[10] have suggested that fixation cells and build-up cells form a continuum. These findings might account for the 'remote distractor effect'[9] in which onset of a stimulus at a remote location from the goal of a saccade delays its initiation.

Two principal descending input pathways to the SC come from the frontal eye field (FEF) region and posterior parietal cortex. Arguments have been presented that both centres can be considered as operating in terms of a salience map[11–13]. These cortical areas also contain 'fixation' cells, whose properties are similar to those found at lower levels. Studies in these brain areas are pioneering our understanding of the way the brain is involved in the details of cognitive processes and the role of the FEF in visual search is discussed at the end of the next section.

Eye movements in visual search

Visual search has proved to be a suitable task to explore selection processes. It has been adopted by a range of workers from cognitive psychologists to neurophysiologists and has been used effectively in studies with both human participants and trained monkeys. Within cognitive psychology, visual search has been a key topic for many years but until recently active eye scanning has received relatively little consideration. This is in part a consequence of the very influential theory proposed by Treisman and Gelade[14] who argued that, although some simple search tasks might be accomplished by pre-attentive processes, more demanding tasks required a sequential attention scanning of elements. This scanning has often been assumed to be covert, using a 'mental spotlight'. The main supporting evidence for the theory came from the search function, showing how the time to make a target present/target absent decision varied as the number of distractors was increased. Simple search tasks show a flat search function whereas in demanding tasks a linear increase in search time is found as the number of items is increased.

Consideration of feature-integration theory in relation to eye scanning raises some very important questions. To what extent must a role be assigned to covert attentional processes in the choice of where the eyes move? (see Box 1). If the spotlight model is adopted, a further question becomes whether several covert attentional movements can precede an overt saccade. There has been considerable controversy over the rate at which covert attention can be redeployed[15] but the fastest estimates (30 ms per item) would allow a number of such movements to occur in a typical fixation pause (250 ms). However the main source of such fast estimates of attentional redeployment speeds comes from the results on the search function that formed the original basis of feature integration theory. This interpretation of the linear search function has increasingly been questioned[16,17,18,19,20] by alternative proposals in which a number of items in the display are processed in parallel.

It can even be argued that covert attention, if regarded as a separate process from oculomotor preparation, plays no role in visual search[21]. When eye movements are recorded in a visual search paradigm in which display size varies, it is found that the number of saccades prior to a target present/target absent decision is an increasing linear function of display size[22,23,24]. A ready interpretation of this result proposes that during each fixation, a number of items are processed in parallel (the number suggested by the data would be 8–10). Further evidence for parallel processing comes from studies which have looked at the very first saccade in search tasks[24,25,26,27] Many accurate short-latency saccades to feature conjunction targets are found and saccades directed to distractors are more likely to land on distractors sharing a common feature with the target (though this result has not always been found[28,29]). Moreover there is no difference in latency between initial saccades landing on target and those landing on a distractor. If an internal scan preceded an overt eye movement, short latency saccades might be expected on the occasions when the scan happened to alight on a target initially. These are not found[24,25].

Several other findings can be readily related to the way in which visual information is processed in the brain. The foveal and central regions of vision are given disproportionate representation in brain projections. The inadequacy of approaches to visual search which ignore this inhomogeneity of the visual projections is increasingly recognised[18,21,30]. A related finding from eye-movement studies is that the probability of target capture by a saccade is often found to increase with proximity to the current fixation location[24,25]. Another feature of brain processes leading to saccadic eye movements is the use of distributed coding principles (large and overlapping receptive and motor fields). This is reflected in saccades directed at 'centre of gravity' positions[31,32].

This integration of visual search into the framework of cognitive neuroscience is complemented by studies that have elucidated the neural computations involved. The frontal eye fields have long been implicated in voluntary saccade control and long term effects on control of saccade sequences occur following their ablation[33]. Some cells in the FEF show visual receptive fields with interesting activity patterns during search tasks[13]. When monkeys were trained to respond to an 'oddball' target of a different colour from a set of distractors, the earliest responses did not differentiate between target and distractor but a differential response from targets and distractors was observed after about 100 ms[34]. It is clear that selection is achieved by suppression of responses evoked from distractor items while the responses evoked by the target are maintained or enhanced. From monkeys trained to search for targets of a particular colour, the cells show feature selectivity from the earliest stages of their response[35]. These results support the position that a plastic set of lateral interconnections between cortical areas underlies attentional selectivity[36].

Eye movements while scanning scenes and pictures

The intriguing patterns of eye scanning as individuals view pictorial scenes and objects[37] have long been a source of fascination. Space considerations preclude detailed discussion here and recent reviews of scene perception have appeared in this journal[38] and elsewhere[39–41]. Although some gist information is acquired from a brief glance at a scene[42], extended viewing of scenes or pictures invariably results in saccadic scanning. This scanning is essential to obtain details of objects[43], although a foveal mask has a somewhat less devastating effect on an object recognition paradigm[44] than on reading[45].

There has been considerable study of statistical patterns of eye movements during scene viewing and how these change during the viewing period. There have also been demonstrations that fixation durations are affected both by low-level visual factors such as contrast[46,47] and high-level semantic properties of the fixated object[48]. The processes that determine the choice of individual saccade destinations, on the other hand, are still very poorly understood. An early report suggested that the eyes would be attracted rapidly to an out of context object[49] (e.g. an octopus in a farmyard). However, several attempts to replicate this finding have now proved unsuccessful[41,50].

Eye-movement research into reading

In this section we will argue that eye movements provide an excellent, on-line behavioural measure of the cognitive processes underlying reading. We provide a description of some general characteristics of eye movements during reading before summarising the contribution that this research has made to the psycholinguistic literature.

There has been a substantial amount of eye-movement research related to reading (see Rayner[39] for a review). Within this field, two distinct research groups have developed each of which uses eye-movement methodology to slightly different ends[51]. The first group aims to understand the mechanics of how the eyes move. This group is primarily interested in the effects of relatively low level visual and linguistic factors on eye-movement control. The second group aims to make inferences about higher order psycholinguistic processes underlying written language comprehension. Factors affecting word identification, computation of structural relationships between words of a sentence (syntactic processing) and understanding the meaning of a sentence or short text as a whole (semantic processing) have all been investigated. To such psycholinguistic researchers the mechanics of eye-movement behaviour is not of principal interest. Instead, they are concerned with how linguistic differences between sentences cause differences in reading behaviour.

Before embarking on a discussion of eye movements and reading it may be useful to consider a typical record of a subject's eye movements as a sentence is read (see also Box 2). A normal eye-movement record comprises a series of fixations and saccades. During each fixation the subject extracts the visual information that they process after which they make a saccade to relocate the point of fixation elsewhere in the text.

General characteristics of eye movements during reading

When people read sentences their fixations are typically between 60 and 500 ms long, being about 250 ms on average. When reading English text, readers move their eyes from left

Box 2. Measures of eye-scanning behaviour

Techniques that allow accurate recordings of the sequential movements of the eyes are now available, which provide an eye-movement record that can be analysed off-line after testing. Such records may be used in investigations by clinicians, vision researchers and those interested in measures of cognitive processing. A normal eye-movement record comprises of a series of fixations and saccades. During fixations, the eye shows only small drift movements. These may reflect intentions to make an eye movement (Ref. a), but are too small to affect significantly the intake of information. Saccades are fast ballistic movements of the eyes that re-locate the point of fixation. They are the result of an active neural command that programs the eye to rotate through a specified angle. The spatial and temporal features of this command can be measured, and are both of considerable interest. Which aspects are used depends on the objectives, and level of detail sought, by the investigator (see below). Importantly, the use of static visual displays (of search elements of text) in this kind of research obviates the need to consider pursuit eye movements, which simplifies the analysis of the eye-movement record considerably.

Although absolute spatial measures of eye movements, such as saccade length, are sometimes of interest, it is generally more useful to relate the spatial aspect of the measurement to the material being viewed. Thus, **saccade landing position** relative to a given element in a display is the most direct spatial measure. **Fixation duration** is another measure, which relates to the temporal aspect of saccade programming. In this review, we consider situations in which eye sampling is related to visual displays of discrete elements, either abstract elements in visual search (Fig. I), or linguistic elements such as the individual words or phrases of sentences in the case of reading (Fig. II). In such cases, it is usual to set up an extended virtual boundary around each element so that saccades that land between elements can be included in the assignment of landing positions to target elements.

Frequently, the eye movement that directs the visual axis onto a visual element is followed by a further small saccade to a new location within the boundary defining that element (for example, in Fig. I, the short saccade after the fixation of 110 ms when the subject first lands on the green cross). The term **corrective saccade** is often used for these movements, which appear to be an inherent component of the oculomotor system. However, for some analyses, it is appropriate to ignore this detail by grouping two or more successive fixations on the same element together in a measure of **gaze duration**. A further level of grouping is the **total viewing time** for a given element, which adds to gaze duration any instances of subsequent refixation of a given element during the trial period.

In reading research, measures of fixation duration and position, saccade length, gaze duration (or first-pass reading time for regions of more than one word) and total reading time are computed in much the same way as they are in studies investigating visual search. However, a number of additional measures can be made that centre around regressive eye-movement behaviour. Regressive saccades occur in order to re-read text when a reader experiences a difficulty in linguistic processing. They provide information about aspects of the reading process, such as the point in a sentence from which a regression was initiated, how long the reader spent reprocessing the sentence, and when in the comprehension process a linguistic factor first affected eye-movement behaviour.

Recently, Liversedge *et al.* argued that the notion of spatial and temporal contiguity may be useful when interpreting differences in reading-time measures (Ref. b). In the analysis of a series of fixations across portions of a sentence or visual array, it must be decided (in a relatively arbitrary way) which fixations should be summed in order that a processing difficulty be detected. Most measures of disruption sum spatially contiguous fixations (fixations occurring within roughly the same location). While such measures provide valuable information regarding processing difficulty, Liversedge *et al.* argue that considering these alone may result in a failure to detect exactly when readers experience processing difficulty. For example, if a reader makes a series of regressive saccades to re-read different portions of a sentence, each successive fixation might occur in a different position in the sentence (e.g. the fixations of 190 and 270 ms in Fig. II) but these fixations may well reflect the same recovery process. For such patterns of eye movements, a measure that sums temporally contiguous fixations may also be required to detect this disruption (e.g. regression path duration; Ref. c).

As we develop more detailed measures of eye-movement behaviour, a greater degree of specificity regarding the relationship between patterns of eye-movement behaviour and the psychological processes underlying reading and visual processing will be obtained.

References

a Kowler, E. and Steinman, R.M. (1979) The effect of expectations on slow oculomotor control: I. Periodic target steps. *Vision Research* 19, 619–32

b Liversedge, S.P. *et al.* (1998) Eye movements and measures of reading time. In *Eye Movements in Reading and Scene Perception* (Underwood, G., ed.), pp. 55–76, Elsevier

c Konieczny, L. *et al.* (1997) The role of lexical heads in parsing: evidence from German. *Lang. Cognit. Process.* 12, 307–348

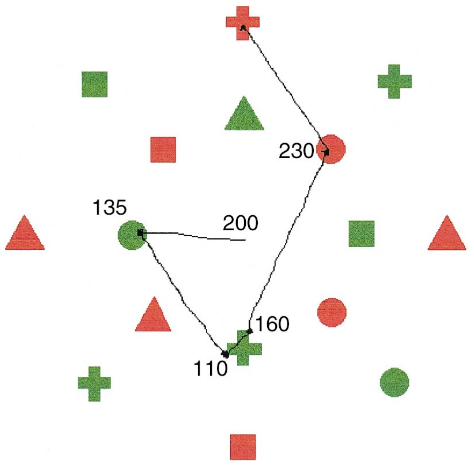
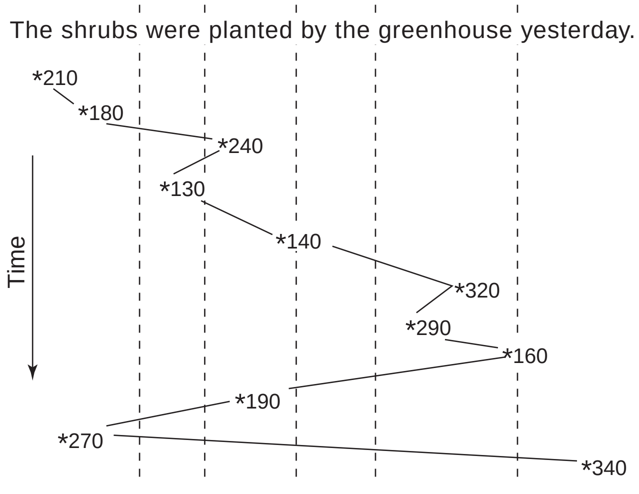


Fig. I. A hypothetical scan path during a visual search task. A typical eye-movement record of a subject carrying out a visual search task. The subject first fixates the central point on an otherwise blank screen and when the display is presented the task is to search with the eyes for a red cross. In this case, the eye-movement record has been superimposed on the viewed display, and shows several fixations, with their durations given in milliseconds alongside.



trends in Cognitive Sciences

Fig. II. A hypothetical eye-movement record of a subject reading a sentence. Each of the fixations made by the reader is represented by an asterisk. The duration of each fixation in milliseconds appears adjacent to the fixation, and each successive fixation appears at a point lower on the page than its predecessor. The vertical dotted lines divide the sentence into regions that are decided by the experimenter. In this case, the reader made their first fixation on the determiner *The* followed by a short saccade and a fixation on the word *shrubs*. They then skipped the next word, making a saccade of about 10 characters before fixating the word *planted* for 240 ms. The reader continued to make a series of saccades (both progressive and regressive) and fixations as they read the whole sentence.

to right approximately 85% of the time and from right to left 15% of the time[52]. Saccades are on average 7–9 characters in size (that is, they typically jump from one character to another, 7–9 characters downstream). However, they vary in length, some being the length of only one character, while others may be almost as long as the sentence itself (e.g. a return sweep saccade from right to left in order to fixate a new line of text). Readers tend to fixate content words, which are usually quite long, but skip function words, which tend to be quite short[53]. Fixations usually land between the beginning and the centre of a word (preferred viewing location[54]) but there is some evidence suggesting that readers fixate informative portions of words (the optimal viewing position[55,56]). The number of characters that a reader can identify on any fixation is termed the visual span[56,57] and the number of characters that a reader processes at least partially during a fixation is termed the perceptual span[44,58]. The perceptual span is asymmetrical about the point of fixation, being extended towards the direction in which the reader progresses through the text.

For English readers the perceptual span is about four characters to the left and 15 characters to the right of fixation[44,57,60,61]. For Hebrew readers, who read text from right to left, the perceptual span is offset in the opposite direction. The perceptual span is under cognitive control with English-Hebrew bilinguals switching their span offset to the right when reading English and to the left when reading Hebrew[62]. Readers not only process text that they are fixating, but also pre-process text in the direction that they are reading[59]. Readers make more fixations and fixate for longer when they experience processing difficulty. Additionally, when readers misanalyse sentences they make regressive saccades to re-read text to recover the appropriate analysis[63]. These decisions about where in the text to fixate, and when to move the eyes following a fixation, reflect the 'where' and 'when' aspects of eye-movement control discussed in the previous section[64,65].

'Lower level' linguistic influences on eye movements

There has been a substantial amount of eye-movement research investigating lexical processing (word identification). The duration of a fixation on a word is affected by its basic lexical properties such as frequency and length. Lower frequency words are fixated for longer than higher frequency words[64, 65], and the longer a word is, the more likely a reader is to refixate it, producing increased gaze durations[59,64,66–68].

Fixation times on lexically ambiguous words (e.g. *bank*) vary depending upon the word's meanings and the within sentence context. When ambiguous words with two equally likely meanings (balanced ambiguous words) are embedded in a semantically neutral sentential frame, then reading times are slower than for control words matched for length and frequency. In contrast, when an ambiguous word has a dominant meaning (biased words), readers fixate it for no longer than they do an unambiguous word, provided the context permits the more frequent meaning of the word. However, when sentential context favours the less frequent meaning of a biased ambiguous word, fixation durations on the word increase relative to those for a control word[69,70]. These findings show that eye-movement behaviour is affected not only by the characteristics of the words being fixated, but also by the relationship between the fixated word and preceding text. Recent work has also shown that the number of orthographic neighbours that a word has (words that differ by just one letter) affects eye movements[71]. When a word has many neighbours, the duration of the fixation immediately after leaving the word is longer than when a word has few neighbours. This effect probably reflects competition between candidate words during the identification process (though it is not clear why this effect does not occur on the word itself).

Given that readers pre-process text to the right of the word they are fixating, the question arises of what kind of information is being extracted. A contingent-change boundary technique[59] has been used in a number of studies to obtain an indication of the information a reader extracts from non-foveal locations. In such studies, a target word will initially appear, possibly in a disrupted form, to the right of the point of fixation. However, when the point of fixation transgresses an invisible boundary, typically two or three letters to the left of the target, the disrupted word is replaced by the target word itself. Hence, the reader fixates the target word in its usual form, but has been prevented from processing it parafoveally. Using this method, it is possible to determine which characteristics of the target word are perceived and used by the language processing system prior to direct fixation. From such studies, we know that visual information such as word length and constituent letter shape are extracted[50]. Somewhat surprisingly, phonological (sound) information is extracted from the parafovea[72,73], whereas morphological information (prefixes or sub-units of compound words, e.g. *cow* in *cowboy*) is not[74].

Semantic pre-processing, that is to say, the extraction of information about the meaning of parafoveal words, is a highly contentious issue. Several studies have shown that semantic information is not extracted from the parafovea[75–79]. However, in contradiction to this, two recent studies report that the duration of a fixation on a word is affected by the semantic relationship between it and the parafoveal word. These findings indicate that both the foveal and parafoveal words must have been semantically processed[80–82]. Work in Finnish[83] and some work in English[84] and French[85] has shown that strings of letters that occur infrequently within the language (e.g. *irk* in *irksome*) attract the point of fixation. Finally, a very recent study by Rayner, Kambe and Duffy has shown that when readers are fixating a word, they make a longer saccade from the word when it is the last word in the clause than when it is not[86]. This suggests that the process of 'wrapping up' a linguistic constituent to determine its meaning affects the subsequent saccade into a new linguistic constituent. This result is striking as it indicates that higher-level as well as lower-level linguistic factors impact upon eye guidance during reading.

'Higher level' linguistic influences on eye movements

The preceding discussion has described research investigating the effect of relatively low level linguistic and visual factors on eye-movement behaviour. This research usually involves taking very fine-grain measurements from the eye-movement record. However, work that investigates higher order processes involved in reading tends to involve the use of more coarse measures (see Box 2). Researchers investigating syntactic processing have typically compared eye-movement records for syntactically ambiguous sentences with records for unambiguous counterpart sentences[87–89]. Such comparisons

Box 3. Eye movements and auditory language processing

Although eye-movement recordings are frequently used to examine reading, a number of recent studies by Tanenhaus and his colleagues, have used eye-movement recordings to investigate spoken language comprehension (Refs a–e), using methodology that was originally described by Cooper (Ref. f). In these studies the experimenters presented particular objects in a visual array whilst carefully manipulating the spoken instructions that the subjects receive. Through the use of a head-mounted eye-tracking system, subjects' eye movements are recorded as they carry out the instructions.

For example, one experiment investigated how listeners process complex noun phrases such as '*the starred yellow square*' (Ref. b). During this experiment subjects were seated in front of a table on which were positioned a series of blocks that differed in shape and colour, and whether or not they were marked with a star. Importantly, the verbal instructions to the subject uniquely identified the object to be touched at different points during the utterance. For example, one set of instructions might have been: 'Touch the plain red square. Now touch the starred yellow square. Now touch the plain blue square. Now touch it again'. If there were two differently coloured squares in the array marked with a star, then the instruction '*touch the starred yellow square*' would only be referentially unambiguous when the subject heard the word *yellow*.

The results of this experiment showed that subjects delayed making an eye movement until after the offset of a disambiguating word when that word came early in the noun phrase. However, when the disambiguating word came late in the noun phrase, at a point when there was only one entity to which it could refer, subjects made an eye movement prior to the offset of that word. These findings indicate that eye movements are time-locked to spoken input and that readers make immediate use of the linguistic information to reduce incrementally the candidate set to which the utterance refers.

Thus, it seems that spoken language comprehension proceeds on a word-by-word basis, and auditory and visual information are rapidly integrated. Clearly, eye-movement recordings can provide important information about both written and spoken language comprehension. Indeed, in further experiments this methodology has been used to investigate a number of other aspects of speech comprehension, including effects of contrastive stress, and the influence of a visual referential context on initial syntactic-processing preferences (Refs c–e).

References

a Allopena, P.D. *et al*. (1998) Tracking the time course of spoken word recognition using eye movements: evidence for continuous mapping models. *Mem. Lang.* 38, 419–439

b Eberhard, K.M. *et al.* (1995) Eye movements as a window into real-time spoken language comprehension in natural contexts. *J. Psycholinguist. Res.* 24, 409–436

c Tanenhaus, M.K. and Spivey-Knowlton, M.J. (1996) Eye tracking. *Lang. Cognit. Process.* 11, 583–588

d Tanenhaus, M.K. *et al.* (1996) Using eye movements to study spoken language comprehension. In *Attention and Performance* (Vol 16) (Inui, T. and McClelland, J., eds), pp. 457–478, MIT Press

e Meyer, A.S. *et al*. (1998) Viewing and naming objects: eye movements during noun phrase production. *Cognition* 66, B25–B33

f Cooper, R.M. (1974) The control of eye fixation by spoken language: a new methodology for the real time investigation of speech perception, memory and language processing. *Cognit. Psychol.* 6, 84–107

often show differences in eye-movement patterns that reflect a syntactic misanalysis of the ambiguous portion of a sentence. When subjects do initially misanalyse a sentence syntactically, they are said to have been 'garden-pathed'[90]. Usually, when readers are garden-pathed the time spent on the disambiguating word will be quite long and readers will often make regressions in order to re-read the sentence. However, there is a growing body of evidence indicating that readers do not always detect an initial misanalysis until slightly after the disambiguating word has been read. In such a situation the effect is said to have 'spilled over' into the region immediately downstream from the critical word[91].

A number of eye-movement studies have shown that readers prefer to process structurally ambiguous sentences in one way rather than another[86,88,89,91,92]. Other studies have convincingly demonstrated that linguistic factors such as sentential and discourse context can modulate this preference[93–98] and that readers are often able to use a contextual cue to guide their initial interpretation of a sentence. Results from such studies have been taken to support constraint-satisfaction models of sentence processing[97–99]. According to such models, sources of linguistic and statistical information act as constraints on the particular analysis that the sentence processor favours at any point in the sentence. Thus, different analyses compete with each other for activation and the competition between the different alternatives can be the cause of observed disruption[100], though other studies have provided evidence against this suggestion[101,102].

Eye-movement data have also been used to investigate aspects of semantic processing. In order for readers to develop a full understanding of a sentence, they must determine antecedents of referential expressions and make inferences in order that the sentence is coherent with preceding discourse. Each of these processes has been shown to affect eye movements. For example, Garrod, Freudenthal and Boyle recorded subjects' eye movements as they read sentences containing a pronoun that could refer to either of two entities mentioned in a preceding passage[103]. Garrod and colleagues manipulated whether the potential antecedents were in or out of linguistic focus and also whether the verb associated with the pronoun was congruous with one or the other of the antecedents. They showed that both variables influenced first pass reading times indicating that higher-order semantic processes such as the formation of co-reference relationships influence how we read.

Another study by Duffy and Rayner investigated the process of linguistic inferencing by monitoring subjects' eye movements as they read referring expressions[104]. They examined reading times for a category noun in a target sentence after it followed either a typical, or an atypical instance of that category in a preceding text. For example, if the target sentence contained the word *bird*, the preceding text may have contained either a typical exemplar of that category (e.g. *sparrow*), or an atypical exemplar (e.g. *ostrich*). Duffy and Rayner also manipulated the distance (in words) between the category and the instance and found that distance and typicality had

Outstanding questions

- Some properties, such as colour, are very effective in guiding eye searches. Colour is predominantly processed by the ventral visual pathways through the cortex, whereas saccade planning is dependent on parietal and frontal regions of cortex. How are the cross-links between these pathways made?
- Can we develop a better understanding of covert attention which places less reliance on metaphors such as 'mental spotlights', which are likely to entail misleading assumptions?
- How are the destinations of successive fixations planned when viewing pictorial material.
- What factors affect when and where we make a regressive saccade during reading?
- What is the precise relationship between eye movements and psychological recovery processes after an initial misanalysis during reading?
- Why do some linguistic factors have a delayed influence on eye-movement behaviour relative to other linguistic factors?
- Some findings (e.g. the gap effect) show that the detailed timing of eye scanning is automatically affected by physical aspects of the visual stimulation. To what extent can cognitive processes such as lexical access exert their effects in a similar automatic way?
- What factors influence eye-movement behaviour when people process interactive displays such as animated sites on the World Wide Web?

an interactive effect on gaze durations on the category noun. Gaze durations on the category noun were shorter when it followed a close, typical instance than in any other condition indicating that referential processing takes place as readers first process anaphoric expressions.

Conclusions

In this review we have argued that eye movements reflect a large number of psychological processes underlying various cognitive tasks. In particular, we have focussed upon visual search and reading, two areas in which eye-movement studies have made a tremendous contribution to our understanding. We have argued that deciding where and when to move the point of fixation are key aspects of eye-movement control and that understanding the relationship between the two is necessary to understand fully the cognitive processes reflected by eye movements. We also noted that investigators examining low-level aspects of eye-movement control and researchers investigating reading have independently formed the conclusion that the 'where' and 'when' components of eye-movement control are separable, both psychologically and physiologically.

We have seen how different algorithms for summing fixations can be useful in making claims about qualitatively different psychological processes. We have described recent studies showing that eye-movement recording can be used to study aspects of human behaviour that we do not intuitively associate with visual processing (e.g. auditory language processing, see Box 3). It can be hoped that future eye-movement research will reveal more of the cognitive processes that are hidden behind eye-movement patterns.

Acknowledgements

We thank Valerie Brown, Keith Rayner, Michael Spivey and the anonymous reviewers for helpful comments on a previous version of this manuscript. The research was supported by ESRC research grant no. R000222647. The order of authors is arbitrary.

References

1 Gilchrist, I.D. *et al.* (1997) Saccades without eye movements. *Nature* 390, 130–131

2 Balota, D.A. and Rayner, K. (1991) Word recognition processes in foveal and parafoveal vision: the range of influence of lexical variables. In *Basic Processes in Reading* (Besner, D. and Humphreys, G.W., eds), pp. 198–232, Erlbaum

3 Wurtz, R.H. (1996) Vision for the control of movement. *Invest. Ophthalmol. Vis. Sci.* 37, 2131–2145

4 Munoz, D.P. and Wurtz, R.H. (1993) Fixation cells in monkey superior colliculus: I. characteristics of cell discharge. *J. Neurophysiol.* 70, 559–575

5 Munoz, D.P. and Wurtz, R.H. (1993) Fixation cells in monkey superior colliculus: II. reversible activation and deactivation. *J. Neurophysiol.* 70, 576–589

6 Paré, M. and Guitton, D. (1994) The fixation area of cat superior colliculus: effects of electrical stimulation and direct connection with brainstem omnipause neurons, *Exp. Brain Res.* 101, 109–122

7 Findlay, J.M. and Walker, R. (1999) A framework for saccadic eye movement control based on parallel processing and competitive inhibition. *Behav. Brain Sci.* 22, 661–721

8 Gandhi, N.J. and Keller, E.L. (1997) Spatial distribution and discharge characteristics of superior colliculus neurons antidromically activated from the omnipause region in the monkey. *J. Neurophysiol.* 78, 2221–2225

9 Walker, R. *et al.* (1997) The effect of remote distractors on saccade programming: evidence for an extended fixation zone. *J. Neurophysiol.* 78, 1108–1119

10 Krauzlis, R.J. *et al.* (1997) Shared motor error for multiple eye movements. *Science* 276, 1693–1695

11 Colby, C.L. and Goldberg, M.E. (1999) Space and attention in parietal cortex. *Annu. Rev. Neurosci.* 22, 319–349

12 Schall, J.D. (1995) Neural basis of saccade target selection. *Rev. Neurosci.* 6, 63–85

13 Schall, J.D. and Thompson, K.G. (1999) Neural selection and control of visually guided eye movements. *Annu. Rev. Neurosci.* 22, 241–259

14 Treisman, A. and Gelade, G. (1980) A feature integration theory of attention. *Cognit. Psychol.* 12, 97–136

15 Egeth, H.E. and Yantis, S. (1997) Visual attention: control, representation and time course. *Annu. Rev. Psychol.* 48, 269–297

16 Pashler, H. (1987) Detecting conjunction of color and form: re-assessing the serial search hypothesis. *Percept. Psychophys.* 41, 191–201

17 Treisman, A. and Sato, S. (1990) Conjunction search revisited. *J. Exp. Psychol.* 16, 459–478

18 Palmer, J. *et al.* (1993) Measuring the effect of attention on simple visual search. *J. Exp. Psychol.* 19, 108–130

19 Wolfe, J.M. (1994) Guided search 2.0: a revised model of visual search. *Psychonomic Bull. Rev.* 1, 202–228

20 Eckstein, M.P. (1998) The lower visual search efficiency for conjunctions is due to noise and not serial attentional processing. *Psychol. Sci.* 9, 111–118

21 Findlay, J.M. and Gilchrist, I.D. (1998) Eye guidance during visual search. In *Eye Guidance in Reading and Scene Perception* (Underwood, G., ed.), pp. 295–312, Elsevier

22 Binello, A. *et al.* (1995) The characteristics of eye movements made during visual search with multi-element stimuli. *Spat. Vis.* 9, 343–362

23 Zelinsky, G.J. and Sheinberg, D.L. (1997) Eye movements during parallel–serial visual search. *J. Exp. Psychol.* 23, 244–262

24 Motter, B.C. and Belky, E.J. (1998) The zone of focal attention during active visual search. *Vis. Res.* 38, 1007–1022

25 Findlay, J.M. (1997) Saccade target selection in visual search. *Vis. Res.* 37, 617–631

26 Motter, B.C. and Belky, E.J. (1998) The guidance of eye movements during active visual search. *Vis. Res.* 38, 1805–1818

27 Bichot, N.P. and Schall, J.D. (1999) Saccade target selection in macaque during feature and conjunction search. *Vis. Neurosci.* 16, 81–89

28 Zelinsky, G.J. (1996) Using eye saccades to assess the selectivity of search movements. *Vis. Res.* 36, 2177–2187

29 Hooge, I.T.C. and Erkelens, C.J. (1999) Peripheral vision and oculomotor control during visual search. *Vis. Res.* 39, 1567–1575

30 Carrasco, M. *et al.* (1995) The eccentricity effect: target eccentricity affects performance on conjunction searches. *Percept. Psychophys.* 57, 1241–1261

31 Findlay, J.M. (1982) Global processing for saccadic eye movements. *Vis. Res.* 22, 1033–1045

32 Zelinsky, G.J. *et al.* (1997) Eye movements reveal the spatiotemporal dynamics of visual search. *Psychol. Sci.* 8, 448–453

33 Schiller, P.H. and Chou, I.H. (1998) The effects of frontal eye field and dorsomedial frontal cortex lesions on visually guided eye movements. *Nature Neurosci.* 1, 248–253

34 Schall, J.D. *et al.* (1995) Saccade target selection in frontal eye field of macaque I: visual and premovement activation. *J. Neurosci.* 15, 6905–6918

35 Bichot, N.P. *et al.* (1996) Visual feature selectivity in forntal eye fields induced by experience in mature macaques. *Nature* 381, 697–699

36 Desimone, R. and Duncan, J. (1995) Neural mechanisms of selective attention. *Annu. Rev. Neurosci.* 18, 193–222

37 Yarbus, A.L. (1967) *Eye movements and vision*, Plenum Press

38 Intraub, H. (1997) The representation of visual scenes. *Trends Cognit. Sci.* 1, 217–221

39 Rayner, K. (1998) Eye movements in reading and information processing: 20 years of research. *Psychol. Bull.* 124, 372–422

40 Henderson, J.M. and Hollingworth, A. (1998) Eye movements during scene viewing: an overview. In *Eye Guidance in Reading and Scene Perception* (Underwood, G., ed.), pp. 269–293, Elsevier

41 Henderson, J.M. and Hollingworth, A. (1999) High-level scene perception. *Annu. Rev. Psychol.* 50, 243–271

42 Schyns, P.G. and Oliva, A. (1994) From blobs to boundary edges: evidence for time and spatial scale dependent scene recognition. *Psychol. Sci.* 5, 195–200

43 Rayner, K. and Pollatsek, A. (1992) Eye movements and scene perception. *Can. J. Psychol.* 46, 342–376

44 Henderson, J.M. *et al.* (1997) Object identification without foveal vision: evidence from an artificial scotoma paradigm. *Percept. Psychophys.* 59, 323–346

45 Rayner, K. and Bertera, J.H. (1979) Reading without a fovea. *Science* 206, 468–489

46 Loftus, G.R. (1985) Picture perception: effect of luminance level on available information and information extraction rate. *J. Exp. Psychol.* 114, 342–356

47 Mannan, S.K. *et al.* (1995) Automatic control of saccadic eye movements made in visual inspection of briefly presented 2-D images. *Spat. Vis.* 9, 363–386

48 De Graef, P. *et al.* (1990) Perceptual effects of scene context on object identification. *Psychol. Res.* 52, 317–329

49 Loftus, G.R. and Mackworth, N.H. (1978) Cognitive determinants of fixation location during picture viewing. *J. Exp. Psychol.* 4, 565–572

50 Henderson, J.M. *et al.* (1999) The effects of semantic consistency on eye movements during complex scene viewing. *J. Exp. Psychol.* 25, 210–228

51 Rayner, K. (1995) Eye movements and cognitive processes in reading, visual search, and scene perception. In *Eye Movement Research: Mechanisms, Processes and Applications* (Findlay, J.M. *et al*., eds), pp. 3–22, Elsevier

52 Rayner, K. and Pollatsek, A. (1989) *The Psychology of Reading*, Prentice-Hall

53 Rayner, K. and Duffy, S.A. (1988) On-line comprehension processes and eye movements in reading. In *Reading Research: Advances in Theory and Practice* (Vol. 6) (Daneman, M. *et al*., eds), pp. 13–66, Academic Press

54 Rayner, K. (1979) Eye guidance in reading: Fixation locations in words. *Perception* 8, 21–30

55 O'Regan, J.K. (1981) The convenient viewing position hypothesis. In *Eye Movements, Cognition and Visual Perception* (Fisher, D.F. *et al*., eds), pp. 289–298, Erlbaum

56 O'Regan, J.K. (1990) Eye movements and reading. In *Eye Movements and their Role in Visual and Cognitive Processes* (Kowler, E., ed.) pp. 395–453, Elsevier

57 O'Regan, J.K. (1992) Optimal viewing position in words and the strategy–tactics theory of eye movements in reading. In *Eye Movements and Visual Cognition: Scene Perception and Reading* (Rayner, K., ed.), pp. 333–354, Springer-Verlag

58 McConkie, G.W. and Rayner, K. (1975) The span of the effective stimulus during a fixation in reading. *Percept. Psychophys.* 17, 578–586

59 Rayner, K. (1975) The perceptual span and peripheral cues in reading. *Cognit. Psychol.* 7, 65–81

60 Rayner, K. *et al.* (1980) Asymmetry of the effective visual field in reading. *Percept. Psychophys.* 27, 537–544

61 Rayner, K. *et al.* (1982) The availability of useful information to the right of fixation in reading. *Percept. Psychophys.* 31, 537–550

62 Pollatsek, A. *et al.* (1981) Asymmetries in the perceptual span for Israeli readers. *Brain Lang.* 14, 174–180

63 Just, M.A. and Carpenter, P.A. (1980) A theory of reading from eye movements to comprehension. *Psychol. Rev.* 87, 329–354

64 Rayner, K. and McConkie, G.W. (1976) What guides a reader's eye movements? *Vis. Res.* 16, 829–837

65 Rayner, K. and Pollatsek, A. (1981) Eye movement control during reading: evidence for direct control. *Q. J. Exp. Psychol.* 33A, 351–373

66 Inhoff, A.W. and Rayner, K. (1986) Parafoveal word processing during fixations in reading: effects of word frequency. *Percept. Psychophys.* 40, 431–439

67 Rayner, K. and Duffy, S.A. (1986) Lexical complexity and fixation times in reading: effects of word frequency, verb complexity, and lexical ambiguity. *Mem. Cognit.* 14, 191–201

68 Rayner, K. *et al.* (1996) Eye movement control in reading: a comparison of two types of models. *J. Exp. Psychol.* 22, 1188–1200

69 Duffy, S.A. *et al.* (1988) Lexical ambiguity and fixation times in reading. *J. Mem. Lang.* 27, 429–446

70 Morris, R.K. (1994) Lexical and message level sentence context effects of fixation times in reading. *J. Exp. Psychol.* 20, 92–103

71 Pollatsek, A. *et al.* The effects of neighborhood size in reading and lexical decision. *J. Exp. Psychol.* 25, 1142–1158 (in press)

72 Pollatsek, A. *et al.* (1992) Phonological codes are used in integrating information across saccades in word identification and reading. *J. Exp. Psychol.* 18, 148–162

73 Henderson, J.M. *et al.* (1995) Evidence for the use of phonological representations during transsaccadic word recognition. *J. Exp. Psychol.* 21, 82–97

74 Inhoff, A.W. (1989) Lexical access during eye fixations during reading: are word access codes used to integrate lexical information across interword fixations? *J. Mem. Lang.* 28, 444–461

75 Balota, D.A. *et al.* (1985) The interaction of contextual constraints and parafoveal visual information in reading. *Cognit. Psychol.* 17, 364–390

76 Rayner, K. and Morris, R.K. (1992) Eye movement control in reading: evidence against semantic preprocessing. *J. Exp. Psychol.* 18, 163–172

77 Henderson, J. and Ferreira, F. (1993) Eye movement control during reading: fixation measures reflect foveal but not parafoveal processing difficulty. *Can. J. Exp. Psychol.* 47, 201–221

78 Rayner, K. *et al.* (1998) Unspaced text interferes with both word identification and eye movement control. *Vis. Res.* 38, 1129–1144

79 Rayner, K. *et al.* (1986) Against parafoveal semantic preprocessing during eye fixations in reading. *Can. J. Psychol.* 40, 473–483

80 Inhoff, A. *et al.* Parafovea to fovea priming during eye fixations in reading. *Percept. Psychophys*. (in press)

81 Murray, W.S. (1998) Parafoveal Pragmatics. In *Eye Movements in Reading and Scene Perception* (Underwood, G., ed.), pp. 181–200, Elsevier

82 Murray, W.S. and Rowan, M. (1998) Early mandatory pragmatic processing. *J. Psycholing. Res.* 27, 1–22

83 Hyona, J. (1995) Do irregular letter combinations attract readers' attention? Evidence from fixation locations in words. *J. Exp. Psychol.* 21, 68–81

84 Underwood, G. *et al.* (1990) How do readers know where to look next? Local information distributions influence eye fixations. *Q. J. Exp. Psychol.* 42A, 39–65

85 Beauvillain, C. *et al.* (1996) The 'center of gravity' of words: evidence for an effect of the word initial letters. *Vis. Res.* 36, 589–603

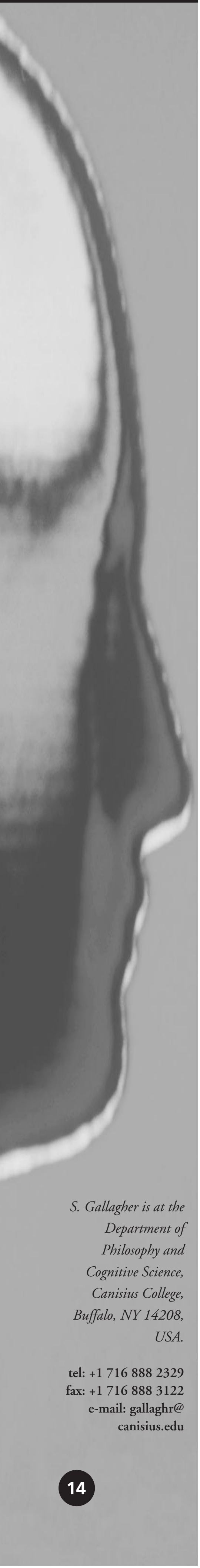
86 Rayner, K. *et al*. The effect of clause wrap-up on eye movements during reading. *Q. J. Exp. Psychol.* (in press)

87 Ferreira, F. and Clifton, C. (1986) The independence of syntactic processing. *J. Mem. Lang.* 25, 348–368

88 Paterson, K.B. *et al.* (1999) The influence of focus operators on syntactic processing of short relative clause sentences. *Q. J. Exp. Psychol.* 52A, 717–737

89 Rayner, K. *et al.* (1983) The interaction of syntax and semantics during sentence processing: eye movements in the analysis of semantically biased sentences. *J. Verb. Learn. Verb. Behav*. 22, 358–374

90 Frazier, L. and Rayner, K. (1982) Making and correcting errors during sentence comprehension: eye movements in the analysis of structurally ambiguous sentences. *Cognit. Psychol.* 14, 178–210



91 Traxler, M.J. and Pickering, M.J. (1996) Plausibility and the processing of unbounded dependencies: an eyetracking study. *J. Mem. Lang.* 35, 454–475

92 Murray, W.S. and Liversedge, S.P. (1994) Referential context effects on syntactic processing. In *Perspectives on Sentence Processing* (Clifton, J. *et al*., eds), pp. 359–388, Erlbaum

93 Altmann, G.T.M. *et al.* (1992) Avoiding the garden path: eye movements in context. *J. Mem. Lang.* 31, 685–712

94 Britt, M.A. (1994) The interaction of referential ambiguity and argument structure in the parsing of prepositional phrases. *J. Mem. Lang.* 33, 251–283

95 Liversedge, S.P. *et al.* (1998) Processing arguments and adjuncts in isolation and context: the case of *by*-phrase ambiguities in passives. *J. Exp. Psychol.* 24, 461–475

96 Spivey-Knowlton, M.J. *et al.* (1993) Context effects in syntactic ambiguity resolution. *Can. J. Psychol.* 47, 276–309

97 Spivey, M.J. and Tanenhaus, M.K. (1998) Syntactic ambiguity resolution in discourse:modeling the effects of referential context and lexical frequency. *J. Exp. Psychol.* 24, 1521–1543

98 Trueswell, J.C. *et al.* (1994) Semantic influences on parsing: use of thematic role information in syntactic disambiguation. *J. Mem. Lang.* 33, 285–318

99 MacDonald, M. (1994) Probabilistic constraints and syntactic ambiguity resolution. *Lang. Cognit. Processes* 9, 157–201

100 Spivey-Knowlton, M.K. and Sedivy, J. (1995) Resolving attachment ambiguities with multiple constraints. *Cognition* 55, 227–267

101 Traxler, M.J. *et al.* (1998) Adjunct attachment is not a form of lexical ambiguity resolution. *J. Mem. Lang.* 39, 558–592

102 Van Gompel, R.P.G. *et al.* Unrestricted race: a new model of syntactic ambiguity resolution. In *Reading as a Perceptual Process* (Kennedy, A. *et al*., eds), Elsevier (in press)

103 Garrod, S. *et al.* (1994) The role of different types of anaphor in the on-line resolution of sentences in a discourse. *J. Mem. Lang.* 33, 39–68

104 Duffy, S.A. and Rayner, K. (1990) Eye movements and anaphor resolution: effects of antecedent typicality and distance. *Lang. Speech* 33, 103–119

Philosophical conceptions of the self: implications for cognitive science

Shaun Gallagher

Several recently developed philosophical approaches to the self promise to enhance the exchange of ideas between the philosophy of the mind and the other cognitive sciences. This review examines two important concepts of self: the 'minimal self', a self devoid of temporal extension, and the 'narrative self', which involves personal identity and continuity across time. The notion of a minimal self is first clarified by drawing a distinction between the sense of self-agency and the sense of self-ownership for actions. This distinction is then explored within the neurological domain with specific reference to schizophrenia, in which the sense of self-agency may be disrupted. The convergence between the philosophical debate and empirical study is extended in a discussion of more primitive aspects of self and how these relate to neonatal experience and robotics. The second concept of self, the narrative self, is discussed in the light of Gazzaniga's left-hemisphere 'interpreter' and episodic memory. Extensions of the idea of a narrative self that are consistent with neurological models are then considered. The review illustrates how the philosophical approach can inform cognitive science and suggests that a two-way collaboration may lead to a more fully developed account of the self.

S. Gallagher is at the Department of Philosophy and Cognitive Science, Canisius College, Buffalo, NY 14208, USA.

tel: +1 716 888 2329
fax: +1 716 888 3122
e-mail: gallaghr@canisius.edu

Ever since William James[1] categorized different senses of the self at the end of the 19th century, philosophers and psychologists have refined and expanded the possible variations of this concept. James' inventory of physical self, mental self, spiritual self, and the ego has been variously supplemented. Neisser, for example, suggested important distinctions between ecological, interpersonal, extended, private and conceptual aspects of self[2]. More recently, when reviewing a contentious collection of essays from various disciplines, Strawson found an overabundance of delineations between cognitive, embodied, fictional and narrative selves, among others[3]. It would be impossible to review all of these diverse notions of self in this short review. Instead, I have focused on several recently developed approaches that promise the best exchange of ideas between philosophy of mind and the other cognitive sciences and that convey the breadth of philosophical analysis on this topic. These approaches can be divided into two groups that are focused, respectively, on two important aspects of self – the **'minimal' self** and the **'narrative' self** (see Glossary).

1364-6613/00/$ – see front matter © 2000 Elsevier Science Ltd. All rights reserved. PII: S1364-6613(99)01417-5