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Theoretical perspectives on eye movements in reading: Past controversies, current issues, and an agenda for future research

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The study of eye movements has become a well established and widely used methodology in experimental reading research. This Introduction provides a survey of some key methodological issues, followed by a discussion of major trends in the development of theories and models of eye movement control in fluent reading. Among the issues to be considered in future research are problems of methodology, a stronger grounding in basic research, integration with the neighbouring area of research on single word recognition, more systematic approaches to model evaluation and comparison, and more work on individual variation and effects of task demands in reading.

Our aim in this Introduction is to provide a brief survey over the field of eye movements and information processing in normal reading. We will start with a discussion of some important methodological issues, intended primarily to help readers from other areas understand the terminology and get a feel for the kind of data that form the base of work in the field. We will then concentrate on what has been a dominant theme of much recent work, the development of theories and models of eye movement control in fluent reading. This discussion will provide a basis for identifying issues that may have been neglected in prior research and might consequently be considered as topics for the future.

Experimental reading research is an innovative and rapidly expanding field of scientific research (see Rayner, 1998; Kennedy, Radach, Heller, & Pynte, 2000;

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Hyönä, Deubel, & Radach, 2003; for recent discussions). Within the area, the study of eye movements has played a pivotal role, partly because they are an inherent behavioural manifestation of the reading process in action (and hence provide the researcher with an excellent nonintrusive methodology), but also because they have proved to be a powerful way of studying the workings of the human mind. There are at least three different, albeit overlapping, theoretical perspectives from which the topic can be approached.

First, from the viewpoint of perception and motor control, reading can be viewed as a task where visual processing and sensorimotor control take place in a highly structured visual environment. The text page contains letters, words, lines of text, and paragraphs, forming a hierarchy of visual objects. However, it is an array of visual information significantly less complex than any realistic scene of natural objects. Reading thus allows for the examination of basic issues in perception and motor control in an ecologically valid situation, while subjects are engaged in a complex visual-cognitive task. In reality, this first approach is more a theoretical possibility than a routine research strategy. One of the relatively few, but influential, examples is the linking of eye movement control in reading to a perceptual centre of gravity phenomenon carried out by O'Regan (1990). Another key import from basic oculomotor research that has had a significant influence on theory building is the principle of temporal overlap in the programming of successive saccades introduced into reading research by Morrison (1984).

A second theoretical perspective, rooted in the mainstream of cognitive psychology, sees reading as a special case of a complex process of information acquisition, functioning at roughly the same level as the process of understanding a pictorial scene. A multitude of processing modules need to work together on several levels to turn the arrays of combined visual features comprising letters into words and concepts that eventually form a mental representation of text. Of central importance in this process are the coordination of processes, the timescale in which they unfold, and their interaction with underlying memory systems. Examples here might be the issue of serial vs. parallel processing of linguistic information at the letter and word level, or the question of whether certain types of information are processed in a modular or an interactive way (Pollatsek & Rayner, 1989). Eye movement research from this perspective has led in the development of several realistic computational models of reading that combine mechanisms of oculomotor control and linguistic processing to account for a wide range of empirical phenomena (see Reichle, Rayner, & Pollatsek, in press, for a detailed review).

Finally, eye movement measures have played a central role as a tool to develop and test psycholinguistic hypotheses about the processing of written language. In the recent past this has been the most prominent, and arguably the most fruitful, approach in the literature. There have been literally hundreds of studies exploiting the potential of temporal measures like fixation and gaze durations as online indicators of processing load, and spatial measures like fixation position and saccade amplitudes as indices of the direction and sequence of processing.

There are strong interrelations between these theoretical perspectives. For example, visuomotor research can make transparent the methodological strengths and weaknesses of eye movement measures in psycholinguistic research, but equally psycholinguistically motivated research has raised questions that demand examination in terms of their visuomotor dimensions (see, for example, the issue of long-range regressive saccades triggered by higher order linguistic processing; Kennedy, 2003). The papers assembled in the present Special Issue of the *European Journal of Cognitive Psychology* contribute, both in isolation and in different forms of interrelation, to all three of these perspectives.

SOME BASIC METHODOLOGICAL ISSUES

During reading, we move our eyes in a sequence of very fast, relatively well coordinated, movements known as saccades. These movements are interrupted by fixations, periods of relative stability in the position of the visual axis, during which visual information can be extracted. It is interesting to note that many basic facts about eye movements in general have been established in the context of reading research and that the present division into more visuomotor vs. more cognitive ways of looking at eye movements did not exist in an earlier research tradition (Dodge, 1903; Dodge & Cline, 1901; see also Wade, Tatler, & Heller, in press).

Research on the metrics of saccades in reading has shown that fixations are positioned in a very systematic, word-based, fashion. There are systematic relations between the duration and number of fixations on a given segment of text and its visual and linguistic processing. Perhaps one of the basic findings in this context is that the information acquired during a given fixation can influence the duration of that fixation as well as the amplitude of the outgoing saccade. This is referred to as *direct* control of eye movements (Rayner & Pollatsek, 1981).

The eye movement data reported in this Special Issue are the result of a relatively complex process of data reduction and analysis that obviously starts with the collection and storage of raw data. At this stage, issues like measurement accuracy and calibration play a significant role (McConkie, 1981). At the next stage, eye movement data need to be segmented and classified, including the determination of basic oculomotor events like saccades and fixations. Here, definitions of, and decisions on, minimal saccade amplitude and fixation duration and the handling of eye blinks play a critical role. At the next level of the process, data must be aggregated into units of analyses that can serve as the basis for statistical analyses. This stage of data analysis contains a number of choice points where the decisions taken can have significant consequences. In recent years, discussion of these methodological issues in their own right has started to gain momentum, but no generally agreed standards have yet emerged (see Inhoff & Radach, 1998; Inhoff & Weger, 2003; Murray, 2000; Rayner, 1998; Vonk & Cozijn, 2003). There is, however, a reasonable consensus (as is evidenced in this Special Issue) on the appropriate measures to describe saccades and fixations relative to critical words in text. Assuming that many readers are not familiar with the terminology and conventions of the field, Tables 1 and 2 present definitions of some of the more important spatial and temporal eye movement measures.

It is evident from Table 1 that word-based spatial eye movement measures reflect three aspects of oculomotor behaviour: the fact that a word is, or is not, fixated; the position fixated; and the amplitude of incoming and outgoing saccades. There are many possible combinations of these properties. For example, it has proved theoretically fruitful to distinguish between the amplitudes of saccades into and out of words and those within them (inter- vs. intraword movements) and to consider separately whether these saccades go from left to right (progressive saccades, when reading English and other left-to-right orthographies) or are directed against the normal reading direction (regressive saccades). Similar refinements are possible in the case of the temporal measures shown in Table 2, for example, distinguishing the first and second of two fixations from cases where exactly one fixation is made on a critical word. Each of these measures is, to some degree, pertinent to a particular theoretical

TABLE 1
Definitions of the more commonly used word-based spatial eye movement measures

Parameter	*Definition*
Saccade amplitude, saccade length, saccade extent	Distance, in character positions, between the mean position of two successive fixations
Fixation probability, inverse measure: skipping rate	Relative frequency with which a word is fixated at least once; inverse measure: frequency of ''word skipping''
Fixation position, fixation location	Position within a word (in characters) where a fixation is located, the empty space between words coded as zero
Launch distance, launch site	Distance in characters between the location of the prior fixation and the beginning (or centre) of the current word
Fixation frequency	Mean absolute number of fixations per word, for the current pass (defined as first, second, etc. encounter with specified text)
Refixation probability/frequency	Relative frequency of making at least one additional fixation before leaving a word

The relevant metric is in terms of letters rather than degrees of visual angle.

TABLE 2
Definitions of the more commonly used word-based temporal eye movement parameters

Parameter	*Definition*
Initial/first fixation duration	Duration of the first fixation within a word, irrespective of whether more fixations follow
Refixation duration	Summed duration of additional fixations within the current pass prior to an exit from the word
Gaze duration	Summed duration of all fixations before leaving the word (within the current pass)
Re-reading time	Summed duration of all fixations made after leaving the word for the first time
Total reading time, total fixation time	Summed duration of all fixations made on the critical word

Aggregated viewing time measures are usually computed without taking into account the durations of intraword saccades.

question, making the measure of mean fixation duration (e.g., per condition or cell in an experimental design) somewhat problematic. For example, effects that manifest themselves in the number of fixations, may become obscured in the measure of their average duration (Blanchard, 1985; see Radach & Heller, 2000, for further discussion of relations between spatial and temporal aspects of eye movement control).

A useful notion for the description of fixation patterns is the concept of a ‘‘pass’’, denoting the first encounter with some defined segment of text, the equivalent gaze durations being referred to as first pass gaze durations. A complication emerges when a segment of text is read more than once. In this case, the respective gaze durations are referred to as second pass gaze durations, although it is possible that a particular word may receive its first fixation during such a pass, and in this case it is clearly necessary to explain whether the relevant data are allocated to the first or second pass.

Typically, the methodology used in eye movement studies of fluent reading involves the construction of experimental sentences or short passages of text that include critical target words. Relevant independent variables can then be systematically manipulated and the consequential effects on eye movement measures observed. An alternative, quasiexperimental approach is the recording of eye movements while corpora of natural text are being read. Kliegl, Olson, and Davidson (1983) refer to the technique of analysing this kind of data as orthogonal sampling. The corpus can be analysed with respect to the eye movements on particular words with specific properties related to some target variable, with other variables controlled. McConkie, Kerr, Reddix, and Zola (1988) used this technique in their seminal analysis of saccade landing site distributions, systematically sampling distributions for many combinations of word length and launch distance relative to the target word centre. This method has weaknesses, because it is always possible that particular outcomes have been mediated by variables not included in the sampling scheme, or arise as a result of hidden interactions. But it can be very useful for exploratory analyses and for the generation of hypotheses to be subsequently tested in more controlled experiments (as was the case with the McConkie et al. data). On the other hand, given that laboratory studies (perhaps particularly those involving single words examined in isolation) are somewhat remote from normal reading, a strong argument for the generality of a result obtained with highly selected stimulus material can be mounted if traces of the particular effect also occur in a normal text reading corpus.

A critical problem in the analysis of eye movement data is that there are at least three different ways to respond to processing difficulty: The eyes can remain on the critical word (or critical region) until the problem has been resolved; they can proceed with a progressive saccade (possibly related to an increase in viewing time measures); or they can execute a regressive saccade to reread segments of text. To handle complexities like this, several authors have proposed hybrid eye movement parameters that aggregate patterns of fixations over several words. One such measure has been termed ‘‘total pass’’ or ‘‘regression path’’ reading time (Kennedy, Murray, Jennings, & Reid, 1989; Konieczny, 1996; Liversedge, Paterson, & Pickering, 1998; Murray, 2000), defined as the sum of all fixations from the first fixation within the critical region until an exit from the region via its right (see also Rayner & Duffy, 1986, and Duffy, Morris, & Rayner, 1988, who used essentially the same procedure). A similar approach is the cumulative region reading time analysis proposed by Brysbaert and Mitchell (1996). Hybrid measures like this are assumed to reflect the time needed to notice and repair a higher level processing problem. Recently, there have been attempts to develop measures that go beyond the scope of sentence processing to describe phenomena such as shift of topic within a text or the detection of global semantic inconsistencies (Hyönä, Lorch, & Rinck, 2003).

The final and most important step in the analysis of eye movements is their interpretation within the context of a given theoretical framework. Until the mid-1980s, interpretation of eye movement data was guided by the *eye–mind* and *immediacy* assumptions proposed by Just and Carpenter (1980). These suggested that processing coincides with, and is bounded by, the position fixated at any point in time, and that this processing starts at the point of fixation and continues until all possible analyses, up the semantic/thematic level, are completed. Numerous subsequent studies have shown that the spatial and temporal relationship between eye movements and information processing cannot be captured by these simple principles (see Rayner, 1998, for a comprehensive review).

First, while fixating a particular word, there is a substantial amount of preprocessing of the next word. Second, processing may spill over from one word to another: Encountering a difficult word can have consequences for the viewing time on a subsequent word (Rayner & Duffy, 1986). The eye and the mind are not tightly synchronised: The mind is sometimes a bit ahead of the eyes, but can also lag a little behind. Nonetheless, the relation between fixation positions and durations and local processing is strong enough to produce reliable effects when sampled over groups of participants and items and in this sense eye movement measures provide an extremely sensitive index of local processing load.

There is, of course, a limitation inherent in any essentially nonintrusive measure and this certainly applies to eye movement recordings. The experimenter is not in control of the specific pattern of data that arise in response to a given experimental manipulation. Further, and in contrast to many research paradigms used to study words in isolation, there is no straightforward way to determine how much visual information is available during a fixation, and precisely what type of information is being extracted. To some extent, this loss of experimental control can be compensated for using the technique of eye-movement-contingent display changes first introduced by McConkie and Rayner (1975) and Rayner (1975). This technique capitalises on the fact that little or no visual processing normally takes place during saccades. Movements of the eyes can be used to trigger changes in the display being processed. It is possible in this way to achieve control over the availability of (as yet uninspected) visual and linguistic information. For example, in the *boundary technique*, crossing an invisible boundary causes a change (during the ongoing saccade) in the text about to be fixated. Such changes (e.g., unmasking a previously masked item) usually go unnoticed by readers, but have profound consequences for processing. O'Regan (1990) has raised the question of whether perceptual consequences of display changes may influence results obtained with eye movement contingent display techniques. Such objections have been resolved to a large degree by direct demonstrations that the speed with which a display change is implemented has no effect on eye movements and fixations made after a saccade has crossed the critical boundary (Briihl & Inhoff, 1995; Inhoff, Starr, Liu, & Wang, 1998).

Display changes can also be implemented during a fixation. In this case, the changes are capable of being noticed by readers and masking techniques can be applied in combination with linguistic variations. As an example, McConkie, Underwood, Zola, and Wolverton (1985), briefly masked a whole line of text and replaced a word with another, visually similar, word at certain intervals after fixation onset. Readers were then asked to report which word they had seen. Similarly, the *fast priming paradigm* was developed by Sereno and Rayner (1992) to examine the time course of information uptake during a fixation. In this case, the movement of the eyes onto a target word causes the brief presentation of a prime stimulus that is replaced after a short time interval with a target word. Viewing time measures on the target are used to index the use of linguistic information conveyed by the prime. Inhoff, Connine, and Radach (2002) recently developed the *contingent speech technique*, where a visual display change is combined with the auditory presentation of a companion word immediately before, during, or after a critical word is fixated. The method provides data on the time course of phonological or semantic representations in working memory as reflected in gaze durations during the course of reading a number of words after the auditory stimulus was presented.

THEORIES AND MODELS OF EYE MOVEMENT CONTROL IN READING

In this section the discussion will focus on the development of detailed explanations of eye movement control. How are saccades generated during reading? How do linguistic processes and the visuomotor machinery interact to produce the observed oculomotor phenomena? These general questions represent an underlying theoretical preoccupation of the past two decades, namely, the identification of factors responsible for the ''*where?*'' and ''*when?*'' of eye movement control in reading.

With respect to the ''*where?*'' issue, there is now a consensus that the positioning of fixations is word-based, such that a key aspect is the decision as to which word is to be selected as the target for the next fixation. Fortunately, there are only a few alternatives to be considered in this decision, as the vast majority of saccades departing from a specific word either land on the same word again (refixations on word N), go to the immediately following word (N+1) or to the word beyond that (N+2). Interword regressions, bringing the eyes to positions *left* of the current word boundary, also predominantly land on words N–1 or N–2 (Radach & McConkie, 1998; Vitu & McConkie, 2000). Word targeting decisions are primarily based on low level information like word length and saccade launch distance, but cognitive factors such as word frequency and predictability also play a significant role (Brysbaert & Vitu, 1998; Drieghe, Brysbaert, Desmet, & De Baecke, 2004). Somewhat independent of the selection of which word to fixate is the specification of the precise saccadic amplitude needed to bring the eyes to the selected target. There are several lines of evidence suggesting that saccades (including refixation saccades) are aimed at the centre of the selected target word, which can be related to the fact that locations near the word centre appear to be optimal both for saccade targeting and foveal word processing. It is also largely agreed that, owing to visuomotor constraints, the eyes are systematically deviated from this target location, creating the well-known difference between the ''optimal'' and the ''preferred'' saccade landing position, the latter being located about halfway between the beginning and the centre of the target word (McConkie et al., 1988; O'Regan, 1990; Rayner, 1979; see Inhoff & Radach, 2002, for a recent review).

The temporal aspect of eye movement control (‘‘*when?*’’) primarily concerns the question as to when a given saccade is triggered or, more precisely, the time course of processing events and control decisions occurring during a fixation. A closely related question is what information is used within this time frame to guide the eyes. As noted above, there is no doubt that control decisions can be based on information acquired online during the ongoing fixation. Effects of information acquired earlier in the text on viewing time measures can be significant when contextual constraint, either in terms of local word associations (Zola, 1984) or more global context, is very strong (Schustack, Ehrlich, & Rayner, 1987). A common way to determine the strength of contextual constraint is via measures of the predictability of the next word on the basis of all prior words in a sentence (e.g., Rayner & Well, 1996) or a longer passage of text (e.g., Vonk, Radach, & van Reijn, 2000).

Attempts to account for the detailed time course of oculomotor control during reading (e.g., Pynte, Kennedy, & Murray, 1991) have recently been buttressed by converging technologies. For example, Sereno, Rayner, and Posner (1998) found in an ERP study of single word processing that the evoked potential responses for low frequency and high frequency words start to diverge at about 130 ms. This represents an estimate of the lower bound of the time to achieve lexical access. At the other end of the timescale, results using the double step paradigm suggest that the amplitude of a saccade can be modified no later than 70–90 ms before the end of the current fixation (Deubel, O’Regan, & Radach, 2000). McConkie et al. (1985) propose a visual stimulus influence deadline of 80–100 ms before the onset of the impending saccade. With these kinds of constraint in mind, Sereno and Rayner (2000b) conclude that the interval during which lexical processing can conceivably influence when the eyes are to move is severely limited. It follows that lexical processing must be sufficiently advanced within the first 100 to 150 ms of a fixation in order to ‘‘intelligently’’ trigger the next eye movement (p. 79).

The issues sketched above have been at the core of a controversy that has dominated discussions in the field for more than a decade. One position in this debate has been that eye movements in reading are largely controlled by lexical processing, with lexical access determining both the position of fixations, their duration, and the probability that a word will be skipped. Typical of this position is the attention-based sequential processing model introduced by Morrison (1984) and reformulated by Henderson and Ferreira (1990) and Rayner and Pollatsek (1989). In the Morrison model, lexical access on a word causes a shift of visual attention to the next word, followed after a certain latency by a saccade. If the next word is easy to process, a second attention shift can take place (the eyes remaining on the first word). In this way, a process of cancellation and reprogramming of the ensuing saccade could lead to the next word being skipped. The Morrison model successfully accounted for some basic phenomena, in particular the existence of parafoveal processing, but suffered limitations such as the lack of a mechanism to handle refixations and an inability to account for the fact that parafoveal processing is modulated by current foveal difficulty. The existence of visuomotor constraints was acknowledged in this model, but they did not play a significant role in its instantiation.

The alternative position has been to claim that low-level visual processing and oculomotor factors are mainly responsible for the positioning of the eyes over a line of text and that it is these factors that have the stronger influence on viewing time measures. This view found its clearest expression in the Strategy–Tactics theory of O'Regan and colleagues (O'Regan, 1990, 1992; O'Regan & Lévy-Schoen, 1987), although work by McConkie et al. (1988) can also be seen in this tradition. As a more recent computational model by Reilly and O'Regan (1998) has shown, simple heuristics like ''fixate the largest word within a window of 20 letter spaces'' can indeed give a reasonable account of the where-aspects of eye movement control. Similarly, the Mr. Chips model of Legge, Klitz, and Tjan (1997) proposed that the eyes are primarily guided by basic visual heuristics. However, models restricted to low-level oculomotor control plainly fail to handle the complexities of temporal control (Rayner, Sereno, & Raney, 1996).

With the benefit of hindsight this controversy (like many others) can be seen as little more than a question of emphasis. The two different approaches in reality define the extremes of a continuum and it is likely that any successful model will have to accommodate both ''cognitive/attentional'' and ''visual/oculomotor'' aspects. Indeed, O'Regan, Vitu, Radach, and Kerr (1994) acknowledge the limitations of an exclusively low-level view and suggest that a successful theory will need to combine elements of both traditions. And, equally, Rayner et al. (1996), while certainly giving precedence to the role of lexical processing, acknowledge the part played by visuomotor factors in arguing for some kind of ''hybrid model''. It may be more productive to view those eye movement patterns which are determined by purely visuomotor processing as providing a ''carrier signal'' which can be modulated by cognitive influences (see also Deubel et al., 2000; Yang & McConkie, 2001).

Reichle, Pollatsek, Fisher, and Rayner (1998) presented the first realistic algorithmic attention shift model of eye movement control in reading in the form of their E-Z Reader model. Although undeniably in the attention-shift tradition, its latest instantiation (Reichle et al., in press) also draws to some extent on low-level oculomotor control processes. The model has been used to fit the corpus of reading data obtained by Schilling, Rayner, and Chumbley (1998) and successfully accounts for a wide range of effects, including variation in viewing time as a function of word frequency, the effects of predictability, short-duration fixations, word-skipping, and spillover effects. Overall, the E-Z Reader model has set a standard against which alternative models will have to be evaluated.

Critical discussion of attention-based sequential control models has taken two main routes. The first points to evidence that more then one word may be processed in parallel rather than in a strictly sequential fashion (Hyönä & Bertram, 2004; Inhoff, Radach, Starr, & Greenberg, 2000; Kennedy, 1995, 1998, 2000; Kennedy, Pynte, & Ducrot, 2002; Pynte, Kennedy, & Ducrot, 2004; Starr & Inhoff, 2004; Underwood, Binns, & Walker, 2000). While the parafoveal preview effect is entirely consistent with the operation of a sequential control model, properties of a word in the parafovea should not influence concurrent foveal processing and demonstrations that they do are clearly embarrassing. The research agenda has now shifted from a focus on *whether* such parallel processing occurs, to determining its precise nature and, in particular, whether such processing cross-talk is restricted to sublexical properties (Reichle et al., in press).

A second source of critical debate has centred on the question as to whether properties of the sequential model, such as lexical processing, attention shifts, and saccade programming can plausibly operate in a serial manner, given the temporal constraints outlined above. For example, for a word to be skipped the following sequence of events needs to occur before any decision to modify the ongoing saccade program can be made: (1) complete lexical processing of the current word, (2) a shift of attention to the to-be-skipped word, and (3) initial lexical processing (at least) of this newly attended word. This may take place under certain, rather unusual, circumstances (e.g., when the next word is short and very easy to process), but doubts can be raised as to whether such a process could plausibly be the default mechanism responsible for all cases of word skipping (Deubel et al., 2000).

In response to such critiques, a number of alternative models have been developed. The SWIFT model (Engbert, Longtin, & Kliegl, 2002; Kliegl & Engbert, 2003), has some features of the E-Z Reader architecture but departs in one important respect in proposing that lexical processing is ‘‘spatially distributed’’. The Glenmore model by Reilly and Radach (2003) has some similarities with SWIFT, but represents an even more radical departure from attention based sequential processing models. The model appeals to the theoretical framework provided by Findlay and Walker (1999), in which the spatial aspect of saccade generation is seen in terms of activation and competitive inhibition within a spatial salience map. It also incorporates a connectionist letter and word processing module that, together with low-level processing, codetermines spatial and temporal control decisions. A very detailed theory of saccade timing that also combines visuomotor and cognitive influences has been developed by Yang and McConkie (2001, 2004).

ISSUES FOR THE FUTURE

Thirty-five years ago it is unlikely that a discussion on the future of reading research would have even mentioned eye movements. Now, their measurement is accepted as an indispensible technology and an understanding of their control processes as a critical step in moving towards a complete theory of that complex cognitive activity. In the face of such a pace of development, it is patently idle to guess at the detail of the direction future research may take, but it is, nonetheless, possible to identify important topics that may have received insufficient attention to date.

It is clear that scientific work in our field will include the continuation of fruitful streams of empirical work, some of which will be discussed in detail below. There can also be no doubt that the development of computational models of information processing and eye movement control in reading will be a central part of the research agenda in the immediate future. New models will be proposed and it will become commonplace to discuss empirical data in close relation to these computational models, in particular as models are developed that are capable of dealing with higher level linguistic processing at a syntactic, semantic, and thematic level (see Rayner, 1998, Table 2, for an overview on these effects).

Methodological problems

It will have become clear from the discussions to this point that research on eye movements and information processing in reading has a solid theoretical and methodological grounding. Nonetheless, there is still room for improvement in the methodological apparatus used. For example, Inhoff and Radach (1998) reported the results of an informal survey to which 32 researchers using oculomotor measures responded. It was clear that a number of important issues have remained either unaddressed or unresolved. All the researchers believed that there is a need for increased discussion of measurement-related and methodological issues. More strikingly, two thirds of them considered the definition of functional oculomotor events (e.g., criteria for defining saccades and fixations) to be controversial. More than one third wished to appraise the specification and interpretation of extant measures. We are at a point where uncertainty over the specification and interpretation of oculomotor measures is limiting the appraisal, comparison, and exchange of empirical findings.

In the last couple of years there has been some progress towards broader discussions of these methodological problems (e.g., Inhoff & Weger, 2003; Murray, 2000; Rayner, 1998), but there is still a lack of empirical work on core issues. As an example, Irwin (1998) has shown that lexical processing continues during saccades, but virtually all studies still report gaze durations excluding saccade durations. Rayner (1998) discussed this problem and argued that, at least when words are the unit of measure, the inclusion of saccade durations has very little effect. It may, however, make more of a difference when larger units of analysis are used. Vonk and Cozijn (2003) were the first to address this question directly by comparing results of a sentence reading experiment with and without the inclusion of intraword saccade durations. The results were reassuring in so far as they indicated that a similar pattern of results emerged in both analyses, but there were, nonetheless, also subtle differences in gaze durations and changes in the significance of results. Another issue that calls for discussion and standardisation is the plethora of measures proposed for the analysis of complex interword eye movement patterns (see Murray, 2000, for a critical discussion). We believe that problems of this kind need more focused attention and that the development of agreed standards will benefit the development of the field.

Grounding of reading research in work on basic visuomotor functions

There is a rich literature on saccade generation in the traditions of oculomotor physiology and systems theory, which has produced explicit and virtually complete theoretical frameworks and models. This neurobiological evidence has recently been reviewed by Munoz (2002; see also Carpenter, 2000, for a brief summary) and van Gisbergen and van Opstal (1989) have provided a detailed discussion of formal biophysical saccade control models. Given this background of affairs it is odd that experimental reading research has remained largely disconnected from the neurobiology relevant either to visual processing or to oculomotor control. A recent attempt to remedy this situation can be found in Reichle et al. (in press), who seek to relate current evidence from neuroscience to the framework of their E-Z Reader model. However, there are still lively debates on the identification of brain areas responsible for even the most basic aspects of processing (e.g., the recognition of visual word forms) within the neuroscience community and it is difficult at present to derive predictions for experimental outcomes or modelling constraints from this literature. Something related in part to the fact that current functional brain image technologies cannot provide online information in a time frame that can be related to the known time course of the subprocesses of fluent reading (Sereno & Rayner, 2000b).

Somewhat similar problems arise in attempts to link relevant aspects of fundamental research in perception to eye movement control in reading. Perhaps the most glaring example is the concept of ‘‘attention’’, which has played a central role in theories of eye movement control for over a century (Allport, 1993; Helmholtz, 1910). Attempts to define this concept can easily become bogged down in a maze of conflicting terms, circular arguments, and contradictory evidence. Both visual selection for the purpose of preparing eye movements and visual selection for the purpose of object (or word) recognition may be termed ‘‘attention’’. Sometimes these are equated; sometimes they are strictly separated; and sometimes they are seen as related by a common mechanism, referred to as ‘‘attention’’ (Schneider & Deubel, 2002). Unsurprisingly, in view of this, opinions about the relation between eye movements and attention range from obligatory coupling to complete independence, depending on definitions, theoretical assumptions, and research paradigms (see Radach, Inhoff, & Heller, 2002, for a discussion). The popular view that attention *moves* in terms of an adjustable spotlight has been challenged and contrasted with activity-distribution models (LaBerge, Carlson, Williams, & Bunney, 1997). If a movement is assumed to take place, the question of how long it takes to prepare and execute such a shift of attention receives answers on a spectrum of opinion ranging from an ''attentional dwell time'' of around 50 ms (Duncan, Ward, & Shapiro, 1994; Treisman & Gelade, 1980) to claims that ''visual attention moves no faster than the eyes'' (Ward, 2002).

A more systematic approach to the problem of relating eye movements in reading to basic research on visuomotor functions could take the same form as the multiple task strategy suggested below with respect to research on word recognition. One successful example here is the principle of temporal overlap in the programming of successive saccades, derived from the double step paradigm (Becker & Jürgens, 1979). It formed an important element of Morrison's (1984) model and provided the starting point for the later distinction between labile and nonlabile stages of saccade preparation in reading (Reichle et al., 1998). In addition to this multiple task approach, a second research strategy may be to address basic issues from within the task of normal reading. Promising lines of research that attempt to establish direct links from phenomena observed in a reading situation to basic perceptual or oculomotor mechanisms are the intriguing studies by Reingold and Stampe (2000, 2003) on the issue of saccadic inhibition evoked via gaze contingent display changes and the current work relating microsaccades in continuous reading to covert attention shifts (Engbert & Kliegl, 2003; Hafed & Clark, 2002).

It seems obvious that the starting point in any attempt to establish a productive relation between reading research and basic work on visuomotor functions must be a theory of saccade generation. Such a comprehensive theoretical framework, with clear relevance for a fuller understanding of reading, has recently been proposed by Findlay and Walker (1999). They suggest that the selection of saccade targets is accomplished via parallel processing and competitive inhibition within a two-dimensional ''salience map'' (in effect, finessing the problem of ''attention''). The trigger for the execution of a saccade arises from a dynamic interrelation between a move centre, implementing the selection mechanism, and an independent fixate centre. This theoretical conception is rooted in a large body of work from different areas of basic research and although there are discussions on many details of modelling, the framework as such is widely accepted. More importantly, the theory explicitly allows for direct and indirect cognitive influences on saccade generation, opening a route for the development of submodels for the specific case of reading. The Competition/Interaction theory (Yang & McConkie, 2001), the SWIFT model (Engbert et al., 2002; Kliegl & Engbert, 2003), and the Glenmore model (Reilly

& Radach, 2003) have all either included or implemented elements of the theoretical framework suggested by Findlay and Walker.

Integration with work on single word recognition

During the last two decades, eye movement research has contributed greatly to our understanding of how words are processed. But in many respects eye movement measurement has been seen primarily as a powerful addition to existing chronometric methods. This has, for example improved our understanding of the role played by phonology in visual word recognition (Pollatsek, Rayner, & Lee, 2000); morphological effects in complex word processing (Andrews, Miller, & Rayner, 2004; Inhoff & Radach, 2002; Pollatsek, Hyönä, & Bertram, 2000); or the role played by neighbourhood (Pollatsek, Perea, & Binder, 1999) and spelling to sound regularity (Sereno & Rayner, 2000a) effects. Nonetheless, the relationship between the well-established tradition of work on single word processing in cognitive psychology and equivalent work on word processing in fluent reading has remained wary and uncertain. The two subfields of reading research have maintained a state of (more or less) peaceful coexistence rather than productive cooperation. This is not to say there has been no interaction, but research questions, hypotheses, and theoretical ideas typically have been transferred from the area of word recognition into the field of research on continuous reading, with virtually no examples of transfer in the opposite direction.

Over the last decade there have been several attempts at the systematic comparison of eye movement data and results obtained using single word recognition paradigms, such as naming and lexical decision time (e.g., Folk & Morris, 1995; Grainger, O'Regan, Jacobs, & Segui, 1992; Inhoff, Briihl, & Schwartz, 1996; Juhasz, Starr, Inhoff, & Placke, 2003; Perea & Pollatsek, 1998). As an example, Schilling et al. (1998) examined word recognition performance in both naming and lexical decision and compared these to eye movement measures of viewing duration in normal reading. The same set of target words and the same group of participants was used. In all three methods a similar pattern of results emerged. Studies like this are an important first step towards collaboration between both research traditions, but it does not necessarily follow from a correspondence in the pattern of results obtained with different paradigms that the outcomes reflect the operation of the same underlying mechanisms. For example, facilitatory effects of orthographic neighbourhood density in both naming and lexical decision may, in fact, originate from very different processing mechanisms (Grainger & Jacobs, 1996). As a consequence, Grainger (2000) suggested: ''the multi-task approach must be supplemented with a clear theoretical analysis of the mechanisms that determine performance in a given task, how these mechanisms relate to those hypothesized to be operational in normal reading outside of the laboratory, and how they relate to the mechanisms hypothesized to be operational in other tasks used to study word recognition and reading'' (p. 154). We believe that this approach of modelling ''functional overlap'' (Grainger, 2003; Jacobs & Grainger, 1994) will be important to achieve progress in the collaboration of both subfields of reading research.

Viewing this issue from the other side, current computational models of the reading process are relatively well specified with respect to eye movement control, but are clearly underspecified with respect to the core process of letter and word recognition. This becomes apparent when comparing the word processing modules of putative models of the reading process, such as E-Z Reader, SWIFT, or Glenmore, and the sophistication of current models of word recognition, such as the activation-verification model (Paap, Chun, & Vonnahme, 1999), the DRC (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001), or MROM (Grainger & Jacobs, 1996; Jacobs, Rey, Ziegler, & Grainger, 1998). Of course, these models are, sometimes to an embarrassing degree, also models of performance in particular word recognition tasks. Given they are freed from the demands of syntactic and thematic processing and need not involve themselves with the oculomotor dynamics characteristic of reading it is unsurprising that it has, so far, proved extremely difficult to demonstrate their range of applicability to normal reading. It simply remains an article of faith that the subprocesses of (largely lexical) processing accounted for by these models are engaged in normal fluent reading. Perhaps, as an alternative to plugging more and more sophisticated word processors into eye movement control models, existing word processing models might accept as a necessary constraint modules for eye movement control. In this case, the move towards convergence of both areas would become a two-way road, including attempts to fine tune word processing models for the task of normal continuous reading.

Evaluation and comparison of reading models

There is no shortage of computation models of fluent reading. However, a gap is opening up between the computational sophistication of the models and an equivalent sophistication in techniques for their evaluation and comparison. Although the concept of ''goodness-of-fit'' itself may be debated, the primary criterion in assessing the success of any model is its fit to as many phenomena as possible. If this remains the primary criterion a situation will shortly arise where several, and possibly vastly different, models will justifiably claim to have achieved their goal. The more models differ in terms of underlying theoretical assumptions, architecture and principles of implementation, the more difficult will be their comparison. Jacobs (2000) discusses in some detail a set of general principles for model evaluation, basically arriving at the conclusion that existing computational models of reading cannot be compared because of their intrinsic heterogeneity. He makes two important exclusions. The first is the principle of ‘‘nested modelling’’ in which the E-Z Reader model provides an excellent example. Here, increasingly complex variants include older versions as special cases and thus represent a better approximation to reality by accommodating a larger empirical content. Unfortunately, this approach to model evaluation must be restricted to comparisons within the same family of models. A second, much more general, exclusion is what Jacobs refers to as the strong inference approach, where alternative models can be compared with respect to identical sets of data and evaluated on identical criteria.

A necessary precondition for this second approach is that the models are indeed comparable, or can be made comparable, and that accepted criteria for comparisons can be established (Jacobs & Grainger, 1994). A critical step in meeting this objective is the development of a common database to be used for the parameterisation and testing of alternative models. Some progress in this direction has already been made by Reichle et al. (1998), who made available the data set collected by Schilling et al. (1998), allowing Engbert and Kliegl (2001) and Engbert et al. (2002) to test their own models against this common baseline. The outcome achieved a high degree of comparability. Similar approaches involving common data sets can be found in the fields of machine learning, data mining, and, most importantly, language acquisition (MacWhinney, 1995). In the case of reading research, such a body of benchmark data should be extended to include a wider range of languages and scripts (Kliegl, Grabner, Rolfs, & Engbert, 2004). In the longer term it may also become possible to compare different computational models within a common implementation framework (Schmidt & Fayad, 1997).

Individual variations in reading and effects of task demands

There is a body of literature on both intra- and interindividual variation in the reading process, but in relation to the total amount of empirical work in the field the proportion is surprisingly small. In his review on the eye movement work of the last two decades, Rayner (1998) refers to the ‘‘classical’’ issues of reading skill, developmental changes in eye movement control, speed reading, and eye movements in dyslexia. However, little is known about the origins of such differences and about how individual variation in basic cognitive functions affect reading and, possibly, vice versa. The problem can be illustrated using the example of individual variation in working memory. Both Kennison and Clifton (1995) and Osaka and Osaka (2002) selected groups of participants on the basis of their performance in working memory span and found significant differences in several measures of oculomotor reading behaviour. Research like this is needed to better understand both the role of underlying cognitive component processes for reading performance and the role of reading in the composition of individual intellectual abilities.

Intraindividual factors, such as reading intention, motivation, or global strategy are widely assumed to affect comprehension, but little is known in detail of the way reading processes may be modulated, if at all, by such top-down factors (Heller, 1982; Tinker, 1958). This problem obviously has an important methodological dimension. At present, it is widely believed that it does not matter all that much whether a reader is asked to respond to a simple word verification task or answer difficult comprehension questions after finishing a sentence or paragraph. Similarly, the differences in eye movement behaviour, if any, in reading sentences, compared to paragraphs or much longer segments of connected text (such as whole books) remain unquantified and it remains an open question whether text processing within new media environments has any specific impact on the reading process. Factors such as the defined reading task and the format of material are likely to affect reading speed and level of linguistic processing on a scale from ‘‘superficial’’ to ‘‘careful’’ reading. But it is also reasonable to hypothesise that they modulate the visuo-motor and cognitive microprocesses of reading, e.g., in terms of local fixation patterns and word processing times. Radach, Huestegge, and Heller (2001) have data that point in this direction, showing, e.g., that word frequency effects are smaller and initial fixation positions shifted to the right when reading the same material in coherent text compared to single sentences presented in random order. It is particularly important in this context to know the exact nature of any global top-down influence on the inner workings of eye movement control (see O’Regan’s, 1992, hypothetical distinction of ‘‘careful’’ vs. ‘‘risky’’ reading). If such factors turn out to be of importance, they will also need to be incorporated as modulating elements in models of the reading process. Knowing the scale and impact of these varieties of the reading process is at the core of defining the content and purpose of experimental reading research as a whole.

There can be no doubt that work on eye movement control has reached a level of sophistication where applied problems, particularly with respect to individual differences and task demands, can fruitfully be addressed. But the research community has, as yet, taken little advantage of these possibilities. As a single example, it is surprising that the issue of ‘‘speed reading’’ has hardly attracted a single scientific study during the last 15 years that would meet the methodological standards raised above (see Rayner & Pollatsek, 1989, for a discussion of earlier work). Equally, the community of experimental reading researchers is patently underrepresented in the vast literature on developmental dyslexia and other forms of impaired reading. There have been virtually no studies attempting to analyse word-based viewing time measures and local fixation patterns in dyslexic readers (see Hyönä & Olson, 1995, for a significant exception). We believe that the progress documented in this introductory paper, together with the range of contributions in this Special Issue, suggest the time is ripe to bring a new level of theoretical and methodological sophistication to bear on this and a number of other applied questions.

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