Commentary on Section 3

Moving Eyes and Reading Words: How Can a Computational Model Combine the Two?

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Historically, since the boom of reading research in the 1970s, work using eye movement techniques, and work on isolated word reading have formed two quite independent and mutually impermeable sectors of research. This is quite a natural evolution given that it was not at all obvious, at that time at least, that eye movement recordings could provide any information relevant to the study of isolated word recognition. During this period, referred to as the third era of eye movement research by Rayner (1998), research into eye movements in reading best interacted with psycholinguistic research at the level of sentence processing. For example, eye movement recordings were used to examine how the syntactic processor handles ambiguous situations such as those created by reduced relative clauses in English (e.g., "the (famous) horse walked past the barn fell").[1] There are obviously some examples of fruitful interactions across research on visual word recognition and research on eye movements in reading, but these are more the exception than the rule. The point here is that the field has, I believe, suffered from a lack of communication across these sub-disciplines. I will now discuss some of the possible reasons for this lack of communication before going on to discuss the more recent, and very encouraging, interaction that appears to be developing. Several of the chapters in this section nicely illustrate this trend.

The interaction between eye-movement research in reading and research on visual word recognition has probably been hampered by several factors, some of which will be discussed here. First, the vast majority of research on visual word recognition has focused on the processing performed "in a single glance" in relatively short, often monosyllabic words (research on morphological processing is an exception here). Second, while many researchers interested in visual word recognition tended to see eye movements as a cumbersome tool that had yet to prove its utility to the field, some eye movement researchers interested in single word recognition tended to see the use of eye movement technology as a superior, more ecological tool that would

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eventually replace "artificial" laboratory tasks such as lexical decision. Third, some people apparently believed that there was nothing more to learn about visual word recognition and that the interesting questions for reading research were to do with comprehension at the sentence level and beyond.[2] Last but not least, before the early 1980s it was not at all clear that lexical processing had any influence on how the eyes moved through printed text. It is this last point that has generated some debate in the area of eye movement research over the last 20 years, and many of the chapters in this section pick up on this on-going controversy.

In this commentary, I will examine the critical role played by computational modelling in developing a healthy cross-fertilisation of visual word recognition research and research on eye movement control in reading. The different contributions to the present section will serve as a basis for this analysis. In particular, the way the different models solve some critical issues in current reading research will be used to illustrate the importance of computational modelling for this field. Finally, I will briefly address the thorny problem of model comparison and evaluation, before examining possible future directions for research in this field.

Computational Modelling and Functional Overlap

Today, the general field of reading research is experiencing an optimistic move toward a possible reconciliation between the sub-disciplines of visual word recognition and eye-movement control in reading. A number of papers over the last ten years have systematically compared results obtained with eye movement measurements and results obtained from the same experimental manipulation in visual word recognition paradigms (e.g., Folk & Morris, 1995; Grainger, O'Regan, Jacobs & Segui, 1992; Inhoff, Briihl & Schwartz, 1996; Inhoff & Topolski, 1994; Perea & Pollatsek, 1998; Schilling, Rayner & Chumbley, 1998). Schilling *et al.* (1998), for example, manipulated the printed frequency of word targets and measured subjects' performance to these words in the standard word recognition tasks of lexical decision and naming. They compared these data to the results obtained using eye movement recordings from the same subjects reading the same set of words embedded in sentence contexts. The good correlation between eye movement measurements and both lexical decision and naming latencies (better for the latter) led the authors to conclude that "both the naming and lexical decision tasks yield data concerning word recognition processes that are consistent with effects found during silent reading". Although this is admittedly an important empirical observation, caution must be exercised when generating model-free conclusions from such data. When two different tasks produce the same pattern of effects, this does not necessarily imply that the two task are sensitive to a common underlying mechanism that is responsible for generating the effects. Schilling *et al.* report a significant correlation across lexical decision and naming latencies (by subjects and by items) in their experiment, while Carreiras, Perea and Grainger (1987) failed to find a significant correlation across these two tasks. Effects of a given variable (e.g., orthographic neighbourhood density) have often been found to be facilitatory in both naming and lexical decision (e.g., Andrews, 1989), yet very different mechanisms may be responsible for this facilitatory effect in the two tasks (Grainger & Jacobs, 1996). Modelling functional overlap is one remedy for this problem, and its prerequisite is the development of computational models. These have been available to visual word recognition researchers since the early 1980s (McClelland & Rumelhart, 1981; Paap, Newsome, McDonald & Schvaneveldt, 1982), and are now available to the field of eye movement control in reading.

Related to the question of modelling functional overlap, I recently suggested (Grainger, 2000) that one means of providing a better integration of these two areas of research would be to abandon the principle that eye movement recordings somehow provide a privileged, more ecological, instrument for measuring reading performance. Certainly at the level of single words, eye movement measurements could be considered as another experimental paradigm at the same level as the classic paradigms of visual word recognition. The critical point here is that, just like you need an appropriate model of the lexical decision task in order to successfully link lexical decision data to a model of word reading, you also need an appropriate model of eye movement control in reading in order to successfully link eye movement data to the same model of word reading. So, one not only needs a *model of the process* that is being investigated (word reading, for example), but one also needs a *model of the task* that is being used to investigate the process. With respect to investigations of single word reading, models of eye movement control therefore play a similar role as models of other laboratory tasks such as lexical decision and word naming. Finally, in order to maximise the amount of constraint provided by data obtained with a given technique, the model of the task must be as highly specified as possible, and expressed at least with the same degree of precision as the model of the process that the task is being used to investigate. Jacobs and Grainger (1994; see also Grainger & Jacobs, 1996) discussed the notion of functional overlap as an essential ingredient of a multi-task approach to understanding visual word recognition. It is the combination of the following factors that provides the critical constraints for model development: (1) empirical data obtained using different tasks, (2) a computational model of the process that one wants to understand, (3) computational models of the tasks used to investigate the given process, and (4) specification of what is task-specific in each of these task-models.

Many of the chapters in this section are a perfect illustration that this level of theorising has been achieved, and that we have now entered a new exciting era (the fourth era)[3] of research on eye movements in reading, where computational models of eye movement control and computational models of lexical processing can mutually constrain each other. I might immediately add that the benefits are clearly for both communities of researchers, since a model of isolated word recognition could not be considered complete without demonstrating how this model functions in a normal reading situation. A significant first step in this direction was made with the publication of the E-Z Reader model of eye movement control in reading (Reichle, Pollatsek, Fisher & Rayner, 1998; see also Pollatsek, Reichle & Rayner, this volume). The fact that lexical processing plays a central role in eye movement control in the E-Z Reader model shows very clearly how the two subfields can now fruitfully interact. However, the chapters by McConkie and Yang, and Reilly and Radach argue convincingly, I believe, against a strong version of the lexical control hypothesis as implemented in the E-Z Reader model (i.e., that each saccade is triggered by ongoing lexical processing). I will examine the arguments proposed in the different chapters of the present section for and against lexical control, but let me first say that a strong version of this hypothesis is not a necessary condition for fruitful interaction among word recognition and eye movement researchers.

In reading the chapters of the section on computational models of eye movement control in reading, one is impressed by the consensus around what are the critical phenomena to be explained. One of the strengths of the modelling efforts presented in this section is the general agreement as to what constitutes a reasonable data-base at present. The scope of the models is deliberately limited for purposes of tractability, and the to-be-modelled phenomena are, in the great majority, well replicated, unquestionable facts about how the eyes move during reading. This is an excellent starting point for any modelling enterprise, and this situation is only possible today thanks to the many years of effort from dedicated researchers in the field (see Rayner, 1998, for a review). As mentioned above, there appears to be a general consensus as to what are the critical phenomena that require explaining. However, two very central questions are still open to debate, as reflected by the varying positions adopted by the contributors to this section. These concern two of the three issues[4] recently summarised by Starr and Rayner (2001): (1) to what extent do higher-level cognitive (linguistic) processes influence eye movement behaviour? and (2) is word recognition in reading strictly serial (one word at a time)? I will examine the different response to these two questions provided by the chapters in this section, in an attempt to converge on a tentative synthesis.

Cognitive Control of Eye Movements in Reading

The original E-Z Reader model, as well as later versions (Pollatsek *et al.*, this volume), is characterized by the way lexical processing is used as the major component of the complex system that guides the eyes through text. To someone, like myself, interested in visual word recognition, this appears to be a very reasonable proposal. Given that the minimal goal of reading behaviour is to extract meaning from individual words, to be combined to allow interpretation of higher level structures such as phrases and sentences, then it seems reasonable to assume that the process of individual word recognition should influence reading behaviour. As such, the E-Z Reader model endorses a rather extreme form of the linguistic control hypothesis, or what McConkie and Yang refer to as *direct* cognitive control. The E-Z reader model is certainly the first computational model of eye-movement control in reading that makes use of a quite complex processing machinery to determine when a saccade will be generated. More specifically, lexical processing on the currently fixated word is evaluated on-line. When an orthographic representation (and possibly a phonological representation) for a word is sufficiently activated (but not yet identified), then the lexical processor "decides" that the word will be processed correctly and that it is now safe to move the eyes onto the next word. At first sight there appears to be a very interesting parallel between the familiarity check mechanism used in the E-Z Reader model and the mechanism used by several researchers to describe the process of lexical decision (e.g., Balota & Chumbley, 1984; Grainger & Jacobs, 1996). However, although a familiarity check makes perfect sense for an information processing device that has to perform lexical decision (where familiar stimuli have to be distinguished from unfamiliar stimuli), there is, on the contrary, no clear theoretical justification for its use in a model of eye movement control in reading.

Kliegl and Engbert's chapter presents the latest version of the SWIFT model and evaluates this model relative to its competitors using the empirical data of Schilling *et al.* (1998) and parafoveal preview effects obtained using eye-contingent display changes (Binder, Pollatsek & Rayner, 1999). Although there are many similarities between the SWIFT model and E-Z Reader, there are some fundamental differences, one at the level of cognitive control, and the other in terms of serial versus parallel processing. Concerning the issue of cognitive control, Kliegl and Engert abandon the familiarity check mechanism that the E-Z Reader model uses for saccade initiation. Instead, in the SWIFT model saccade initiation occurs autonomously. However, lexical activity can influence this autonomous saccade generation programme by delaying saccade initiation. The lexical activity associated with the currently fixated word modifies the timing interval that is sampled for determining the initiation of the next saccade.

McConkie and Yang's chapter begins with the presentation of some critical data against direct cognitive control theories of eye movement control in reading. Yang and McConkie (2001) demonstrated that strings of random letters and Xs which preserve the word spacing pattern had hardly any effect on the distribution of onset times of most saccades. McConkie and Yang conclude that saccade initiation times depend very little on whether the currently fixated stimulus is a word or random letters. This is not what one would expect if some measure of lexical processing was determining when a saccade will be triggered. The Interaction/Competition (I/C) theory discussed by McConkie and Yang adopts the mechanism described by Findlay and Walker (1999) whereby saccade timing and target selection in eye movement control result from competitive processes between so-called move and fixate centers. This mechanism is adapted to the specific case of reading and provides a system for saccade timing that is not directly influenced by cognitive events. Similarly to the SWIFT model, this saccade timing mechanism can be indirectly influenced by cognitive activity via inhibitory control. The basic idea is that when some processing difficulty is encountered, then a kind of "distress signal" is triggered that results in inhibition in the saccadic system. This processing-based inhibition influences fixation and gaze durations primarily by reducing the number of normal saccades and increasing the number of late saccades. It is interesting to note that a similar proposal had already been made by McConkie (1979) who claimed that the eyes are moved in response to unsuccessful processing of parafoveal words: "Assume that at some point during a fixation, as the attended region is shifted along the line of text visual information is sought from a region too far from central vision to readily supply the visual detail needed for identification . . . Assume that seeking visual detail from a retinal region that is not readily available causes the saccadic system to initiate a saccadic eye movement . . . This is assumed to be the primary basis for saccadic eye movement control in reading" (p. 43). Just as in the I/C theory, the system is hypothesized to respond to the fact that something "does not compute", rather than responding to successful processing as in the E-Z Reader model.[5]

Reilly and Radach present a computational model of eye movement control in reading (Glenmore) that has many points in common with McConkie and Yang's I/C theory. Both of these approaches appear to be heavily influenced by (i) Findlay and Walker's (1999) general theory of saccade generation; and (ii) by the earlier work of the "Groupe Regard" in Paris, and most notably the visual scanning routine proposed by Lévy-Schoen (1981), and O'Regan's (1990) strategy and tactics theory. Findlay and Walker's theory provides a specific mechanism (the saliency map) for implementing a "dumb" oculomotor strategy in a model of eye movement control in reading. However, Reilly and Radach go one very significant step further than their mentors. They describe a specific mechanism for how lexical processing influences oculomotor heuristics.

Coming back to the issue at stake here (cognitive control of eye movements in reading), Reilly and Radach hit the proverbial nail on the head when they say that ". . . the question of interest in not whether eye movements are determined by visuo-motor factors or linguistic processing, but to what degree these two types of factors are involved and how they interact". The relative involvement of these two factors and their interaction can only be appropriately described within the framework of a computational model, as very nicely illustrated by several of the chapters of this section. So the debate around the issue of cognitive control of eye movements (see the chapters of this section, and Deubel, O'Regan & Radach, 2000; Rayner, 1998) could well be abandoned. One does not need to know whether or not linguistic factors are the *main* driving force behind eye movements in reading in order to make progress in this area. Adopting a much more practical stance, one simply needs to specify when and how linguistic factors can intervene and influence the observed pattern of eye movements. This amounts to describing the functional overlap between the system that controls eye movements in reading and the system that recognizes printed words.

Serial vs. Parallel Processing of Words

The second main issue addressed by all the contributions to this section concerns whether or not serial attention shifts precede eye movements during reading, thus dictating a strictly serial processing of words. Reingold and Stampe's chapter is centred on this particular question. These authors present a new phenomenon related to saccadic control in reading, referred to as saccadic inhibition, that is taken as evidence in favour of attentional guidance models. In a generic attentional guidance model (as originally proposed by Morrison, 1984), an attention shift occurs to the next word to be fixated before the saccade to that word is executed. So, when reading normal text, attention skips along from word to word just slightly ahead of the eyes. According to Reingold and Stampe, this predicts that one ought to be able to observe some form of perceptual enhancement in the direction of the next saccade, due to preallocation of attention to that location. By creating screen flicker either to the right (congruent) or to the left (incongruent) side of a currently fixated point, these authors observed a stronger effect of a large flicker manipulation in the congruent condition. They interpret this finding as resulting from a perceptual enhancement of the large flicker due to attentional preallocation in the direction of the next saccade.

The E-Z Reader model described by Pollatsek *et al.* adheres to the basic principles of attentional guidance models. The familiarity check mechanism (based on partial lexical processing) governs saccade generation, and attention is allocated to the newly targeted word once lexical processing is complete. The timing associated with saccade programming allows attention to be shifted to the next word before a saccade is actually executed. However, apart from the E-Z Reader model, all the other models described in this section have abandoned a strictly serial allocation of attention. Each of the relevant chapters summarizes the key results that have led the authors to abandon this hypothesis. Since this is one of the critical differences between SWIFT and the E-Z Reader model, Kliegl and Engbert provide a good summary of the empirical findings. They describe three results that are difficult to handle by a serial attention shift mechanism. These are: (1) parafoveal on foveal influences; (2) influence of information extracted to the left of the fixated word; and (3) variation in fixation durations as a function of whether the next word is skipped or not. For Kliegl and Engbert, although there is still some doubt as to the first two effects, it is the third type of evidence that is critically damaging.[6] According to serial attention shift models, word skipping arises when a saccade to the next word is cancelled and re-programmed to the following word. This necessarily causes an increase in the fixation duration prior to the re-programmed saccade. However, this clear prediction has not been upheld in some empirical analyses, such that the issue remains under debate (McConkie, Kerr & Dyre, 1994; Radach & Heller, 2000; see Kliegl & Engbert, this volume, for a discussion).

These considerations have led Kliegl and Engbert, and Reilly and Radach to abandon the idea of a serial attention shift mechanism in favour of spatially distributed processing around fixation in the form of an attentional or processing gradient. This takes the specific form of a saliency map in the Glenmore model. In this particular approach, there is no deliberate shifting of attention during reading, just a gradient of bottom-up activation spreading right and left of fixation that can be modulated by higher-level factors (Findlay & Walker, 1999). This activation gradient or saliency map provides a mechanism for explaining parafoveal influences on foveal target processing. Its precise instantiation in the Glenmore model raises the very interesting issue of how different words at different retinal locations can be processed at the same time. I will come back to this point.

Which Model is Best?

The apparent success of the computational models described in this section to account for a given target set of data, raises the obvious question as to how one might be able to decide which one does the job best. Jacobs (2000) has already tackled this question and provided some answers for computational modellers of eye movement control in reading. The chapters in the present section provide some admirable applications of basic principles in the development and testing of computational models. As already noted by Jacobs (2000), the E-Z Reader "suite" (continued in the Pollatsek *et al.*

chapter) is a nice illustration of the practice of "nested modelling", where the old version of the model is embedded in the new version, thus preserving the core principles of the original model. One can also applaud the testing strategy applied by Kliegl and Engbert where two models of similar structure (E-Z Reader and SWIFT) are evaluated relative to fits with the same set of data, thus allowing strong scientific inference (Estes, 1975).

However, rather than getting bogged down in the complex intricacies of model comparisons (number of free parameters, comparing free parameters to weight strengths, number of units and layers of algorithmic models, etc., etc.), here I would like to make a more general comment on *modelling style*. There are many different styles of computational modelling in cognitive science, and the present contributions illustrate part of the spectrum. There are some more mathematical-style models (E-Z Reader and SWIFT) using closed-form expressions, and one example of an algorithmic model of the interactive-activation family (Glenmore). In the more general area of reading research, currently dominated by research on single word recognition, the vast majority of models are of three basic kinds: verbal-boxological (pre-quantitative), mathematical, and algorithmic connectionist models (as opposed to algorithmic symbolic models, although Coltheart, Rastle, Perry & Ziegler's, 2001, dual-route model is an example of a hybrid symbolic-connectionist algorithmic model). There are two types of algorithmic connectionist models of the reading process: localist connectionist models (e.g., McClelland & Rumelhart, 1981, for printed word perception), and PDP models with distributed representations (e.g., Seidenberg & McClelland, 1989, for reading aloud printed words).

In the preface to their volume on localist connectionism, Grainger and Jacobs (1998) summarized the advantages of the localist approach as opposed to a more distributed approach (typically involving the use of the backpropagation learning algorithm) under the headings: continuity, transparency, and unification. In terms of continuity, Grainger and Jacobs (1998; see also Page, 2000) have argued that algorithmic models of the localist connectionist variety are the most apt at preserving an understandable link with less formal verbal-boxological theorizing. More specifically, the architecture of the processing system can be quite accurately described in a boxological model (e.g., Grainger & Ferrand, 1994), before being implemented in an algorithmic model (e.g., Jacobs, Rey, Ziegler & Grainger, 1998). The study of eye-movement control in reading has benefited from a good deal of informal, pre-quantitative theorizing (e.g., Morrison's, 1984, attention-guidance model, and O'Regan's, 1990, strategy-tactics theory) that serves as the basic ground matter for developing computational models. This is true for most areas of cognitive science, where the normal course of events is to first sketch a verbal theory, which may or may not be implementable as a mathematical model (depending on the complexity and the precision of the verbal theory), and then develop a computational model on the basis of prior theorizing.

The tight link between localist connectionist models and their verbal-boxological predecessors, allows these models to provide a (more) transparent mapping between model structure and model behaviour. In some PDP models with distributed representations the model is a complex as the phenomena it seeks to explain. This led Forster (1994) to wonder about the utility of such models. He discusses this point using his next-door neighbour analogy: "Suppose I discover that my next-door neighbor can correctly predict the outcome of every word recognition experiment that I do. This would be a surprising discovery, certainly, but it would not have any scientific utility at all until it was discovered how she was able to do it. I could scarcely publish my next-door neighbor as a theory without having explicated the reasoning involved (p. 1295)". It is the "black box" aspect of fully distributed models that hinders explanation.

Grainger and Jacobs (1998) argued that localist connectionist models provide a unifying account of human cognition. Page's (2000) "localist manifesto" is another such appeal for a unified account of human information processing that adopts a localist connectionist stance. Page (2000) documents the long-standing role played by Stephen Grossberg as a key figure in this area of computational modelling. Grossberg's modelling work is characterised by the application of a small set of computational principles (e.g., adaptive filter, lateral inhibition, 2/3 matching rule, masking fields) that are applied to the explanation of a very wide range of human information processing, from low-level vision (e.g., Grossberg, 1999) to higher-level cognitive processes such as word recognition and recall (Grossberg & Stone, 1986). I suspect that progress in the development of computational models of eye movement control during reading will show, once again, the superiority of localist connectionism as a general approach to the study of human cognition. The Glenmore model is a good example of how such an approach facilitates integration across neighbouring fields of research (a theory of eye movement control, and a model of visual word recognition).

Finally, all computational modellers must ask the question: *what has been gained from the modelling enterprise*? The critical gain must be expressed in terms of improved understanding of the phenomena to be explained, in terms of improved understanding of the processes under study, and in terms of the generation of new predictions for further experimentation. Converting a verbal statement to a mathematical equation is generally accepted as an improvement in science (e.g., Estes, 1975), but the gain in understanding can be quite minimal. For example, a mathematical model of visual word recognition that predicts word recognition time as a function of word frequency and the number and frequency of all orthographic neighbours of the target word (using Luce's , 1959, choice rule, for example), would not be doing much more than re-stating the empirical evidence that word frequency and orthographic neighbourhood density and frequency influence visual word recognition (e.g., Luce & Pisoni's (1998) neighbourhood activation model of spoken word recognition). The critical gain only becomes obvious when the computational model proves its utility (1) as an explanatory device and (2) as a heuristic for generating scientific research. The "winning" model is typically one for which a general consensus builds up around these last two points. A single critical test between two models is rarely a deciding factor in this field of research.

Reading Words and Moving Eyes: Future Developments

It appears that the recent development of quantitative models of eye movement control in reading has opened the door for more intense and fruitful interaction with the field of printed word perception. The importance of such an interaction has become more obvious given the dominant role played by lexical processing as a precise implementation of the (direct or indirect) "cognitive control" aspect of these models. After reading the chapters in this section, it seems that one key question that has guided recent research in this field, and should continue to guide future research, could be formulated as follows: Given initial oculomotor and linguistic constraints, how would an information processing device proceed in order to extract visual information from text with the aim to translate it into meaning? Some tentative answers to this question have been formulated in the different chapters of this section, in the form of explicit descriptions of the information processing that is performed (i.e., as computational models). However, this general question or research goal can be usefully broken up into smaller questions that could serve to guide future research. These "sub-goals" reflect the fact that, although some very simple oculomotor strategies appear very capable of providing a good first response to the general question, several of the chapters in this section argue that the timing and targeting of eye-movements also depends to some extent on lexical processing. It is therefore important to be able to specify (1) how oculomotor and perceptual constraints affect eye movement control in a "reading-like" situation; (2) how linguistic constraints affect visual word recognition in the absence of eye movements; and (3) how these two situations can combine to generate the phenomena observed in eye movement investigations of reading. For each of these points we need to specify the critical empirical observations, and define the potentially viable explanations in terms of computationally explicit mechanisms.

Thus, concerning the first point, we need to specify the basic phenomena associated with eye movements in a reading-like situation but in the absence of linguistic input (e.g., Vitu, O'Regan, Inhoff & Topolski, 1995; Yang & McConkie, 2001). Here the goal is to determine the basic oculomotor constraints that govern eye movements before any lexical influences have operated. This will enable us to define the functional overlap between a general model of eye movement control (e.g., Findlay & Walker, 1999) and a model of eye movement control in reading. Pursuing the development of "non-linguistic" models of eye movement control in reading will help define the limits of such an approach, and therefore facilitate the integration phase described in point three.

Concerning the second point, we need to specify the basic phenomena associated with visual word recognition that a model of reading should attempt to capture. Here, the goal is to describe the constraints on lexical processing that apply independently of whether or not eye movements are required to enable this processing. Jacobs and Grainger (1994) proposed a list of basic phenomena observed with standard visual word recognition tasks. The list included the word frequency effect, the word superiority effect, the regularity/consistency effect, and the effects of orthographic neighbourhood, which appeared a reasonable list at that time for evaluating different models of visual word recognition. The field has evolved since then, and researchers working with isolated word recognition techniques still need to establish a solid set of replicable phenomena that reflect the core mechanisms of printed word perception. For example, phenomena observed in the word naming task but not in other word recognition tasks (e.g., the regularity/consistency effect) are likely to reflect the operation of mechanisms involved in generating an articulatory output, and are probably not very good candidates for providing constraints on models of silent reading.[7] Once again, applying the principle of modelling functional overlap is critical here. For a given effect observed in a given task it is vital to know whether the machinery generating the effect will overlap with the lexical processes implicated in eye movement control during reading.

This leads us to the final integration phase, point three. Here we raise the question that most of the contributions to the section on computational modelling have attempted to address. Namely, how oculomotor constraints combine with lexical constraints to produce the patterns of eye movements that are recorded in empirical investigations of eye movement control in reading. However, all the models described in this section take the performance of skilled adult readers as the target to be explained by the different models. Developmental investigations of eye movement control in reading will become increasingly important for the field. Observations of how the oculomotor system learns to adapt to different types of linguistic stimuli (isolated words, sentences, texts) in the process of learning to read will provide significant additional constraints on computational models of eye movement control in reading. Localist connectionist learning models, such as adaptive resonance theory (Grossberg, 1980) may prove useful in establishing the link between algorithmic models of adult performance and an account of how oculomotor and attentional control develop during the process of learning to read.

Finally, research on printed word perception now needs to make the complementary step in the other direction, reflecting on how issues of eye-movement control can affect the way we think about basic issues in visual word recognition. This step has already been partly made in research considering how initial fixation location can affect the way we process printed words (O'Regan & Jacobs, 1992; Nazir, Heller & Sussmann, 1992; Clark & O'Regan, 1998; Stevens & Grainger, 2003).The concept of spatially distributed processing and the saliency map described by Reilly and Radach automatically spark the debate as to how parallel processing of words can operate. Clearly, if two words that receive input from different spatial locations can compete within a single lateral-inhibitory word identification network, then we are led to make some very clear predictions relative to paradigms involving simultaneous presentation of two or more printed words. This opens up a whole new area of investigation, even for those researchers who remain stubbornly attached to word perception in a single glance.

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Notes

1 See, for example, the number of cited works in this area on page 390 of Rayner (1998).
2 I distinctly remember Don Mitchell saying to me, over ten years ago, that "visual word recognition had been solved". This happened at one of those excellent workshops organized on

several occasions by Alan Kennedy and Joel Pynte, that allowed researchers like myself not using eye movement recordings, to be confronted with the results obtained with this technique.

3 The 4th era can be seen as the next step in the evolution described by Rayner (1978, 1998), and its initiation can be situated at the end of the 20th century and associated with a number of critical events such as Rayner's (1998) review, the Reichle *et al.* (1998) paper, and the conference held at Luminy, Marseille, France in November 1998 (Kennedy, Radach, Heller & Pynte, 2000).

4 The other issue discussed by Starr and Rayner (2001) concerned the amount of information that can be extracted from the right of fixation in reading.

5 I thank Ralph Radach for pointing out the early contribution of McConkie (1979).

6 Jacobs (2000) defined the notion of a "strongest falsificator" for a given model and urged cognitive modelers to define such a situation for their models. The word skipping data would appear to be a good candidate as a strongest fafsificator for the E-Z Reader model.

7 Reading aloud is, of course, an interesting activity to study in its own right.

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