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Models of the Reading Process

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Abstract

Reading is a complex skill involving the orchestration of a number of components. Researchers often talk about a "model of reading" when talking about only one aspect of the reading process (for example, models of word identification are often referred to as "models of reading"). Here, we review prominent models that are designed to account for (1) word identification, (2) syntactic parsing, (3) discourse representations, and (4) how certain aspects of language processing (e.g., word identification), in conjunction with other constraints (e g., limited visual acuity, saccadic error, etc.), guide readers' eyes. Unfortunately, it is the case that these various models addressing specific aspects of the reading process seldom make contact with models dealing with other aspects of reading. Thus, for example, the models of word identification seldom make contact with models of eye movement control, and vice versa. While this may be unfortunate in some ways, it is quite understandable in other ways because reading itself is a very complex process. We discuss prototypical models of aspects of the reading process in the order mentioned above. We do not review all possible models, but rather focus on those we view as being representative and most highly recognized.

Reading is a complex skill that is a prerequisite to success in our society where a great deal of information is communicated in written form. Reading is also a process that has attracted the attention of many cognitive scientists because many fundamental cognitive processes are involved in reading. As Huey (1908) noted in a now classic quote: "And so to completely analyze what we do when we read would almost be the acme of a psychologist's achievements, for it would be to describe very many of the most intricate workings of the human mind, as well as to unravel the tangled story of the most remarkable specific performance that civilization has learned in all of its history".

In a chapter on reading in the *Foundations of Cognitive Science* (Posner, 1989), Pollatsek and Rayner (1989) identified ten central questions regarding reading of central interest to cognitive scientists. Those questions were:

1. How are written words identified?
2. How does the system of oral language interact with word identification and reading?
3. Are words identified in text differently than in isolation?

Cross-References
COGSCI 067 - Computational models of the lexicon
COGSCI 071 - Eye-tracking and language processing
COGSCI 093 - Models of processing: Lexicon
COGSCI 094 - Models of processing: Discourse
COGSCI 201 - Discourse processing

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4. In reading, the eyes move across the page. How does this process shape the answers to the above questions?
5. How does the reader go beyond the meaning of individual words? (For example, how are sentences parsed, the literal meaning of a sentence constructed, anaphoric links established, inferences made, and so on?)
6. What is the end product of reading? (That is, what new mental structures are formed or retained as a result of reading?)
7. How does the skill of reading develop?
8. How can we characterize individual differences among readers in the same culture and differences in readers across cultures?
9. How can we characterize and remediate reading disabilities?
10. Can we improve on "normal reading" (e g., is "speed reading" possible)?

These ten questions remain highly relevant 20 years later, and indeed, they are the focus of textbooks on the psychology of reading (Rayner & Pollatsek, 1989; Rayner, Pollatsek, Ashby, & Clifton, 2010). And, while the questions remain highly relevant and are the focus of a considerable amount of current empirical research, our goal here is to focus on another aspect of reading that is central to cognitive science. Specifically, we will focus on the development of various models (often computationally implemented) that describe some component of the reading process. It is quite instructive that there is not yet a complete model that accounts for all of the different components of reading[1]. Rather, what has developed over the past 20–30 years is the emergence of models designed to account for some specific aspect of the reading process. Thus, as we shall review below, there are models that account for (1) word identification, (2) syntactic parsing, (3) discourse representations, and (4) how certain aspects of language processing (e.g., word identification), in conjunction with other constraints (e.g., limited visual acuity, saccadic error, etc.), guide readers' eyes. Unfortunately, it is the case that these various models addressing specific aspects of the reading process seldom make contact with models dealing with other aspects of reading. Thus, for example, the models of word identification seldom make contact with models of eye movement control, and vice versa (though the latter type of models perhaps make more contact with the former type of model than the reverse; e.g., see Reilly & Radach, 2006). While this may be unfortunate in some ways, it is quite understandable in other ways because, as we have suggested, reading itself is a very complex process.

We will discuss prototypical models of aspects of the reading process in the order mentioned above. Our goal will not be to review all possible models, but rather focus on those we view as being representative and most highly recognized (with all due apologies to architects of models we do not focus on). (For a more complete review of existing models of reading and an attempt to integrate them into a single framework that describes what occurs during reading, see Reichle, 2010a). It is generally the case that, for many of these models, there are two central examples that make very different theoretical assumptions and that have been the impetus for considerable empirical work. Our goal will be to make clear the nature of these assumptions and how the models differ, and how these differences have helped inform our understanding of what happens in the minds of readers.

[1]Just and Carpenter (1980) portrayed their model as a comprehensive theory of reading from initial eye fixations to comprehension and Rayner and Pollatsek (1989) presented the outlines of a more complete model of reading. However, both attempts were rather preliminary.

Models of Word Identification

Numerous models of word identification have been proposed during the last 30 years, including the *Interactive-Activation* (McClelland & Rumelhart, 1981), *Activation-Verification* (Paap, Newsome, McDonald, & Schvaneveldt, 1982), *Multiple-Levels* (Norris, 1994), *Multiple Read-Out* (Grainger & Jacobs, 1996), *Multiple-Trace Memory* (Ans, Carbonnel, & Valdois, 1998), *Connectionist Dual-Process* (Zorzi, Houghton, & Butterworth, 1998), and *Bayesian Reader* (Norris, 2006) models. However, the two models that have received the most attention and motivated the most research are the *Dual Route Cascaded* (*DRC*) model (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001) and various parallel distributed processing or connectionist versions of what have become known as *triangle* models (Harm & Seidenberg, 1999, 2004; Plaut, McClelland, Seidenberg, & Patterson, 1996; Seidenberg & McClelland, 1989). Although these models are often referred to by their designers (as well as others in the field) as "models of reading," they are really models of reading aloud or what happens during the identification of single words displayed in isolation and thus are not models of reading per se. Like most of the models that will be discussed, they are fully implemented as computer programs that can be used to simulate tasks that have been used to study word identification (e.g., lexical decision) and a variety of phenomena (e.g., word-frequency effects) that have been used to make inferences about the cognitive processes and representations that are involved in identifying printed words (Taft, 1991). These models also share the basic assumption that bottom-up information, in the form of orthographic input, interacts with lexical knowledge to produce word pronunciations and/or meanings.

Here, we will focus on the DRC and triangle models, providing brief descriptions of the models and how they differ. We will focus on these two models because they provide contrasting frameworks for explaining the two most prominent theoretical perspectives in the on-going debate about how words are identified and represented in the mental lexicon. This debate has specifically focused on whether word identification is guided by linguistic "rules" that are used to access a word's pronunciation and/or meaning from its orthography, or whether this process is more accurately described as being one in which different types of lexical information provide mutual "soft" constraints on the pronunciations and/or meanings that are generated during word identification. The DRC model is more consistent with the former view, whereas the triangle models are more consistent with the latter view.

There are two fundamental assumptions in the DRC model (Coltheart et al., 2001). The first is that a word's pronunciation can be generated in two ways through the application of grapheme-to-phoneme correspondence "rules" that convert the individual graphemes (e.g., letters) of a word into their corresponding phonological representations (i.e., phonemes), and through a more direct mapping of a word's spelling onto its pronunciation. The model thus belongs to a class of dual-route models (Carr & Pollatsek, 1985) in that a word's pronunciation can either be generated using specific linguistic rules that specify how individual graphemes are pronounced to assemble the pronunciation, or in a more direct manner by retrieving the whole word's pronunciation directly from the lexicon. The second fundamental assumption of the DRC model pertains to the nature of lexical representations: According to the model, both the orthographic and phonological forms of words are represented holistically, as discrete processing units in the lexicon, so that known words can be pronounced by mapping a word's graphemes onto the orthographic unit that provides the best matches, and then using the orthographic unit to directly activate a phonological unit corresponding to that word's pronunciation. In contrast to other dual-route models, however, the assembled and direct routes operate in parallel in the DRC model, with the pronunciation of any given word in most cases being jointly determined by the products of both routes. Because activation propagates more efficiently among the representational units of frequently encountered words, frequent words are pronounced more rapidly and accurately than infrequent words. And because the assembled and direct routes operate in parallel, words with regular pronunciations are pronounced more rapidly and accurately than irregular words because the two routes cooperate to provide robust pronunciations of regular words, but not irregular words.

As already mentioned, the two fundamental assumptions of the various triangle models (Harm & Seidenberg, 1999, 2004; Plaut et al., 1996; Seidenberg & McClelland, 1989) are completely the opposite of those of the DRC model. First, according to the triangle models, a word's pronunciation is generated via propagating activation from processing units representing orthographic input along connections to other units representing phonological output. Thus, in stark contrast to the DRC model, the knowledge that allows a reader to identify printed words is contained in a single set of input-to-output connections, in a manner that allows the sum total of all of the knowledge to influence the pronunciation of each and every word that is generated. Second, lexical information is represented in a distributed manner in the triangle models, with the dominant variants positing that orthographic input and phonological output are not represented by particular units per se but instead by specific patterns of distributed activity across the units. Thus, in stark contrast to the DRC model, the triangle models do not assume that lexical information is represented by discrete processing units in the lexicon, but instead assume that such information is contained in the connections that mediate between the orthographic input and phonological output. And because the strengths of these connections are learned through repeated experience with words, the triangle models predict that frequent words are pronounced more rapidly and accurately than infrequent words. Similarly, because the connections that mediate the pronunciation of regular words are more consistent with each other than those that mediate the pronunciation of irregular words, regular words are pronounced more rapidly and accurately than irregular words.

As already mentioned, both the DRC and triangle models (as well as several of the models that we have not discussed) make predictions about response latencies, error rates, and the types of errors that are observed in tasks like naming and lexical decision. The models also explain a large number of important "benchmark" phenomena that have been reported in experiments that have used these tasks, such as the finding that frequent words are identified more rapidly than infrequent words (Forster & Chambers, 1973), and that this frequency effect is typically larger for words with irregular pronunciations (e.g., words like *pint*, *colonel*, and *yacht*) than those with regular pronunciations (Seidenberg, Waters, Barnes, & Tanenhaus, 1984). Finally, the models provide accounts of the patterns of behavioral deficits that are typically observed with different types of acquired dyslexia. For example, the DRC model posits that *phonological dyslexia*, which can be characterized by difficulty pronouncing novel (i.e., unknown) words and non-words (i.e., pronounceable letter strings like *burk*) but not known words (Coltheart, 1996), stems from selective damage to the assembled route, which prevents the use of grapheme-phoneme correspondence rules to generate the correct pronunciation for letter strings that are not already represented in the lexicon. The DRC model also posits that *surface dyslexia*, which can be characterized by difficulty pronouncing irregular words but not regular words (Patterson, Marshall, & Coltheart, 1985), results from selective damage to the direct route, so that items can only be pronounced via the use of grapheme-to-phoneme correspondence rules. The triangle models offer a somewhat different account of phonological dyslexia: It reflects damage to some fraction of the orthography-to-phonology connections, so that only words that have already been learned can be pronounced, with little capacity to generalize across words to pronounce new words or non-words. The triangle models also offer an alternative account of surface dyslexia: It happens when the orthography-to-phonology connections become overly specialized for pronouncing consistent words because the pronunciation of inconsistent words is too reliant upon the semantic system, which is selectively damaged. Thus, while both the DRC and triangle models are able to explain the patterns of behavioral deficits that are observed with both types of dyslexia, the two models do so in very different ways. Given this, along with the fact that both models explain a variety of other findings from the word identification literature, it is perhaps not too surprising that the debate about which model provides a more accurate and useful description of what happens in the mind of a reader when s/he identifies printed words is still an on-going one (e.g., see Andrews, 2007). We suspect that future efforts to understand the cognitive processes and representations involved in identifying words during reading might benefit from a more careful consideration of how lexical processing both constrains and is constrained by the other components of reading. We shall now turn to one of these other components that of integrating the meanings of individual words to construct the meanings of whole sentences.

Models of Syntactic Parsing

As with the word-identification models, there are many existing models of sentence-level processing that explain how the linguistic structures and constraints (e.g., syntax) guide the construction of the representations that are necessary understand individual sentences. Thus, these models presumably take as bottom-up input the meanings of individual words that are provided by the types of word-identification models that were reviewed in the previous section. These models can be classified into three broad categories to include the various *garden-path* models (Ferreira & Clifton, 1986; Frazier, 1977, 1987, 1990; Frazier & Clifton, 1996; Frazier & Fodor, 1978; Frazier & Rayner, 1982; Rayner, Carlson, & Frazier, 1983), *constraint-based* models (Jurafsky, 1996; MacDonald, Pearlmutter, & Seidenberg, 1994; McRae, Spivey-Knowlton, & Tanenhaus, 1998; Spivey & Tanenhaus, 1998; Tanenhaus & Trueswell, 1995), and various models that have been implemented using connectionist frameworks (Elman, 1991; McClelland, St. John, & Taraban, 1989; Tabor, Juliano, & Tanenhaus, 1997). Because the first two of these groups of models have received the most attention, and because the main assumptions of the various connectionist models are largely congruent with those of the constraint-based models, we will limit our discussion to the garden-path and constraint-based models below. The major theoretical distinction between these two classes of models concerns the amount of priority given to syntactic processing during reading.

The garden-path models (Ferreira & Clifton, 1986; Frazier, 1977, 1987, 1990; Frazier & Clifton, 1996; Frazier & Rayner, 1982; Rayner et al., 1983) give logical priority to the grammatical structure of a sentence. These models posit that the reader initially constructs a single grammatical analysis of the sentence and then interprets it, revising the analysis if necessary. While constructing a single analysis is not an obligatory part of the model that gives grammar logical priority in sentence comprehension (Gibson, 1991, 1998), serial "depth first" models (Frazier, 1995) assume that a single analysis is chosen and that the initial analysis is simply the first one that is completed (see Frazier, 1987; Frazier & Clifton, 1996). While technically, none of these models have actually been implemented within a formal computational framework, the types of linguistic analyses that are described are amenable to being implemented within a production system (Newell, 1990) in which *productions* (i.e., "if ⟨X⟩ - then ⟨Y⟩" rules) specify the cognitive operations that guide syntactic analysis (e.g., if ⟨word = noun⟩ - then⟨structure = noun phrase⟩). One recent demonstration of how such a syntactic parser might be implemented is provided by Lewis and Vasishth (2005) who used the *ACT-R* production system architecture (Anderson & Lebiere, 1998) to simulate the syntactic operations involved in sentence processing.

The major contrasting approach, the constraint-based models (Jurafsky, 1996; MacDonald, Pearlmutter, & Seidenberg, 1994; McRae, Spivey-Knowlton, & Tanenhaus, 1998; Spivey &

Tanenhaus, 1998; Tanenhaus & Trueswell, 1995), posit that grammatical structure is just one of multiple interacting constraints on sentence interpretation. In such constraint-based models, grammatical structure may carry considerable weight in determining the interpretation of a sentence, but it does not take precedence over factors such as plausibility or contextual constraint (or appropriateness). For example, using the *competition-integration* framework developed by Spivey-Knowlton (1996), McRae et al. (1998) simulated the patterns of self-paced reading times on reduced relative clause sentences (e.g., "The crook/cop arrested by the detective was guilty of taking bribes.") in which the thematic role of the initial noun phrase (i.e., *crook* vs. *cop*) had semantic features that were more consistent with the patient versus agent roles (respectively). The constraint-based model used a variety of different types of information, such as the goodness of the thematic role of the initial noun phrase, the bias to interpret the initial phrase as a main clause versus reduced relative, etc., to predict the qualitative patterns of reading times over various regions of interest (e.g., *arrested by*, *the detective*, etc.). To make these predictions, the different types of information propagated activation along connections to support each of the two possible sentence interpretations, so that, after a number of processing cycles, the model eventually settled into a state that was consistent with one of the two interpretations (i.e., one that is most consistent with all of the different types of information).

Both classes of models attempt to explain the patterns of reading times that are observed in self-paced reading and eye-movement experiments when readers encounter sentences containing syntactic structures of varied complexity. The classic example involves sentences containing structural ambiguities (e.g., "The horse raced paced the barn fell.") that are often interpreted incorrectly during the first pass through the sentence. The goal is to explain why such misanalysis occurs, and the process whereby such misanalyses are repaired so that the readers can construct the correct interpretation of the sentence.

Perhaps because of their conceptual transparency, the serial, depth-first models stimulated a lot of early research, including many experiments that yielded relatively strong support to the hypothesis that a single analysis of a sentence is generally computed (Ferreira & Clifton, 1986; Frazier & Rayner, 1982; Rayner et al., 1983; Rayner & Frazier, 1987). However, much subsequent research was designed to show that non-grammatical factors could affect the difficulty of comprehending sentences, even obscuring or eliminating the apparent contribution of grammatical factors (see Clifton & Duffy, 2001; and Rayner & Clifton, 2002, for reviews). As Clifton, Traxler, Mohamed, Williams, Morris, and Rayner (2003) pointed out, it appears that many cognitive scientists (especially cognitive psychologists) judge that constraint-based models have carried the day. Several factors apparently contribute to this judgment. First, constraint-based models have been implemented, often in connectionist models (McRae et al., 1998; Spivey & Tanenhaus, 1998), whereas the garden path model has not[2]. Second, cognitive psychologists have been extremely cautious about basing cognitive processes on grammatical rules, which appear to change frequently with seemingly arbitrary theoretical changes in linguistics. Third, some results provide fairly dramatic evidence that factors of meaning and plausibility can completely override the grammatical factors that take precedence in a depth-first model of sentence parsing.

One of the most convincing and often-cited example of meaning and plausibility information overriding grammatical factors is provided by Trueswell, Tanenhaus, and Garnsey (1994) which followed up on the classic Ferreira and Clifton (1986) study. They claimed to show that readers make use of semantic information to avoid being garden-pathed. More recently, Clifton et al. (2003) utilized the stimuli from Trueswell et al. and

[2]It is interesting to note that Binder, Duffy, and Rayner (2001) implemented a constraint-satisfaction model that didn't fit with the data they obtained.

presented evidence which they took to be more consistent with serial, depth-first models of parsing. At the moment, both types of models have empirical support, but there are also studies that are difficult to reconcile with either view.

Although the garden path and constraint satisfaction models have provided a great deal of impetus for research on sentence parsing over the past 25 years, more recently other proposals have emerged[3]. One that was already mentioned is the model of Lewis and Vasishth (2005). This model attempts to embed a computational model of syntactic parsing in the more general framework of an existing cognitive architecture (ACT-R; Anderson & Lebiere, 1998). While it is probably too early to evaluate the utility of this approach, we suspect that, by considering how the different components of reading relate to the both the cognitive architecture and the many other task demands of reading, one might stand to make rapid progress in discovering the limitations of existing models, as well as identify areas of residual ignorance. We shall return to these ideas in the final section of this article.

Finally, despite the progress in modeling sentence processing, all of the models that have been developed to date suffer from the same limitations they generate predictions about reading times by converting some arbitrary measure of processing difficulty (e.g., number of processing cycles needed for a network to settle into one sentence interpretation; McRae et al., 1998) for arbitrary regions of text (e.g., multiple-word regions of sentences). Thus, in contrast to several of the models that will be discussed later (in the section on models of eye-movement control), the sentence-processing models fail to make direct predictions about the time required to process meaningful units (e.g., morphemes, words, phrase structures) in real units of time. As we suggested earlier, we suspect that these limitations might be addressed by considering how sentence processing might be related to the other components of reading. We shall now turn to one of these components discourse processing, or the process of connecting the meanings of two or more sentences to generate the overall meaning of the text.

Models of Discourse Processing

In contrast to the models discussed in the previous sections, the models that been proposed to explain discourse processing are more difficult to categorize into groups that define opposing positions on some central theoretical question[4]. The models instead tend to describe certain aspects of the processes and representations that are necessary to connect the meanings of individual sentences into more global representations that support text comprehension. As such, they could be viewed as being like the proverbial “blind men feeling the elephant”, with each model describing some aspect of discourse processing but none of the models doing so in a manner that is complete. What these models have in common, however, is that they build upon the representations that are presumably provided by the types of word-identification and sentence-processing models that were reviewed in the previous sections, using these word- and sentence-level representations as bottom-up input to build even larger discourse representations. Examples of these discourse-processing models include the *Construction-Integration* (Kintsh & van Dijk, 1978), *Situation-Space* (Golden & Rumelhart, 1993), *Landscape* (Van den Broek, Risden, Fletcher, & Thurow, 1996), *Resonance* (Myers & O’Brien, 1998), and *Distributed Situation Space* (Frank,

[3]In addition to the Lewis and Vasishth (2005) model, these models include surprisal (Hale, 2001; Levy, 2008), the race model (von Gompel, Pickering, & Traxler, 2001) and Dependency Locality Theory (Gibson, 1998). Some of these newer models have been tied more directly to and tested by eye movement data (Boston, Hale, Patil, Kliegl, & Vasishth, 2008; Demberg & Keller, 2008), and thus begin to build bridges between models of parsing and models of eye movement control (see also Reichle et al., 2009).

[4]One important dimension that we will not discuss on which theoretical views of discourse processing have differed relates to the extent to which readers are minimalists (McKoon & Ratcliff, 1992; Myers & O’Brien, 1998) and only generate inferences when necessary, or constructionists (Graesser, Singer, & Trabaso, 1994) who are constantly generating hypotheses and making inferences.

Koppen, Noordman, & Vonk, 2003) models, along with several connectionist and production system models of discourse processing (e.g., Goldman & Varma, 1995;Langston, Trabasso, & Magliano, 1999;St. John, 1992). In this section, we shall focus on only one of these models to illustrate a few important facets of discourse processing that must be explained by any complete model of reading. This model of discourse processing is the *Construction-Integration* (*CI*) model that was originally developed by Kintsch and van Dijk (1978) and subsequently modified across subsequent incarnations (e.g., see Kintsch, 1988,1998;Schmalhofer, McDaniel, & Keefe, 2002).

The CI model assumes that the reader generates a propositional or meaning-based representation of the text across two successive stages of processing. During the first, *construction* stage, the meanings of the individual words are used in conjunction with syntactic operations to generate a *text-base*, or literal interpretation of the text. Information contained in the text-base also triggers the retrieval of additional, related information from schemata in long-term memory. Together, this information forms a loose associative network of *propositions* (i.e., elementary units of meaning consisting of a predicate and one or more arguments; e.g., fell⟨actress⟩) that represents the meaning of the text and any inferences that might be drawn from the text. This construction stage is done on one phrase or sentence at a time, with the total number of propositions that can be actively maintained at any given time being limited by the capacity of working memory, and with the strengths of the associations that are formed between any given pair of propositions being a function of how long the propositions were actively maintained together. Finally, during a subsequent *integration* stage, the activation that supports the propositions is reiteratively “normalized” across processing cycles so that the associations among important propositions (i.e., propositions that are associated to many others and thus central to the meaning of the text) are strengthened while the associations among less important propositions are weakened. This integration stage allows textual inconsistencies and/or information that is less important to the central meaning of the text to be minimized or eliminated.

The CI model as described accurately predicts that types of information that readers will recall upon reading a passage of text, including the types of summaries that people provide of the text, which propositions are more important and hence more likely to be remembered, how this recall changes with the passage of time and forgetting, and the types of information that readers are likely to introduce in attempting to make sense of the text. The latter finding has to do with the types of inferences that people seem to make during reading.

The CI model explains two important types of inferences (Schmalhofer et al., 2002). The first are *forward* or *predictive* inferences, which allow the reader to anticipate events or outcomes that have not been explicitly stated in a text. Using an example taken from Schmalhofer et al., upon reading the sentence ”The director and the cameraman were preparing to shoot close-ups of the actress on the edge of the roof of the fourteenth story building when suddenly the actress fell.”, one might infer that the actress died. The second type of inference allows the reader the maintain coherence between events in a text and are called *backward* or *bridging* inferences. After reading the previous example sentence, one might make the bridging inference that the actress died after reading the sentence ”Her orphaned daughters sued the director and the studio for negligence.” The simulations of Schmalhofer et al. demonstrated that the CI model provides a natural account of both types of inferences because the normal process of generating textually related information from schemata during the construction stage of the model is sufficiently liberal to produce the types of associations among propositions that are necessary to make both forward and backwards inferences. In their simulations, Schmalhofer et al. showed that the CI model is capable of simulating the priming effects that were observed when Keefe and McDaniel (1993) had participants read short passages of text containing the sentences like the preceding examples and then tested their participants with probe words like *dead*; the model predicted the priming effects that were indicative of the two types of inferences in the experiment, as well whether or not the priming would be observed when the key phrase ("… the actress fell.") was followed by additional text material. Such demonstrations, along with many others (e.g., see Kintsch, 1998), demonstrate the generality of the CI model and its capacity to account for a variety of discourse processing phenomena.

Finally, it is worth emphasizing that, like the CI model, the other models of discourse processing attempt to describe how information in the text is used to construct representations using the literal meaning of the text and information that is already in memory (i.e., facts contained in schemata) for the purpose of understanding and remembering the text. As such, the models are designed to make explicit predictions about reading comprehension (e.g., whether or not readers notice textual inconsistencies), the kinds of inferences that people make when reading text, and the amount and type of information that is subsequently remembered. The models are limited in that they generally say nothing about on-line reading, making few predictions about the time course of reading. Such predictions are important for the final models that we will discuss models that specify how the various components of reading (e.g., word identification) in conjunction with general perceptual, cognitive, and motor constraints determine the moment-to-moment movement of readers' eyes through the text. These models are most often described as being models of eye movement control in reading, and as such they specify how top-down constraints (e.g., lexical representations) interact with the bottom-up extraction of visual information (e.g., information about printed word length) to produce the patterns of eye movements that are observed when people read text.

Models of Eye Movement Control in Reading

There are now a large number of models of eye movement control in reading. The development of such models was motivated by the appearance of the *E-Z Reader* model (Reichle, Pollatsek, Fisher, & Rayner, 1998). Although there were prior verbal (Morrison, 1984; O'Regan, 1990, 1992; Rayner & Pollatsek, 1989) and implemented models (e.g., Just & Carpenter, 1980; Reilly, 1993; Reilly & O'Regan, 1998; Suppes, 1990; for a review, see Reichle, Rayner, & Pollatsek, 2003) that attempted to document aspects of eye movements in reading, E-Z Reader clearly stimulated the development of a number of competing models, of which *SWIFT* (Engbert, Nuthmann, Richter, & Kliegl, 2005) is generally regarded as the main competitor. Other models include *Mr. Chips* (Legge, Klitz, & Tan, 1997)[5], *EMMA* (Salvucci, 2001), *SERIF* (McDonald, Carpenter, & Shillcock, 2005), *Glenmore* (Reilly & Radach, 2006), *SHARE* (Feng, 2006), and the *Competition-Interaction* model (Yang, 2006). These models are all fully implemented, but they differ on a number of dimensions. For example, whereas Mr. Chips is an ideal observer type of model in that it attempts to simulate optimal performance given an initial set of psychological, physiological, and task constraints, whereas each of the other models attempt to explain the actual performance of human readers. Other important dimensions include the determinants of when the eyes move from one word to the next, and the nature of attention allocation. For example, in E-Z Reader and EMMA, the completion of lexical processing mainly determines when the eyes move forward, whereas most of the other models posit that an autonomous timer largely determines when the eyes move unless saccadic programming is inhibited by cognitive processing difficulty. Similarly, models like E-Z Reader and EMMA posit that attention is allocated serially, to only one word at a time, so that lexical processing of word n+1 does not begin until the meaning of word n has been accessed. In contrast to

[5]Technically, Mr. Chips appeared before E-Z Reader, but it is the case that the latter model has attracted more attention than the former (perhaps in part because Mr. Chips is an ideal observer model).

this, models like SWIFT and Glenmore posit that attention is allocated in parallel (so that several words can be identified in parallel) and models like SERIF, SHARE, and the Competition-Inhibition model posit that attention plays little or no role in guiding readers' eye movements. Due to space limitations, only the E-Z Reader and SWIFT models will be discussed here (for an overview of these models, see the 2006 special issue of *Cognitive Systems Research*).

In actuality, the E-Z Reader model is a family of models with the initial versions discussed in Reichle et al. (1998) and subsequent versions presented by Reichle et al. (2003), Rayner, Ashby, Reichle, and Pollatsek (2004), and Pollatsek, Reichle, and Rayner (2006). In all of these versions of the model, an early stage of lexical processing is the engine that drives eye movements during reading. This early stage of lexical processing is called the *familiarity check* and it is posited to correspond to the point during word identification when it is ”safe” to begin programming a saccade to the next word (i.e., initiating programming any sooner or later would cause the eyes to move too soon or too late and thereby make reading less efficient; Reichle & Laurent, 2006). The subsequent stage of lexical processing, called the *completion of lexical access,* is then the signal to shift attention to the next word. The initiation of saccadic programming is thus decoupled from the shifting of attention, with the latter being done (as already mentioned) in a strictly serial manner (Reichle, 2010b). The remaining model assumptions are directly related to saccadic programming. The first is that saccadic programming is completed in two stages: a initial labile stage that is subject to cancelation by the initiation of subsequent saccadic programs, followed by a non-labile stage that if reached results in an obligatory saccade. The second assumption is that saccades are always directed towards the centers of words, but due to systematic and random motor error often undershoot or overshoot their intended targets, resulting in Gaussian-shaped fixation landing-site distributions. The final assumption is that cases involving large saccadic error often result (in a probabilistic manner) in an ”automatic” refixation saccade; these corrective saccades rapidly move the eyes to a better viewing location (i.e., closer to the center of the target word) to support more rapid lexical processing. Finally, the most recent version of the model (*E-Z Reader 10*; Reichle, Warren, & O'Connell, 2009) has been extended to account for higher-order (i.e., post-lexical) influences of language processing on eye movements during reading. This model has been used to simulate a variety of ”benchmark” findings that have been reported in eye movement experiments (Rayner, 1998, 2009), including the effects of low-level oculomotor constraints (e.g., landing-site distributions; McConkie, Kerr, Reddix, & Zola, 1988), the effects of lexical variables (e.g., word frequency effects; Inhoff & Rayner, 1986; Rayner & Duffy, 1986; Schilling, Rayner, & Chumbley, 1998), and the effects of higher-level linguistic variables (e.g., violations of semantic plausibility; Rayner, Warren, Juhasz, & Liversedge, 2004; Warren & McConnell, 2007). The model has also been extended to simulate Chinese (Rayner, Li, & Pollatsek, 2007), French (Miellet, Sparrow, & Sereno, 2007), and older readers (Rayner, Reichle, Stroud, Williams, & Pollatsek, 2006), as well as a variety of other reading-related phenomena (e.g., lexical ambiguity resolution; Reichle, Pollatsek, & Rayner, 2007). (For a complete review of the different versions of E-Z Reader and the issues that have been addressed with the model, see Reichle, 2010b.)

Although the basic components of the SWIFT model have also remained fairly constant across its various instantiations (see Engbert & Kliegl, 2001; Engbert, Kliegl, & Longtin, 2004; Engbert, Longtin, & Kliegl, 2002; Richter, Engbert, & Kliegl, 2006), the model has also grown in theoretical scope, having been used to simulate older readers (Laubrock, Kliegl, & Engbert, 2006) and tasks like visual search (Trukenbrod & Engbert, 2007) and z-string ”reading” (Nuthmann & Engbert, 2009). There are two core assumptions of the model. The first is that attention is allocated as a gradient to support the lexical processing of two or more words. The second is that the moment-to-moment decisions about when to move the eyes from one viewing location to the next are determined by a random timer that causes the initiation of saccadic programming at random intervals; variables like word frequency influence fixation durations only indirectly, by inhibiting the random timer, delaying the initiation of saccadic programming and thereby increasing fixation durations. (The remaining assumptions about saccade programming and execution are nearly identical to those of E-Z Reader.) In the most recent version of the SWIFT model, this saccadic inhibition is delayed by a significant amount of time to be consistent with the hypothesis that higher-level (e.g., cortical) control of fixations is relatively slow, intervening only occasionally to modulate fixation durations (Findlay & Walker, 1999). Like E-Z Reader, SWIFT can account for the full range of benchmark phenomena that have been used to evaluate models of eye-movement control in reading (Reichle et al., 2003). However, to date, the model has not been explicitly used to simulate the effects of higher-level language processing, but has instead been used to explain how fairly low-level variables (e.g., visual acuity, oculomotor constraints, lexical variables, etc.) influence readers' eye movements. We suspect that the recent efforts to develop E-Z Reader as a framework for ”bridging” higher-level language processing to eye-movement control will force the designers of SWIFT to be more explicit about how their model explains the interface between language processing and eye movements. We shall return to this issue in the final section of this article.

Comments about Models of Reading

As already mentioned, the cognitive processes that support reading are both varied and complex. This is undoubtedly the reason why to date efforts to develop computational models of ”reading” have largely been directed towards explaining only one or two components of the reading processing (e.g., how printed words are identified), with little effort being directed towards explaining how these components interact with the remaining processes that are important in reading (e.g., attention allocation). We suspect that, although this strategy may have proven effective in that it allowed cognitive scientists to focus on their own particular problems, the approach may be limited in that it tends to provides a narrow view of what actually transpires in the minds of readers. An alternative view of the role that computational models play in cognitive science is that it is better to develop large-scale models of the overall cognitive ”architecture” than it is to develop smaller-scale models of specific cognitive tasks (Anderson & Lebiere, 1998; Just & Carpenter, 1980; Newell, 1990; Newell, Rosenbloom, & Laird, 1989; Rumelhart, 1989). The argument for this view is that, by adopting the former approach, one is forced to consider the domain-general constraints that apply to all cognitive tasks, thereby forcing the designers of models to ”see the big picture.” If one accepts Huey's (1908) assertion that to understand reading would be to understand ”the most intricate workings of the human mind,” then it is not unreasonable to advocate a more integrative approach to the modeling of reading one in which models of the reading ”architecture” force theorists to explicitly state how the assumptions of their models fit into the larger framework of what is being explained. For example, designers of word-identification models would have to specify how words are identified across two or more fixations (i.e., from different viewing locations) and given the acuity limitations of human vision.

Another concrete example of the types of issues that might be addressed through this more integrative approach to modeling reading is the on-going debate about the nature of attention allocation during reading (i.e., whether it is serial or parallel); careful consideration of existing models of word identification indicate the conceptual challenges faced by models of eye-movement control (e.g., SWIFT and Glenmore) that posit attention gradients and the parallel lexical processing of two or more words, including, for example, the potential need for multiple lexicons (Reichle, Liversedge, Pollatsek, & Rayner, 2009). Although the task of developing more integrated computational models of reading will undoubtedly be a challenging one, it is easy to imagine how one might leverage such models to gain important new insights into the nature of reading and human cognition (e.g., how the time course of syntactic parsing affects the construction of the discourse representation, how top-down constraints of sentence- and discourse-level representations might constrain the identity of an ambiguous word, etc.). Indeed, if one reconsiders the ten questions that were posed at the beginning of this article, then it is clear that all of these questions (with the possible exception of the first) seem to suggest this type of more integrative approach.

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