Stochastic Models of Reading

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Introduction

This chapter discusses stochastic models of reading, concentrating on a minimal control model that I introduced several years ago (Suppes, 1990). It is not claimed that this minimal control model is fully satisfactory. Features that are not are discussed. Here however, rather than concentrate on extending and modifying it in ways that are suggested by a variety of experiments on eye movements in reading, the chapter ends by discussing how it might be extended to a full model of comprehension. As might be expected the suggestions are certainly tentative. They will undoubtedly need serious modification if systematic experiments are conducted to study in detail the relation between comprehension as reflected in semantic paraphrasing and reading eye movements of the text to be comprehended.

A second methodological point of the chapter is to exhibit a stochastic model of reading that is at some level of analysis a complete model. This means the model postulates from a theoretical standpoint a stochastic process that provides a setting for an indefinitely detailed testing of its consequences for many different aspects of eye movements, not just those that arise in some particular experiment. Because the model is complete in this sense it does not mean that it is not lacking in many details that one would want because it does not operate at a deep enough level. It does provide, however, an example of how such models may be formulated. It is also emphasized that there is no attempt to give a really satisfactory technical description of the underlying stochastic process that the model postulates, but the intuitively formulated axioms and various comments should make clear how this is a relatively straightforward matter to make completely explicit.

Minimal Control Model of Reading

The minimal control model lets the process of reading influence eye movements in only a restricted way. Probably no one would be willing to accept this model as correct, but it constitutes an interesting model from which to examine the way in which the context of reading text forces deviations from this model. In this minimal control model it is assumed that most reading is an automatic low-level process, little disturbed by cognitive and linguistic features of the text. The two basic assumptions of the model are, first, that durations of fixations are not affected by stimulus context, that is, by the content of the text, and, second, the length of saccades is not influenced by text content, but only by the physical layout of the page.

Axioms on duration of fixation

- F1. *The execution of time of each eye-control instruction is independent of past processing and the present stimulus context.*
- F2. *Each fixation lasts for the execution of* n *internal instructions, for* n = *1,2,...*
- F3. *The execution times for the* n *instructions executed during a given fixation are identically distributed.*
- F4. *In reading algorithms,* n = *1 or* n = *2.*

The important point of the axioms is that little variation in the distribution of durations is permitted, only that based upon the number of internal instructions $n = 1$ or $n = 2$, which leads to the mean distribution:

$$f(t) = \frac{\alpha}{\lambda^1} e^{1/\lambda} + \frac{(1-\alpha)t}{\lambda^2{}_2} e^{1/\lambda_2}$$

The distribution $f(t)$ of fixation durations is a convex combination of two distributions. The one with weight a is a purely exponential distribution, the case of executing one instruction, in accordance with Axiom F1. The second component distribution with weight $(1-\alpha)$ is a convolution of two independent exponential distributions, the case of executing two instructions. The single parameter of the exponential distribution is l_1, of the convolution distribution l_2, and for the convex combination a. Since it is no problem to collect data with upwards of 100 000 fixations for a single subject, the form of the above equation, with just three parameters to be estimated can be rigorously tested. (For such tests for arithmetic, see Suppes *et al.*, 1983.)

Axioms on saccades in reading

D1. *If processing is complete in a given region of regard, then move to the next word of text.*

D2. *If processing in a given region of regard is not complete, stay put on the same word.*

D3. *If processing in the present region of regard is not complete and non-stimulus-supported memory has decayed, backtrack to the immediately preceding word or phrase.*

D4. *If the present region of regard also provides a perceptual image of the next word and the processing of it has been completed, then skip over the next word to the following one.*

D5. *A saccade is independent of past motion and earlier stimuli.*

These axioms characterize a random walk consisting of four movements: *forward, stay put, backtrack,* and *skip*. It will also be obvious in any real data that the catchall motion *other* needs to be added for a fifth possibility. The division of backtrack into several kinds can also be done here by examining whether the backtracking is to the immediately preceding word or two words preceding, etc. Data from various sources, for example, Hogaboam (1983), support the hypothesis that regression or backtracking beyond the two preceding words rarely occurs.

Direction and size of a saccade are under cognitive control in this minimal model. It is to be noted, therefore, that this is not in any true sense a minimal model. A strong minimal model would put a probability distribution on the four types of saccadic movement formulated in the axioms and then limit cognitive control to the choice of movement. Given the overwhelming data showing that saccadic movements do move from word to word and very seldom, for example, focus on the empty spaces between words, it seems reasonable to reject such a strongly minimal model.

Data Support for Minimal Control Model of Reading

Independence

The axioms of the minimal control model embody some very strong assumptions about independence and stationarity. First, consider independence. The bulk of the data seems to support the assumption of independence of fixation duration from previous fixation durations. Correlations reported in the literature seem to be quite small. Good examples are Andriessen and Devoogd (1973), Rayner and McConkie (1976) and Hogaboam (1983).

Stationarity

The evidence for stationarity of process seems to be quite positive, in the sense that, once adulthood is reached, reading behavior remains quite stable, but there are two riders to this conclusion. First, there is a developmental process which is not meant in any way to be covered by the axioms stated for the minimal model. Second, there is the issue, not to be addressed at this point, of whether the type of text influences the parameters of the distributions and random walk assumed as part of the minimal model.

Robustness

There is one conclusion which seems to be generally agreed upon and which supports the robustness of the axioms of the minimal model. This is the conclusion that direct training of ocular activity does not have very much effect, in fact no more or perhaps less than well-motivated reading practice alone (Tinker, 1958; Morton, 1966).

Random walk

The basic axioms of the minimal control model concerned with the random walk incorporate effects of the reading context on the probability of forward, stay put, backtrack or skipping motions. The model is not compatible with probabilistic sequential dependencies. An example of such a sequential dependency would be that the probability that a forward motion is followed by a forward motion is greater than that a stay put motion is followed by a forward motion. It is to be noted that the nonexistence of such dependencies in the random motion itself does not, of course, prove that the reading context itself will not have significant effects on the random walk, a matter already postulated in the basic axioms.

What the author has not been able to find in the literature on reading is a summary of data for the random-walk motion corresponding to that given for arithmetic in Suppes *et al.* (1983). For example, I have not been able to determine any estimate of the miscellaneous category *other* than for competent adult readers.

Other tests needed

The current literature on eye movements in reading has not been oriented toward the testing of overall models of the reading process. To evaluate the minimal control model we need, in addition to the random-walk analysis mentioned above, tests of independence of successive fixation durations and tests of scanpath. It is difficult to obtain from the literature on eye movements in reading some idea of how good the fit is to various normative models. What would be especially interesting would be the data on wandering fixations on the part of good readers compared to dyslexic readers. The lowest percentage of *other* movements in the case of arithmetic was something of the order of 9% for the two adults doing addition exercises (Suppes *et al.*, 1983). In the case of subtraction, a notably more difficult task for everyone, the category of *other* movements rose to above 15%. For the child subjects these percentages were higher.

Status of global variables

In evaluating the fit of the minimal control model, it is necessary to distinguish global variables from local ones. Local variables such as features of individual words are considered in the next section. Only local variables affect the evaluation of fit. Global variables are determined by individual differences in readers, individual differences in entire texts, and individual differences in approach to the task, which can vary with a given subject from one occasion to another. Broadly speaking, it is these three different kinds of global variables — those of *reader, text* and *task* — which do not affect the validity of the minimal control model for the following reason. We expect the parameters of the minimal control model to vary for each of these global variations. Typically, the length of fixation durations and, even more, length of saccades will vary direction with the skill of the reader. Early studies of eye movements tended primarily to look in fact at variations cased by global variables (Woodworth, 1938). More recently, good examples of dependence of length of saccade on type of text are to be found in Heller (1982). Especially interesting is the recent study of reading with spaces between words eliminated — the standard practice in the ancient world (Epelboim et al., 1994).

Similar results have for example, been found by Levy-Schoen (1980). The Levy-Schoen results and also those of Heller show that instructions to adjust reading speed have systematic effects in the intended direction. Another interesting effect of task instruction reported by Heller (1982) is that when subjects are instructed to look for typing errors a significantly greater number of corrective saccades followed the return sweep. A radically different sort of global variable is the language being read. Eye movements in reading English and Chinese are in many ways surprisingly similar (Sun *et al.*, 1985), but as yet only eye movements in reading a few languages have been studied in real detail.

A quite different kind of global variable is generated by tasks such as solving word problems in mathematics or science. At least in the case of arithmetic word problems, the data and analysis in DeCorte and Verschaffel (1987) indicate the feasibility of beginning with the minimal control model, even though the evidence of incomplete reading is much more extensive than in standard reading experiments. As could be expected, incomplete reading of the problems was a main cause of failure to find a correct solution. Greater deviations from eye movements in standard reading are to be found in the studies by Groner and his associates of eye movement behavior in multi-term series problems (Groner and Groner, 1982, 1983).

This is only a sample of the many different studies showing the effects of global variables on reading. In qualitative terms, none of the effects is enormously surprising. It is important to establish them and also to have a sense of their quantitative magnitude. The existence of so many different significant global variables in no way directly invalidates the minimal control model because it is assumed in this model that changes in the global variables simply mean different parameter values in the model. In this sense, the model makes fundamental assumptions about the qualitative character of eye movements in reading. It is left to specification of the global variables to fix the numerical values of the various parameters.

Evidence Against Minimal Control Model of Reading

First, a demurrer about what is to count as evidence against the model needs to be made. Details of oculomotor characteristics that go beyond the specification of the model will be ignored. This does not mean that such characteristics are not important. The model is not sufficiently refined to take account of ballistic characteristics of the saccadic eye movement, or variation in saccadic size smaller than the length of a word. Such variables are ignored because the goal is to describe and test a normative model of saccadic eye movement that looks at the most important features of the cognitive task. Thus, for example, in the conception of a random walk, the difference between forward movement along a line and the return sweep with a possible corrective saccade movement has been ignored.

The number of local variables relevant to testing the minimal control model of reading is still enormous. McConkie (1983) gives a table of more than 30 such local influences, as he calls them. Most of them would be classified as 'cognitive variables'. In spite of the large number of references to experimental studies McConkie gives to document his list, it is still only a small sample of the many relevant experiments. For the model-theoretic orientation adopted here, we cluster local variables into certain main categories which raise various cognitive questions that are of importance in trying to improve on the minimal control model. It is not meant to suggest that the categories considered here are necessarily the best ones, and certainly not the only ones, but they are ones that naturally arise in any discussion of reading as a cognitive activity.

As a preliminary step, it is natural to divide the consideration of local variables into two classes, those which affect duration of fixations and those which affect saccadic movements.

Fixations

The local variables affecting fixations have been divided into three broad classes, which are identified as line, word, and grammatical variables.

Line variables

That there are variations in fixation durations, with a special feature being that the first fixation on a line tends to be longer, has been known for some time and has also been recently confirmed (Woodworth, 1938; Rayner, 1977; Heller, 1982).

Word variables

The evidence on the influence of word features is overwhelming in terms of the number of significant studies. But the exact assessment of these effects in terms of their magnitude is more difficult. There is no doubt that there are effects which can easily be demonstrated. A complicated controversy surrounds some variables which are relatively highly correlated. These are the effects of number of letters in a word, number of syllables, and relative frequency of the word. Fortunately the untangling of these various variables has been done in some detail by Kriegl *et al.* (1982, 1983). They show that the fits of eye fixation data are better when not just number of syllables and frequency are considered but also number of letters. Moreover, once the number of letters is introduced in a stepwise regression, for example, the additional effect of syllable length is non-existent and the contribution of word frequency is 'decreased from 12 to 3%'. They make the point that this dominance of number of letters over the other two variables makes a case for the reduction of cognitive variables to perceptual ones.

Grammatical variables

One of the relatively clear results concerning the impact of grammatical function on fixations is that short function words are often skipped (O'Regan, 1979). A natural hypothesis is that when anaphoric reference is appropriate and unambiguous, fixation time will be less than when it is ambiguous or incongruous. Kerr and Underwood (1984) found that this was true, but the results are not at all strong. For example, the duration of first fixations for congruous pronouns was at a mean value of 231 ms, for ambiguous pronouns 232 ms, and for incongruous ones 261 ms. The small differences in these numerical results indicate the difficulties of identifying, in a highly significant form, grammatical effects on fixation durations.

Saccadic movements

Local effects on saccadic length have been grouped under the same three categories.

Line variables

The obvious effect of position on the line on saccadic movement is the return sweep. What is important is to take particular account of small corrective movements following the return sweep. The rather complicated character of the data is well illustrated by Heller (1982).

Word variables

O'Regan (1979) reports two effects on length of word. The saccadic movement is longer when a longer word lies to the right of the fixated word, that is, when enough information about the word to the right is given in peripheral vision to control the central tendency of the movement to that word. A second related effect is that a longer movement occurs following a fixation on a longer word.

Another typical result is that saccade length decreases when, in the peripheral vision on the right, erroneous letters replace correct letters in words. A similar effect is observed when letters in peripheral vision are replaced by a grating. Relevant studies include those of McConkie and Rayner (1975), McConkie and Underwood (1981), O'Regan (1980), Rayner and Bertera (1979), Rayner *et al.* (1981) and Rayner and Pollatsek (1981).

Grammatical variables

Wanat (1976) showed that the number of regressive eye movements differed between active and passive sentences. The effects were stronger in oral than in silent reading but present in both cases. A well-known study is that of Mehler *et al.* (1967), who tried to relate both movement and fixation to surface syntactic structure, but general results, including theirs, have not been successfully replicated or clearly established. For example, in an attempted replication, O'Regan (1975) obtained quite different results. In addition, Communale (1973) and Rayner (1975b) found no differences in eye-movement behavior in the immediate neighborhood of the main verb of a sentence, perhaps the most significant grammatical element of a sentence. Rayner (1975a) and O'Regan (1980) show that the degree of linguistic control on saccadic movement does not extend in any significant way beyond six or seven letters to the right of a given fixation point.

Without providing a detailed structural theory, Frazier (1983) shows that eye movement is affected by complex structural features. For example, the number of regressions, as would be expected, is greater for garden-path sentences, that is, sentences in which the reader is led down a certain path of analysis but then finds he is mistaken and must retreat and begin again.

Suppes (1990) proposed a revised control model to take account of much of the evidence that counts against the minimal model, but I shall not go into the details here.

From Eye Movements to Comprehension

In reviewing the evidence that either supports the minimal model or counts against it, has been said about actual comprehension of reading text. The omission is not an oversight, but rather is a reflection of the kind of results reported in the preponderance of studies of eye movements in reading. Some of the grammatical studies, for example those concerned with garden-path sentences, as mentioned earlier, do bear on semantic questions, as do other aspects. What however is missing is a theoretical conception of what insight eye movements might give us into the task of computing the semantic, especially storing the semantic information permanently kept from what has been read (Suppes, 1990).

What is missing in the minimal model, and perhaps in other like models of eye movements in reading, is a serious account of the processing that takes place to store very quickly in long-term memory a semantic paraphrase of what has been read. The evidence is incontrovertible that for almost all reading, human memory and cognition function beautifully at semantically paraphrasing what has been read, but are exceedingly limited in the exact and explicit recall of the actual sequence of words read. The same is also true of the words we speak ourselves or listen to. In this matter of memory and semantic paraphrasing there is no fundamental difference between spoken and written language, although of course there are various differences in detail that naturally arise from the different modalities.

Before attempting to relate features of semantic paraphrasing to eye movements, some mention should be made of the most salient aspects of paraphrasing.

1. Our human use of language completely depends on paraphrasing either as consumers or producers of language, as just emphasized. It would be intolerable to have stored and to be able to access everything that we have ever heard in spoken speech or read in written form. Even if we had the storage capacity, the unbelievable problems of accessing so much data would make its actual availability almost certainly impractical. Paraphrasing is essential to our use of language.
2. The second point is the fleeting quality of the syntax in which the language heard or read is expressed. It is a salient feature of semantic paraphrasing that with certain exceptions we cannot remember at all the detailed syntax of what was spoken or read. We cannot even remember the actual sequence of words. The implication of this is that the study of the relation of eye movements to syntax is perhaps a mistaken one. It is really the processing that takes place after the syntax is stripped away that we should go after.
3. Another feature that must be stressed that is implicit in what has already been said is that we in general never have access to the whole truth. We cannot remember and reproduce much of what was heard or read. In fact the evidence on speed readers is that they remember only the general idea of a text and very little of the details. But all of us lose an enormous amount of information, especially as we scan newspapers and engage in our own forms of fast reading.
4. Another fundamental feature of semantic paraphrasing is that of idiosyncratic and private processes of paraphrasing. It is absolutely evident to everyone who has experimented with any kind of comprehension of text by various kinds of individuals that no two individuals will reproduce exactly the same paraphrase of any text of any size. We all retain our private and idiosyncratic paraphrasing residuals produced by our own private and idiosyncratic processes of paraphrasing. This does not mean there will not be good correlations between salient features of text, but what it does mean is that strong individual differences will be evident in any sustained investigation of comprehension.

Inferences from eye movement

Keeping in mind these uncontroversial features of the process of paraphrasing, we can ask what kinds of questions about this process could be answered by a study of eye movements. Until a number of specific and focused experimental studies are conducted, it is not possible, of course, to provide a really satisfactory analysis of the kinds of questions that might be answered. On the other hand, it is reasonable to conjecture some of the things that it might be possible to uncover.

In looking at aspects of semantic processing that might be revealed by eye movements, it is important to emphasize how inaccessible this processing is from any direct standpoint. In the case of paraphrasing spoken utterances that are heard there are few if any direct behavioral cues that can be observed on a systematic basis. It is fortunate that eye movements are so closely connected with reading that there is some hope of gaining significant information about the semantic processing of written text.

The presence of backtracking in reading eye movements is well-documented. It is often conjectured that backtracking mainly concerns purely lexical processing, partly because in ordinary cases the backtracking, as already noted above, is only to one or two preceding words. However, the author knows of no studies that relate the analysis of backtracking to semantic processing as exhibited in the paraphrases individuals will give of what they have been reading. Backtracking has not been successfully associated in a detailed way with grammatical structure. It would certainly be worth investigating whether more specific positive results can be found in the case of the deeper operations of paraphrasing. It might be thought that because paraphrasing is even more remote from the eye movements themselves than the stripping away of the surface syntax, less can be learned about the semantics processing. On the other hand, the syntax is clearly not held in long-term memory, that is the syntax of what is read, but the paraphrase is.

A second line of attack on the problem of paraphrasing is not to simply look at the details of some fixed homogeneous text but to investigate, by using quite different kinds of text, the possible relations between eye movements and paraphrasing. It is quite a different thing to paraphrase a novel that one is reading than it is to paraphrase the formulation of a tricky physics word problem or group of such problems. Can the paraphrasing of rather large blocks of text in comparison with very focused and difficult items like mathematical or physical word problems be related to eye movements and give us insight into the problems of paraphrasing in these various cases?

In recent work on machine learning of natural languages, the author and his colleagues have been developing completely detailed models of the semantic processing required to execute simple robotic commands like 'put the screw in the left hole' (Suppes *et al.*, 1992, in press). Human processing is undoubtedly much more complicated, but it does not seem out of the question to use eye movement data to test a variety of hypotheses about the many-step process of paraphrasing a given text.

Let us conclude by giving one example of the kind of analysis we have been making of elementary physics word problems. Picking a completely trivial physics problem to illustrate the approach, presented here is the analysis of performance after learning has taken place. There is not space here to attempt to describe in detail the postulated learning process that is implemented in the machine-learning program. Viewed from the standpoint of performance, we first present a natural language sentence such as:

The dog runs 100 meters. (1)

We then form the category generalization of this sentence where O is the category of common nouns, A is the category of actions, N is the category of numbers and U is the category of units of measurement. We thus obtain:

The O A N U (2)

Notice that we do not give a category analysis of the words that do not denote, such as the definite article. We then retrieve the associated semantic representation of this category generalization, which, using LISP as our internal language, has the form:

(fs (fa1 A (io (fo O) (fq N U)))) (3)

This just takes us to the stage that anyone can get a representation of an English physics word problem but without as yet any real understanding of the physics. This is, so to speak, sweeping away the surface syntax to get a high-level internal semantic representation. We now get down to the first real physics analysis step, the associated generalization in terms of the data language of (3). We thus obtain:

((EQ ((PM (fq N U)A) (io (fo O))) (fq N U))) (4)

where EQ stands for equation, PM for physical magnitude, and A, O, N and U the meanings as given above as categories. The next step then is to specify the data language specification by putting in the data for the problem and we obtain:

((EQ ((dist (fq $100 $meter) $run) (fo (to $dog *)))
(fq $100 $meter))) (5)

We next move to the equation language, still another internal level of language, to obtain something close to what one would finally expect:

dist (d_1, run) = 100 m (6)

To complete the analysis of this simple word problem, but not showing as much detail for the other sentences, the second sentence of the word problem presents the data on the dog's running time:

The dog runs for 20 s. (7)

Which is converted by the same process into an equation corresponding to:

$$\text{time } (d_1, \text{run}) = 20 \text{ s.} \quad (8)$$

And the third sentence of the problem is the question about speed of the dog:

What is the average speed of the dog? (9)

Which is converted by the same sort of analysis into an equation in the form:

$$\text{speed } (d_1, \text{run}) = ? \quad (10)$$

Applying then the standard formula for average speed we obtain equation (11) with the solution shown.

$$\text{speed } (d_1, \text{run}) = \frac{dist\ (d_1, run)}{time\ (d_1, run)}$$

$$= 5 \text{ m/s.} \quad (11)$$

Of course, this most certainly does not mirror in any exact way the process by which a student would work on this problem. But something corresponding to the data language representation and the equation representation is required and some of this is externalized in the way the problem is finally presented and solved by the student. This is an extreme example of paraphrasing. Yet the equation representation of the natural-language sentences are good examples of paraphrase. They express in this case all of the pertinent information but have a syntactic form that is completely unrelated to the syntactic form of the original natural-language sentences. It may in fact be that the solving of complicated word problems in mathematics and science is one of the best arenas to understand initially the process of paraphrasing, just because the process does move slowly and ends up in a very explicit structure that can be related in rather specific ways to eye movements in reading the original natural-language formulation of the problem.

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