Eye movements and their role in visual and cognitive processes
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CHAPTER 9

Eye movements and reading

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1. Introduction

1.1. Why study eye movements in reading? Reading as a domain in its own right and as a microcosm of visual perception

The main characteristics of eye movements in reading have been known since Lamare (1893) and Javal (1878) placed what was essentially a stethoscope on the closed eyelid, and heard the clicks made by saccades. Ever since, researchers have studied the sequence of fixations and saccades that characterize eye movements in reading, either with a view to understanding the underlying perceptual processes (the earliest work, in particular by Dodge and Huey) or in order to find the most favorable conditions for reading (work in the 1950s: Tinker, Buswell) or in the last decade, because of interest in linguistics and psycholinguistics, to use eye movements as an indicator of the reader's cognitive processes. This latest trend has been particularly active, because eye movements appear to be an ideal, unobstrusive probe of the mind: unlike the more classic tools of the psychologist, e.g., manual button presses or oral responses, they are the very means by which information is extracted and require no conscious action by the reader; they are also continuously present, and so are a moment-to-moment index of processing.

In addition to being interesting in itself, the study of eye movements in reading is also a convenient place to start studying visual perception in general. Whereas reading has its own specificities, perhaps involving scanning routines and types of (linguistic) processing not found in scene understanding, it is nevertheless a microcosm whose objects (letters, words, sentences,...) are more easily described than the tables, faces, scenes, of everyday life. We have a set of units (letters) which can be used to describe the visual world of reading; we have the rules (of lexical structure and grammar) that govern how the units can combine to form larger units (words, sentences). Finally, psycholinguists provide us with knowledge about the processes that underlie language comprehension. We have no such units or grammar for visual scenes; we have no such well-developed theory of scene understanding.

1.2. Organization of the chapter

Comprehensive reviews have appeared in the past years on recent work on eye movements in reading (Rayner, 1978; Rayner and Inhoff, 1981; Lévy-Schoen and O'Regan, 1979; O'Regan and Lévy-Schoen, 1979; McConkie, 1983; Rayner and Pollatsek, 1987; Jacobs and Lévy-Schoen, 1987). These reviews show that our knowledge has reached a 'Mendeleevian' state: data have been organized and statistical regularities discovered. But what is lacking is the equivalent of a theory of atomic structure to explain the observed facts. We would like a more mechanistic explanation of why each individual saccade goes where it goes and why each fixation lasts the length of time it lasts. The present chapter will attempt a step in this direction by proposing a 'strategy-tactics' theory of eye movement control in reading. The theory derives its main inspiration form a recent discovery showing that in each word there is a position, called the 'optimal viewing position', which the eye must fixate first in order to recognize the word most rapidly. An efficient eye movement strategy in reading must take account of the existence of this optimal viewing position, and the fact that it may be different in different words. In addition, the strategy must take into account a number of purely motor or visuo-motor constraints that place limitations on saccade accuracy and fixation durations. These low-level constraints have not been adequately considered in the past.

The present chapter will trace again the steps which led me to the optimal viewing position phenomenon and the strategy-tactics theory. Before starting, however, there are two preliminary sub-sections: one that recalls the basic characteristics of reading eye movements and some problems of definition, and a second sub-section which gives a brief historical overview. Section 2 will then start the main line of argument by discussing the notion of 'perceptual span'. This notion has been central to eye movement work since the introduction of computer-controlled eye-movement registration systems. Its importance derives from the supposition that eye movements in reading might be intimately linked to perceptual span: the eye might at each new saccade be moving so that successive spans just touch. However, I will show that, as generally used, the notion of perceptual span is not sufficiently precise. Section 2.6 remedies this by distinguishing 'visual' span from 'perceptual' span, and then gives conclusive evidence that eye movements in reading are actually not directly linked to perceptual span: other factors must be active in determining eye movements. Sections 3 and 4 consider some low-level spatial and temporal visuo-motor factors that might be active, of which some will prove to be useful for the strategy-tactics theory. Section 5 then presents the optimal viewing position phenomenon and section 6 the strategy-tactics theory. Section 7 confronts the theory with evidence in the literature, thereby providing an opportunity to review some recent work on the relationship between linguistic processing and eye movements.

One consequence of the decision to organize this review chapter around the strategy-tactics theory is that the chapter will not do full justice to the impressive work that has been done by other research groups, in particular those of K. Rayner and G. McConkie. Also, two important issues are not discussed directly, but only appear incidentally as needed in the text. These are: types of eye guidance model, and the use of parafoveal information. For better treatment of these issues, and for a less theoretically oriented account, the review articles cited above should be consulted.

1.3. *Eye movement characteristics in reading*

Fig. 1A shows a typical record of the horizontal eye movements during reading, obtained using a photoelectric eye movement recording device. The most striking and well-known aspect of such records is the staircase-like sequence of intersaccadic pauses, called 'fixations', separated by saccades (which are generally rightwards or 'progressive', but sometimes also leftwards or 'regressive'), terminated at the end of each line by a large leftwards 'return sweep' that takes the eye to the beginning of the next line of print. The return sweep is often rapidly followed by a correction saccade intervening after a shorter latency than the average fixation duration. This is similar to the undershoot found for large (> 10 deg) saccades in other visual tasks (c.f. Frost and Pöppel, 1976). Several microscopic aspects of the eye movements are also visible in Fig. 1A, such as dynamic overshoot and post-saccadic drift, but these are usually disregarded in reading research, since they presumably do not contribute to, or appreciably modify, the information-extraction process.

The eye movement parameters which are generally used to quantify reading behavior are derived from the basic fixation-saccade sequence: the number of fixations, the number of regression movements, the size of saccades (regressive and progressive), the duration of fixations, and their precise positions in the line. However, controversy has

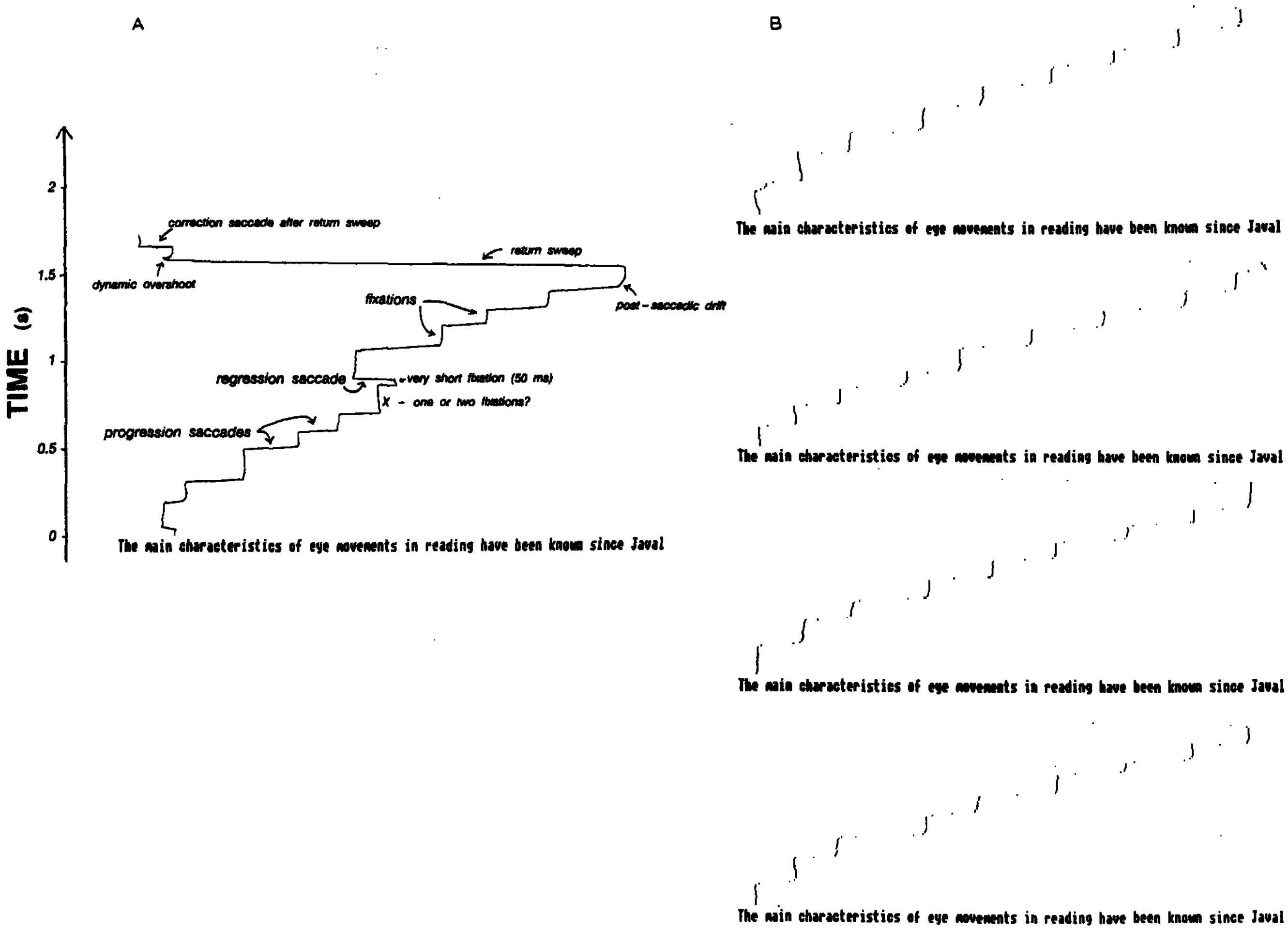

Fig. 1. Records, obtained by an infra-red photo-electric scleral reflection technique, of eye movements while reading the sentence shown on the abscissa. Sampling was done every 10 ms. Time (in seconds) increases vertically along the ordinate, so to recreate the eye's movement the traces should be read from bottom to top. A. A record showing various typical aspects of eye movements in reading. For visibility individual eye position samples have been connected with lines. B. Records of the author reading the same sentence four times in succession. The positions of the samples with respect to the sentence are shown by small dots (visible particularly in saccades). Note that while average saccade sizes and fixation durations are comparable in all the records, the exact places where the eye stopped are not the same across the four records.

arisen around the question of which measures are the 'correct' ones to use. 'Correctness' can only be relative to some purpose, in this case that of using eye movements as an indicator of cognitive processes in reading.

An initial, fundamental, debate concerns fixations. What is a fixation? Looking very closely at the record in Fig. 1A, it might be possible to argue that the long fixation marked X is in fact two shorter fixations separated by a very small saccade, only a fraction of a letter in size, visible as a discontinuity in the record near the X. Such very small saccades certainly exist: in fact Cunitz and Steinman (1969), Haddad and Steinman (1973) and Steinman et al. (1967) claim that the processes controlling small saccades are not different from those controlling the large saccades that occur during reading. Further, during long fixation of stationary targets, Boyce (1967) observed that the smallest (< 1.5 min arc) saccades are the most numerous (for further discussion of fixational eye movements, see Ch. 1 of this volume). If there is no lower limit to saccade size, then the notion of fixation becomes vacuous, since we can never be sure that what we call a fixation is not in fact a number of shorter fixations separated by invisibly small saccades. The solution to this problem is to realize that one's definition of 'fixation' must depend on one's theoretical motivations. Thus, if one believes, as seems reasonable, that saccades smaller than a fraction of a letter are irrelevant to information-extraction processes in reading, then these can be ignored. This is the view taken by most authors, and we will also henceforth (and somewhat arbitrarily) use the term 'fixation' to mean the time during which the eye makes no saccades, and 'saccade' to mean a movement of more than half a letter taking place in less than 20–30 ms. Note, however, that this is not the only possibility: there is another theoretical approach, taken first by Just and Carpenter (1980), which dispenses entirely with the notion of fixation. Under this approach it is supposed that the unit of processing in reading is not the letter, but the word or small group of words. Saccades within these units are considered irrelevant, and what counts is only the total time or 'gaze duration' spent by the eye in such regions.

A second debate concerns the units in which saccade sizes should be measured. It might be thought that since text can only be visually resolved within the fovea, saccades in reading would proceed by moving from approximately one fovea-full of text to the next. In fact, Javal, listening to saccades through his stethoscope, noted that when viewing distance is changed over a large range, saccades modify their angular size so that about the same number of letters are crossed at each jump. This result, which has been confirmed many times (cf. Morrison and Rayner, 1981; O'Regan et al., 1983), is not consistent with the idea that the eye jumps one fovea-full at a time, since changing distance changes the number of letters falling in the fovea, and so should change saccade size measured in letters. An explanation for the fact that saccades actually cover the same number of letters independently of viewing distance will be given in section 7.1. Meanwhile, Javal's and subsequent results suggest that, rather than angular size, the number of characters is a more reasonable choice for measuring saccade size. However, alternative measures such as number of words or fractions of the line of print are also possibilities. A related question is whether 'average saccade size' should be an algebraic measure that takes account of the backwards regressive movements, or whether these should be considered separately.

It is clear that problems of what eye movement measures should be used in reading research cannot be resolved until we have a better theory. Until then, the choices we make for the discussion of existing experimental data will necessarily be arbitrary.

1.4. Brief history of eye movement research: 'local' and 'global' studies

Fig. 2 gives an idea of the variability of saccade sizes and fixation durations in reading. For each of several readers, the solid and the dotted histograms in the figure correspond to readings of a first and a second text. As has been found classically, mean progressive saccade sizes are about 7 letters long, with a standard deviation of 3 letters. Regressive saccades have a smaller mean size, about 3 or 4 letters. Fixation durations are about 250 ms (standard deviation 100 ms). It is interesting that distributions can be quite different from one reader to the next. But a given reader's distributions for first and second texts are similar when, as was the case here, the texts have identical word lengths and identical grammatical structure. Nevertheless, the precise positions that the same reader fixates in the first and in the second text will not necessarily be the same. This is also true of successive readings of the same text, as shown in Fig. 1B.

Parenthetically, it is worth noting that fixation duration distributions in reading are not normally distributed, but have a longer tail for long latencies. The same is true for the distribution of latencies for making a saccade to a suddenly appearing stimulus. It is of course obvious that fixation durations or latencies should not be normally distributed, because fixation durations can never be less than 0 ms, but can be infinitely long. In fact, as might be expected, fixation duration distributions resemble

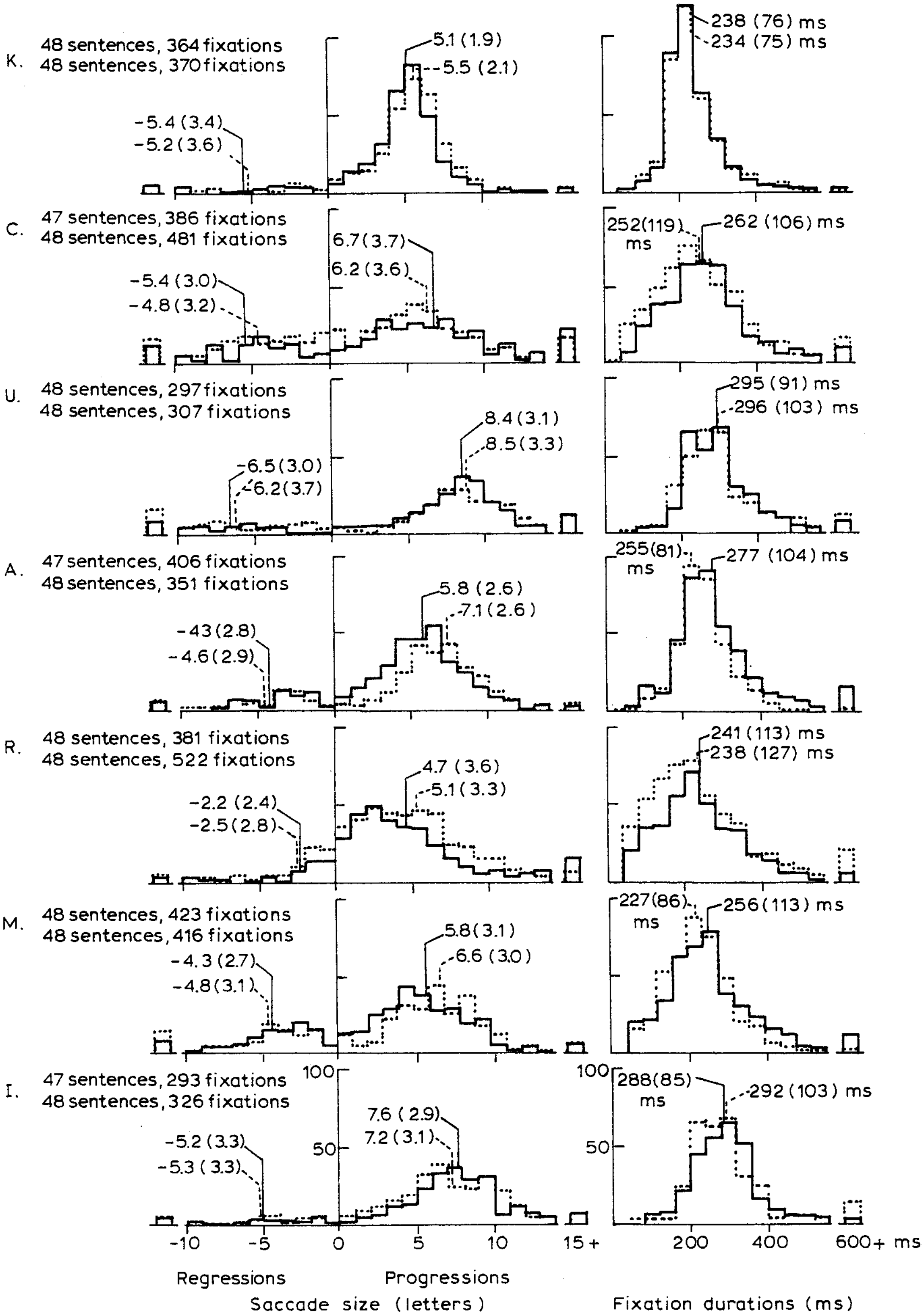

Fig. 2. Distributions of saccade size and fixation durations for seven subjects reading two blocks of 48 unrelated upper-case sentences. The sentences in the two blocks had identical word lengths and syntactic structures. The data for the first block are shown by solid lines, and for the second block by dotted lines. Note that on the second block saccade sizes are slightly larger and fixation durations slightly shorter. Means and standard deviations of the distribution of saccade sizes are indicated in letters and of the distribution of fixation durations in ms. (Adapted from O'Regan and Lévy-Schoen, 1978)

classic reaction time distributions. A rich literature exists to explain the shape of these, and aspects such as the fact that when the mean of a distribution changes, the standard deviation changes proportionately (see Ch. 10 of this volume).

Returning to Fig. 2, what is the source of the variability of fixation duration and saccade size? Undoubtedly there are several sources: inherent variability in oculomotor precision (this may possibly be affected by visual factors such as text layout, or by particular scanning strategies used by the reader), variability associated with perceptual processing, and variability associated with linguistic and cognitive processing. Up until recently, most research has been nourished by the hope that the variability does not reflect low-level visuo-motor processing, but mainly linguistic and cognitive, or at worst perceptual processing: for if this is true then eye movements can be used as a convenient online monitor of the reader's perceptual and thought processes.

The first step in making use of eye movements as a clue to cognitive and perceptual processes is to proceed backwards: manipulate processing in a known way, and try to understand the accompanying changes in eye movements. Later, when it is known how eye movements react to processing changes, one can use eye movements to understand the cognitive and perceptual processing that occurs in particular cases. But the first step, in which researchers try to understand how eye movements react to different cognitive or linguistic factors, has up to now given disappointing results. Systematic dependencies have been observed between eye movements and cognitive and linguistic processes. However, essentially all that can be said is that if things are hard to see or understand, the eye spends overall a longer time in the zone of difficulty: it may make more or longer fixations, it may make shorter saccades or more regressions. But which of these possibilities occurs, and exactly where in the difficult region, is not satisfactorily explained.

Early research on eye movements (up to about 1960) studied the effects of different factors on 'global' eye movement parameters, that is, the mean values of parameters such as fixation duration or saccade size, when measured not locally, but globally over a whole body of text. The goal was not to understand precisely where in the text eye movements were being modified, but it was hoped that particular patterns of eye movement effects would be associated with particular kinds of processing. However, in a review of this early work (O'Regan and Lévy-Schoen, 1978; Lévy-Schoen and O'Regan, 1978), we found that independently of whether the factors studied were the physical aspect of the text (e.g., type size, type font, spacing, color, contrast, viewing distance), the content of the text (type of text, difficulty) or aspects related to the reader (age, reading ability, familiarity with the material), no pattern emerged that enabled us to link particular factors to particular eye movement parameters.

Probably because, at the time, researchers were also aware of this unsatisfactory situation, a lull in interest occurred in the 1940s–60s (c.f. review by Tinker, 1958). Interest in eye movements built up again starting in about 1975. This rebirth was partly due to the impetus given by developments in psycholinguistics, which provided hypotheses about moment-to-moment processing in reading that could be tested using eye movements. An additional motivation has undoubtedly also been the technical fascination of building computer-aided measurement systems, and the possibility they give of changing what is displayed on a computer screen from moment to moment as a function of what part of the display the subject is looking at. (The first such systems were built by Reder, 1973, McConkie and Rayner, 1975, and O'Regan, 1975.) A large amount of work has been done using such computer-controlled eye-movement-contingent display change techniques.

A number of the modern studies, like the pre-1960 studies, were studies of global eye movement parameters and did not attempt to understand local behavior. The most successful of these have been studies of the 'perceptual span', that is, the zone around the instantaneous fixation point from which useful information is being extracted. These studies will be reviewed in section 2.1. They are the starting point for the line of argument to be presented in this chapter. The effects of viewing distance, of size and type, contrast, and spacing have also been looked at again, both in reading, and in the (probably) cognitively simpler task of scanning meaningless lines of letters in the search for a target letter. As was the case for the early studies, the rather obvious conclusion that emerges is that when things are difficult, reading slows down. But up to now no-one has been able to predict which eye movement parameters will be modified by which factors.

The real hope in modern computer-controlled eye movement measurement systems stems from their ability to pin down eye movement effects to fairly precise points in a text. Recent studies have attempted to measure local effects of perceptual and cognitive variables on eye movement parameters. Unfortunately, while a lot has been learned, if one is looking for a mechanistic explanation of why each saccade goes where it goes and why each fixation lasts the length of time it lasts, then the fruit is meagre.

Some success appeared to have been achieved by the influential work of Just and Carpenter (1980), whose production system model of reading correlated well with eye movement measures. However, the eye movement variable they showed to correlate with cognitive processing was 'gaze duration', defined as the total time spent by the eye on each word. This is not really a local measure, since the durations of several fixations occurring within a word are summed together. It tells us little about the moment-to-moment eye movement behavior, and so questions remain, such as: When will the eye skip the next word? What makes it fixate twice in a word? If it does, where will it refixate? Futher, Kliegl et al. (1982, 1983) have criticized Carpenter and Just's way of analysing the data, and claimed that the only strong correlation shown by Carpenter and Just's data was between word length and gaze duration: linguistic and semantic variables accounted for only a small part of the eye movement behavior (see Blanchard, 1985, for an excellent discussion). Analysis of a few of the more recent studies of linguistic variables will be done in section 7.4, after the strategy-tactics theory has been presented.

Studies looking at local variations in saccade sizes and fixation durations have not turned up any very strong dependencies with perceptual and cognitive processes. A number of studies show that if, by use of computer-controlled eye-movement-dependent display techniques, display changes are made to occur during reading, then these may immediately influence the fixation durations and the saccade sizes. But I will suggest in section 2.2 that these effects may be due not to changes in perceptual or cognitive processing, but to changes in visuomotor strategies caused by the display changes.

2. The perceptual span

One of the most obvious questions that might be asked when trying to understand eye movements in reading is: how much can be seen at each fixation pause of the eye? This question has been asked since the beginnings of psychology in the last century, and a number of the old studies were reviewed by Huey (1900, p. 296 ff) and in Woodworth's (1938) classic textbook.

While apparently innocent, the question has hidden depths. What do we mean by 'see'? It may be that at a fixation, information is 'seen' but not processed. It is known, for example, that in search and memory tasks a subject may directly look at the target and yet not notice or remember it (Mackworth et al., 1964; Mackworth and Mackworth, 1958). It happens to many people that when they get tired while they read, their eyes move over the lines, yet they are thinking of something quite different from the text. One might say they 'saw' the text, but 'perceived' nothing!

It is tempting to assume that the size of saccades in reading might be an indication of the span of perception in reading. But actually there is no guarantee that this should be the case. It is possible, for example, that at each fixation the material that can be seen comes from a wide region, but that the eye moves onwards only a fraction of that region so that semantic integration processes have time to occur.

It may also be the case that at each saccade, the eye moves further than the region from which information can be gathered. This might happen, for example, if the text is so easy to read that imperfectly viewed portions can easily be completed or guessed.

Most research has ignored these problems and has assumed that eye movement measures actually do indicate the extent of the perceptual span. Research has also been motivated by the converse hypothesis, namely that the edge of the perceptual span might be what is determining where the eyes go at each saccade: the eye might move forward in such a way that successive spans just touch each other. Temporarily setting aside the difficulties with the concept of perceptual span, I will now review a number of recent studies. However, it will become apparent that the notion is ill-defined. Section 2.4 will therefore define a new notion, that of 'visual span', and calculations and empirical data will be presented to show its dependence on viewing distance and character size. Section 2.5 will redefine 'perceptual span' in a precise way with respect to visual span, and section 2.6 will then show that in reading, eye movements are not directly linked to changes in perceptual span: an alternative theory to explain eye guidance in reading is needed.

2.1. Measuring perceptual span by perturbing the visual field in reading

Many of the early attempts to measure the span of perception during a fixation used tachistocopic presentations of text material (Cattel, 1885; Korte, 1923). However, as pointed out by Huey (1900, p. 298), tachistoscopic experiments must use presentation durations which are sufficiently short to prelude eye movements. This necessitates much shorter durations (< 100 ms) than the fixation durations commonly observed in reading (250 ms). This and other differences between reading and tachistoscopic experiments (cf. Rayner, 1975) led researchers to search for other techniques to measure perceptual span. Among these, Reder (1973), McConkie and Rayner (1975) and O'Regan (1975) pioneered the one that has recently generated the most attention, namely using a computer to create eye-movement-contingent perturbations in the text being read.

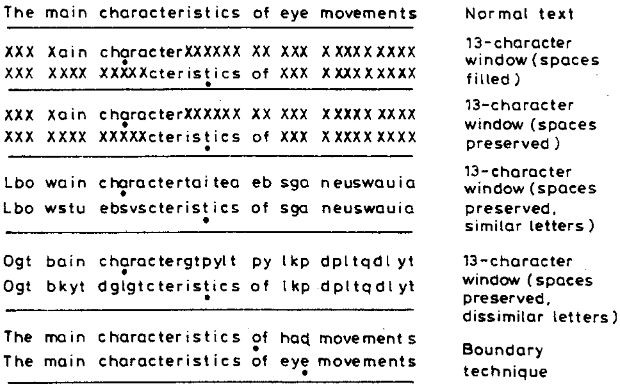

Fig. 3. Examples of techniques used to study the perceptual span. The top example shows a normal segment of text. The second to fifth examples show what is seen during two successive fixations in the moving-window paradigm. The eye's instantaneous position is indicated by the dot under the text line. The last example shows the boundary technique, where the word 'had' becomes the word 'eye' when the eye passes an invisible boundary after the word 'of'.

In one example of this technique, the 'moving window' method, a computer continuously monitors the eye's position during reading. The goal is to ensure that only the test material in a 'window' surrounding the instantaneous fixation point is visible to the reader at each moment. The letters of the text outside the window are replaced by other letters. The window of visible text may be of variable width, and the letters outside the window may be replaced by various other letters (see Fig. 3). In another example of the technique, the 'boundary' method, some portion of the text is replaced by an alternative portion, but only when the eye crosses a pre-defined, imaginary boundary placed at a particular position in the text (see Fig. 3, bottom).

These techniques are essentially 'perturbation' techniques: they perturb the information in parafoveal vision in various ways. The effect of these perturbations on eye movements (e.g., saccade size, fixation durations, gaze durations, total reading rate) are measured, and conclusions are reached concerning the kinds of information that are gathered by the eye at different eccentricities in parafoveal vision. For example, reading slows down when information about the length of words in parafoveal vision is removed by filling inter-word spaces outside the window by X's. Reading speed is not affected when the X's are further than 15 letters from the instantaneous fixation point. This suggests that word-length information is gathered up to 15 characters from the instantaneous fixation point: the perceptual span for word length is 15 characters. By doing other kinds of manipulations, such as replacing letters outside the window by letters that are more or less similar to the original letters, it is possible to deduce the size of the perceptual span for word shape or letter identity. A large number of studies have been done in this vein, and summaries of their results can be found in Rayner (1983) and Rayner and Pollatsek (1987). In the next paragraphs I will briefly sumarize the most important conclusions that were reached. But in the subsequent sections I will present some methodological and theoretical problems with these 'perturbation' techniques that have not been sufficiently considered.

One conclusion that has been reached about perceptual span is that there is not one perceptual span. Different spans are found, depending on the type of perturbation that is used. When gross features of the text, such as the position of the spaces that separate words, are perturbed, a large span will be found. When finer features such as individual letters are perturbed, a smaller span is found. This is coherent with the idea that different kinds of information can be extracted at different distances from the fixation point. Information about inter-word spaces can be obtained as far as 15 characters to the right of fixation (McConkie and Rayner, 1975; Rayner and Bertera, 1979; Rayner et al., 1981; Ikeda and Saida, 1978; Rayner, 1986). Word-shape information is no longer available beyond about 10 characters to the right of fixation (McConkie and Rayner, 1975; although see below for more on the problem of word shape), and information about specific letters is available no further than six to ten letters to the right of fixation (Underwood and McConkie, 1985; Pollatsek et al., 1986).

The size of perceptual span depends on the eye movement measure used. Fixation durations and saccade sizes are not affected when individual letters are perturbed beyond 8 letters to the right of fixation (Underwood and McConkie, 1985). Gaze duration is affected even when perturbations are 10 letters from fixation (Pollatsek et al., 1986). This kind of difference is reasonable when one considers that information takes time to be processed, and so the more subtle kinds of perturbations may affect more delayed eye movement measures such as gaze duration, which may include fixations occurring after the one in which the perturbation occurs.

The perceptual span appears to be asymmetrical, being greater on the right than on the left (the reverse is true for Hebrew; cf. Pollatsek et al., 1981). To the left of fixation, Rayner et al. (1980b) showed that the perceptual span extended to the beginning of the fixated word, or four letters leftwards, whichever was smaller. But to the right of fixation, Rayner et al. (1982) showed that perceptual span for individual letters went out to somewhere between 9 and 15 letters (also McConkie and Rayner, 1976; Rayner, 1986; although Underwood and McConkie, 1985, find a smaller value). Rayner et al. (1982) claim that to the right, perceptual span should be measured in letters, not in words. In addition, only the first three letters of the word to the right of fixation appear to facilitate the recognition of that word on the subsequent fixation (Rayner et al., 1980a, 1982).

A point related to perceptual span concerns whether the span can extend over word boundaries. Some controversy exists about this, since McConkie et al. (1982) present evidence that words in the parafovea are either completely identified or not identified at all, and that partial letter information can only be used if it enables the word to be completely identified. If not, processing must start anew on a subsequent fovealization of the word. However Balota et al. (1985), Inhoff and Rayner (1986) and Rayner and Pollatsek (1987) dispute the claim, citing various sources of evidence.

A further interesting point concerns the nature of the information about individual letters which is integrated from one fixation to the next. Whereas older studies (but considered now to possibly contain artefacts related to display changes; see section 2.2) had suggested that word shape played a role in information extraction (Rayner, 1975; McConkie and Rayner, 1975; Rayner et al., 1978), recent results show no effect of word shape (Inhoff and Rayner, 1986). In fact several studies have now conclusively demonstrated that letter features such as line segments or global shape are not integrated across saccades. Rather, letter information is transformed into an abstract code, independent of the letter's physical appearance, typography or case, and only this code can be combined across successive fixations. This is shown by the fact that facilitation from parafoveal preview of a word is equally strong when the letters in the previewed word have a different case in parafovea than when they are subsequently directly fixated by the eye (McConkie and Zola, 1979; Rayner et al., 1980a). Two other studies also show that shape information as such cannot be integrated across the saccade (O'Regan and Lévy-Schoen, 1983; Rayner and Pollatsek, 1983).

2.2. Technical issues in the moving-window and the boundary techniques

The moving-window and boundary techniques have been extensively used to measure visual span in reading, and certain authors (e.g. Rayner, 1975; Pollatsek and Rayner, 1987) claim that they are preferable to tachistoscopic and other methods which do not involve normal reading. There is no doubt that a large amount of converging evidence and excellent research has been assembled using these techniques over the past decade. However, several problems sometimes make interpretation of results difficult, particularly with one of the two techniques, namely the moving-window technique. The first kind of problems are technical problems related to apparatus delays and persistence of displays on the screen. Because these problems have not been treated extensively, I shall list them in detail in this section. The second kind of problem is actually much more important and fundamental than the technical problems, and concerns the question of what is really meant by 'perceptual span'. It will be the subject of the next sections.

The basic assumption in the use of display changes is that they have their effect because of the kind of information they are perturbing (spaces, letter shapes, letter identities), and not as a result of the flicker or contrast changes associated with the display change. Thus, researchers have gone to great pains to ensure that display changes occur during saccades, and not during fixations, where flicker and contrast change would be readily noticed. However, in some of the earlier studies, delays in the eye movement recording apparatus or in the time taken by the computer to change the screen were long, with visible display disturbances lasting up to an estimated 20 ms (Rayner, 1975) or 40 ms (McConkie and Rayner, 1975; O'Regan, 1979) after the saccade ended, and this could have accounted for a portion of the observed effects.

Even in the more recent studies, delays in the recording apparatus or in the screen-change algorithms cannot be totally discounted. For example, in the experiments of Rayner et al. (1982) and Inhoff and Rayner (1986), possible delay before display changes were accomplished was estimated at 5 ms, and in Rayner et al. (1981) at 2–10 ms following saccade termination. If slight flicker is visible after the saccade, this may act as a warning stimulus which modifies saccadic latency. Changes in the display may also affect sensory information extraction and thereby fixation duration. Of course, masking and suppression phenomena associated with the saccade probably minimize the perceptual effects of these disturbances, and this may explain why in most cases display changes using modern techniques are invisible to the reader. Unfortunately however, there is evidence that even a subliminal flash occurring near the end of a saccade can modify the subsequent saccade endpoint (Deubel et al., 1984).

However, even if it could be proved that the delay in the recording apparatus or in the screen-change algorithms was too small to be of visual significance, there is still an inevitable delay associated with the persistence of the screen phosphor. Even for the fast P31 phosphor used in most reading research, where luminance drops to 1% after only 0.25 ms, after this, luminance remains fairly constant for many tens of milliseconds (cf. Hewlett Packard Application Note 115). Whether this 1% level will be visible or not depends on the initial luminance level from which the drop occurred, on what the background luminance is, and on what is superimposed on the decaying trace. If nothing is superimposed, the decaying trace may still be visible, particularly if the background is dark and the eye is adapted to dim conditions. Thus, when a letter is replaced by a new letter on the screen, then the parts of the old letter that lie in the gaps of the new letter may 'shine through' slightly, and diminish the contrast of the new letter. Again, metacontrast and masking may render screen changes subjectively invisible, and this may explain why subjects are usually unaware of the changes. But, objectively, the disturbance to the display may nevertheless have contributed to the observed effects on reading behavior. There are many examples in the eye movement literature where this problem may have occurred. My own work provides a case in point: In O'Regan (1980) I observed that when information about the upcoming word in parafovea was perturbed by writing the word backwards, then when the eye subsequently fixated that word, even though the word has returned to normal, the fixation on that word was longer than when no perturbation occurred. I claimed that the effect was evidence that when there was no parafoveal perturbation, parafoveally gathered lexical information about the word could be used to preprocess the word, thereby shortening the subsequent fixation. However an alternative interpretation is that in the case of the parafoveal perturbation, the contrast of the letters of the fixated word was poorer than in the unperturbed case, and so processing took longer.

Another point concerning the effect of screen persistence on contrast is important to note: the greater the difference in shape between the perturbing letters and the original letters, the larger the resulting 'smear' on the screen will be. In studies where similarity between perturbing parafoveal letters and original letters is manipulated, for example when experimenters attempt to determine the extent of the perceptual span for different kinds of information, there is thus a potential confounding factor. Effects assumed to be caused by differences in the type of information integrated across the saccade (word length, word shape, individual letters) may in fact be due to physical differences in contrast arising from the residual persistence of the screen.

Leaving aside the possible difficulties associated with display changes, other problems are associated with the visibility of the material outside the moving 'window'. Older studies (O'Regan, 1979; McConkie and Rayner, 1975) and some of the recent studies (Rayner et al., 1980a, 1982; Inhoff and Rayner, 1986) have employed sequences of X's or 'interlaced square wave gratings'. The edges of such spatially extended, repetitive patterns are detectable far from the fixation point even when the quickest display-change techniques are used, because they form blocks of uniform texture easily discriminable from the pattern formed by the letters they replace. Particularly when whole blocks of text are read with the masks present, as has been the case in the studies just cited, subjects may adopt specific strategies such as aiming saccades at the edge of the window or at least modifying their saccade aim (see the center of gravity effect, section 3.1). Effects observed using such masks may be specific to them, and may give no information about the zone normally used in reading to extract visual information. The situation is even worse when masks are used foveally rather than peripherally (Rayner and Bertera, 1979; Rayner et al., 1981).

Even when types of parafoveal mutilation other than gratings or X's are used as the stimuli outside the central window, strategy effects may appear when subjects read several sentences at a time in a given condition of parafoveal mutilation. For example, Rayner et al. (1982) suggested that, contrary to the usual claim that perceptual span extends only a small distance to the left of fixation, when span is artificially restricted to the right, more use of material to the left can be made. This may also have a strategic explanation, since the different window conditions were run in blocked rather than mixed groups. Underwood and McConkie (1985), aware of the possibility of strategic effects, did an experiment where mutilations occurred only 20% of the time at random text locations, and found a somewhat smaller perceptual span than had previous research.

2.3. The problem of defining the 'perceptual span'

As noted by McConkie (1983), Well (1983) and Hogaboam (1983), studies of the perceptual span using the moving-window technique fail to distinguish possible momentary changes in the region attended to during a single fixation, and the possible variations in the size of the span at different points in a text. McConkie et al. (1985b) have also pointed out that conclusions are often based on differences in the size of effects caused by different kinds of windows. Different-sized effects may occur because they occur with different frequencies, or because they occur with different amplitudes. Underlying these two possibilities may be two quite different mechanisms, with different implications for eye movement guidance.

But the most serious limitation of the work using window and boundary techniques is the problem of definition. This problem overshadows by far the technical problems discussed above. Researchers have generally assumed that the window and the boundary techniques measure the 'perceptual span'. This is taken as the region in which letters can be identified, or at least the region which contributes to recognition and language-processing. But the window and boundary studies did not measure the perceptual span in this sense. Instead they measured the region of the text whose contents can affect eye movement guidance and reading rate. As already noted briefly by McConkie (1983), this may not be the same. The reason is that in reading, eye movements may be determined not only by perceptual span (in the sense of region of perceptual information extraction), but also by a more or less independent eye movement guidance strategy that keeps the eye moving across the text. Whereas word recognition and language-processing require the extraction of certain kinds of information (e.g., letter identities) from the visual field, the eye guidance process may require other kinds. The perturbations in parafoveal vision created by the window and the boundary techniques may interfere either with the language-processing or with the eye guidance process, or both. For the effects of an experimental manipulation to be interpretable, these possibilities must be distinguished. Unfortunately, in the studies using display changes up to now, this has not been done.

In order to demonstrate that 'perceptual span' in the sense of 'what can be seen in a fixation' is not the only factor determining eye movement guidance, the following sections suggest first a way of calculating and estimating the perceptual span based on psychophysical rather than oculomotor measures, and then of testing how the eye movements react to changes in the span. It will appear that psychophysically measured changes of perceptual span do not produce the expected changes in eye movement parameters.

2.4. Visual span

Before discussing the estimation of the perceptual span by psychophysical means, it will be necessary to define a precursor to perceptual span, namely what I call 'visual span' (O'Regan, 1975, 1979; O'Regan et al., 1983). The difference between the two types of span is that 'visual span' refers to what can be seen without the help of linguistic knowledge or context, whereas perceptual span includes what can be seen with that help.

Fig. 4A shows a tangential cross-section of the human retina, with the center of the fovea indicated by the cross on the left. The circles are the cones, and the black dots that start to appear beyond an eccentricity of about 1 degree are the rods. Super-

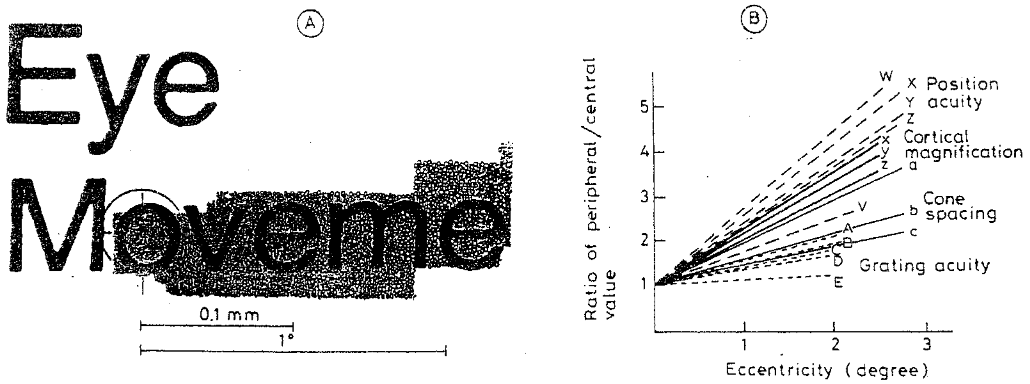

Fig. 4. A. A tangential cross-section of the human retina including the fovea, whose center (on the left) is indicated by cross-hairs. Small circles are cones; dots, appearing only beyond about 1 degree, are rods. The words 'Eye movement' are superimposed as they would appear on the retina when reading them in Vision Research at a distance of 30 cm (except they would appear upside down and in mirror image from). (Modified from O'Regan, 1989; Osterberg, 1935; Pirenne, 1967)
B. Ratio of eccentric to central values of various measures of resolution or cortical scale, as a function of eccentricity. Data compiled partially from tables given in Levi et al., 1985. Measures of grating acuity: A: Limb and Rubinstein, 1977; B and D: Levi et al., 1985; C: Westheimer, 1982; E. Wilson and Bergen, 1979, based on Hubel and Wiesel. Measures of position acuity: V: Jacobs, 1979, Landolt C without masking bars; W: Jacobs, 1979, Landolt C with masking bars; X and Z: Levi et al., 1985 (vernier); Y: Fendick and Westheimer, 1983 (stereoacuity); also Y: Klein and Tyler, 1981 (phase discrimination). Measures of cone spacing: a: Williams, 1988, using his moiré technique; also Williams' estimations from Osterberg, 1935; b: my estimation from the cross-section shown above, in A, also from Osterberg, 1935; c: Rolls and Cowey, 1970. Measures of cortical magnification: x: Dow et al., 1981; y: van Essen et al., 1984; z: Tootell et al., 1982.

imposed on the retinal mosaic is the image that would be formed by the words 'Eye movement' written in 8 point typography (as might be found in a journal article) viewed at 30 cm from the eye (each letter subtends about 10 minutes of arc), with the eye fixating the 'o'. If one defines the fovea as a zone of radius 1 degree around the optic axis, then the word 'movement' extends from the center to the edge of the fovea.

Although the letters shown are all within the fovea, they are being sampled by the retina in a dramatically different way. The 'o' being fixated centrally is sampled by a matrix of approximately 20 × 20 cones. The 'e', two letters from the 'o', is sampled by a matrix of approximately 15 × 15 cones, and the 'e' two letters further on is sampled by only 10 × 10 cones. Thus: four letters from the fixation point, but still well within the fovea, resolution has dropped to half its central value. The non-homogeneity of the retina is of course well-known physiologically and psychophysically, where an approximately linear increase in cone spacing or, equivalently, minimum angle of resolution, is observed up to eccentricities of about 10–14 degrees. However, the non-homogeneity exists even within the fovea. Some debate centers on the question of the actual rate of increase with eccentricity: in particular it appears that cortical receptive fields increase in size faster than cone spacing does. As suggested by Levi et al. (1985), this may explain why acuity measurements requiring position judgements, such as optotype or vernier acuity, give faster rates of drop-off than simple psychophysical tasks such as detecting gratings. Fig. 4B illustrates these ideas by plotting, for physiological and psychophysical measurements made at different eccentricities, the ratio of the eccentric value to the central value. The important point to be made from the figure is that, for all measures, the data fall on straight lines. Thus, sampling of the visual field at eccentricity Φ can be considered to take place at a sampling interval which is larger than sampling at the retinal center by a scale factor of $(1+m\Phi)$. Here, m is a constant between about 0.3 and 2, depending on which data you observe. If the scale factor for cortex and position acuity is used, which is reasonable for reading, then m is about 1.7 (when Φ measured in degrees; this gives m = 100 when Φ is measured in radians). Grating acuity and retinal cone spacing would give values around 0.5. The notion that parafoveal and eccentric vision can be considered a 'scaled-up' version of vision at the center of the fovea will be developed below.

In addition to the dramatic constraint on visibility imposed by the fall-off in retinal and cortical sampling rates, a further, very strong constraint is imposed by lateral interactions. As an illustration of this, consider the following example taken from Bouma (1978):

. v
. ovo
. xvx
. x v x
. vs
. sv

In the first line, if you fixate the central fixation point, it is fairly easy to identify the letter 'v' in the right parafovea. However, in the second line, when the 'v' is laterally flanked by other letters, identification becomes harder. Identification is even harder if the flanking letters have similar features to the target letter (third line). The phenomenon extends over fairly large retinal distances (about 0.4 Φ, where Φ is the target letter's eccentricity; cf. Bouma, 1970; Andriessen and Bouma, 1976), as shown by the fourth line. A further interesting fact is illustrated in the last two lines: it is easier to see a letter, here the 'v', when it is flanked by another letter on the foveal side than on the peripheral side (for studies of this curious asymmetry, see Chastain, 1985).

Most authors have argued that lateral interaction cannot be explained purely from the drop-off of resolution in parafovea, since it is hard to see how this would predict the large zone of interaction, the increased effects for similar letters, or the counter-intuitive fovea/periphery asymmetry. A higher-level explanation appears necessary. Krumhansl and Thomas (1977) suggested the existence of feature-specific interference, plus the idea that features tend to migrate towards the fovea. Detailed models have been proposed by Estes (1982), Wolford and Shum (1980) and others. However, it is also possible (O'Regan, 1989) that a contribution to the effects comes from the inhibitory part of the psychophysical point spread function (e.g., Blommaert and Roufs, 1985, or the N channel postulated by Wilson and Bergen, 1979). In any case, to get the effects over large retinal distances it must be assumed that in eccentric vision the cortical scale factor of about (1+1.7Φ), rather than the smaller retinal scale factor, should be applied compared to central vision.

In order to permit simple modelling of the effects of acuity drop-off and lateral interactions on reading, it is convenient to lump them into a single measure, which might be called 'effective' resolution. Jacobs (1979) had compared acuity in peripheral vision for ordinary Landolt C's to acuity for Landolt C's flanked by bars. As expected from lateral interference, resolution was worse for the flanked targets than for the unflanked targets. Nevertheless the recognition of flanked targets still followed a linear function of the form:

$$r' = r_0' (1 + m\Phi)$$

where r' is the effective resolution at eccentricity Φ, r_0' is the effective resolution in the center of the field, and m is the scaling parameter; m is about 2 in Jacobs's data. Thus, in this case, a single simple expression sufficed to express the effects of both resolution and lateral interactions. Now, in general, when the flanking elements differ or are at different distances from the targets, the value of r_0' may differ. But, again, under the assumption that the properties of peripheral vision are simply a version of the properties of central vision scaled by the factor (1 + $m\Phi$), the function will remain linear.

With these assumptions it is possible to calculate how many letters should be visible on each side of the eye's fixation point in a text, that is, the 'visual span'. To make the calculation, it is necessary to make some assumption about the size of the smallest featural elements which allow the characters of a

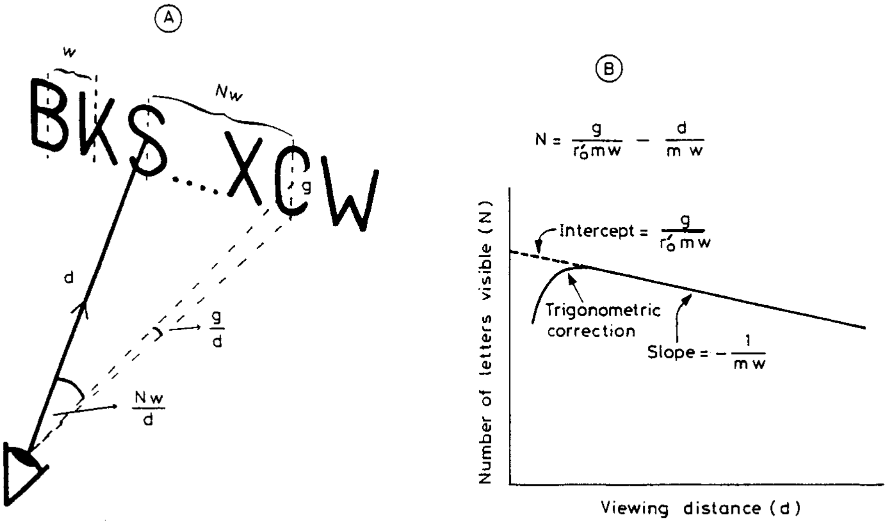

Fig. 5. A. Illustration showing how to calculate how far from the fixation point a letter can just be recognized. Assume the eye is looking directly at the letter S, from a distance d. Suppose the distance from letter to letter is w, and that, for them to be recognized, distinctive elements with characteristic size g (the 'grain size', measured in linear units, e.g., centimeters) must be resolved. Suppose the Nth character can just be recognized. Then at the eye its distinctive features of size g subtend an angle of approximately g/d radians, and project on the retina at an eccentricity of approximately Nw/d radians. Effective resolution (which includes masking phenomona, see text) at this eccentricity is $r_0' \cdot (1 + m\Phi)$. If this is just sufficient to resolve the distinctive features of the letters, we must have: $g/d = r_0'(1 + m\Phi)$. This gives $N = g/(r_0'\ mw) - d/mw$, which is plotted in B. This relation applies only for small angles, and a trigonometric correction, necessary when d is small, is shown on the left-hand portion of the curve.

given typography to be distinguished from one another. Characters in a given typography differ, but one can define a parameter, g, which is the average resolution necessary to make all distinctions between the characters. I call g the 'grain size', in analogy with photographic grain. Factor g will depend on the particular typography, and, since it must include lateral interactions due to flanking letters, it will depend on the particular flanking letters and spacing. On average it will be of the order of some fraction of the character size. Note that grain might naturally be defined as an angular measure: that is, it would be related to the average angle subtended at the eye by the distinctive elements of the typography. However, this definition would have the disadvantage of making the grain change when the viewer changes his distance from the text. For this reason I prefer to use a definition in terms of the size, in *linear* units, for example centimeters, of the letters' distinctive features. This ensures that 'grain' is a characteristic only of the typography, and not of the viewer. Of course, the resolution needed to recognize letters viewed from a particular viewing distance, d, can be obtained by calculating the angle subtended by the grain, that is g/d radians (for d large compared to g).

Fig. 5 shows how to obtain theoretical predictions of the number of letters visible as a function of the eye's distance from the text. The calculation predicts that there should be an optimal value of the viewing distance, where the largest number of letters can be seen. When you move closer to the text than this optimum, the number of letters drops rapidly. However, when you move further away from the text, the number of letters also drops, but relatively slowly. The rate of drop-off should be $-1/mw$, where w is the character width and m is the parameter in the cortical scaling factor. Inserting the typical values $m = 100$ per radian and $w = 0.3$ cm, the prediction is that you should see one character less on either side of the fixation point for every 30 cm you move away from the text.

(Note that changing viewing distance is exactly equivalent, from the point of view of the retina, to

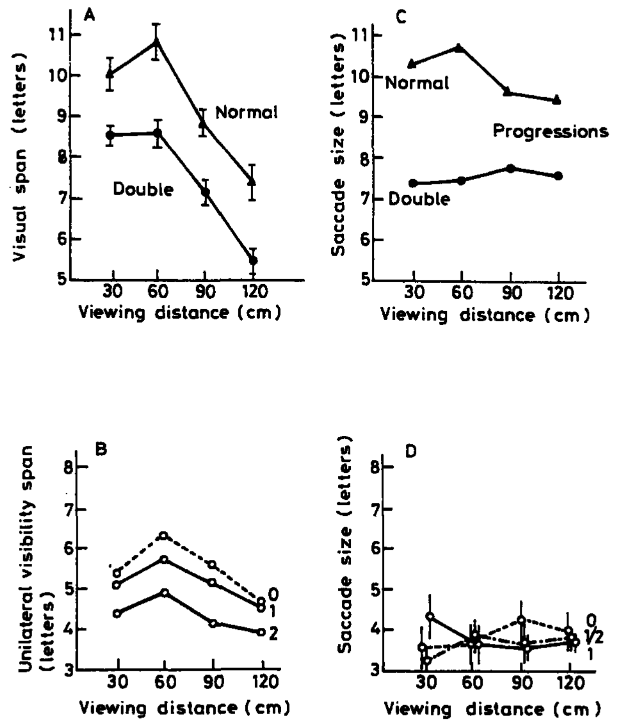

Fig. 6. A. Means and error bars (showing two standard errors on each side of the mean) over four subjects of empirically measured (unilateral) visual span, i.e., number of character spaces from the fixation point at which letters can be seen with 50% chance of being correctly reported, as a function of distance of the eye from the screen. The letters were lower case, and defined within an 8 × 8 matrix of pixels approximately 0.3 cm square. They were presented flanked on each side by a random numeral between 1 and 9. The letters were taken from a set of only ten possible letters. In the 'DOUBLE' condition, each letter (and numeral) contained additional white space on either side of it, so when words were written in the DOUBLE typography, they appeared doubly spaced as compared to the NORMAL condition. (From O'Regan et al., 1983)

B. The same as A, except a different letter set, upper-case letters, and different subjects, and using three degrees of spacing flanking each letter: 0 (equivalent to NORMAL in A), 1 (equivalent to DOUBLE) and 2 ('triple' spaced). (From Lévy-Schoen et al., 1984)

C. Mean progression saccade size made by the same four subjects as in A, reading texts printed in the same typographies as in A (but using all letters of the alphabet). Saccade size is measured in letter-spaces, so in the DOUBLE condition one 'letter-space' was twice as wide as in the NORMAL condition.

D. Mean progression saccade size made by the same subjects as in B, searching for the letter 'B' in lines of random letters taken from the set used in B. Three spacing conditions were used: 0 and 1, corresponding to 0 and 1 in B, and condition 1/2, with half as much spacing as 1.

changing character size. The same arguments above apply therefore.)

The small dependence on viewing distance (or character size) can be understood intuitively in the following way: suppose you move twice as far from the text. Characters now subtend an angle twice smaller, but they also move twice as close to the center of the visual field, where, because of the linear dependence with eccentricity, resolution is twice better. The characters therefore remain equally visible. (One can show that this argument would be exactly true if the minimum angle of resolution at the eye's center were zero. Since it is not, a slight drop-off with viewing distance is predicted. This corresponds to the right-hand sloping portion of the curve in Fig. 5B).

Fig. 6A,B shows some empirical data, which agree well with the predictions. An optimal viewing distance at about 60 cm is found, and a drop-off of about 1 character per 30 cm of viewing distance increase. The number of characters visible indicated in the data is the number of characters visible at a recognition criterion of 50%. The data show that, depending on the experiment and the conditions, about 3–11 characters were visible at this level of accuracy or better on each side of the fixation point. Several points should be noted about this number. First, had a 90% accuracy criterion been used instead of a 50% criterion, the estimate would have dropped considerably, to about 2–5 letters, depending on conditions. Second, in the experiments performed to obtain these data, only ten test letters rather than the whole alphabet were used. Third, the test letters were laterally masked by only a single flanking character on each side, rather than a whole string of flankers. For these reasons the present estimates are somewhat larger than the visual span in normal reading. Nevertheless, the dependence of the obtained values on viewing distance will not be influenced by these provisos, and I will use these curves in the next section as a basis for comparison with data on saccade size in reading and in visual search.

A more direct estimate of visual span, albeit without investigating the effect of changing viewing distance, can be found in the data of Townsend et al. (1971), who trained (with difficulty) three subjects to report letters in a letter string without moving their eyes. These authors found that the limit of 50% accuracy was attained at 5 letters from the fixation point using characters of size 1/3 degree, which is half-way between the angular size of our letters in the 30 cm and 60 cm conditions. This shows again that surprisingly few letters can be seen in normal reading conditions, where lateral masking is strong. I have recently confirmed this result using a method where, through an eye-contingent display technique, a string of letters is effectively stabilized at a given retinal location despite small eye movements. Work using brief displays also shows that only a few letters can be reported accurately around the fixation point (for an excellent review of studies on the recognition of letter sequences, see Estes, 1978).

2.5. Perceptual span as distinct from visual span

Visual span being so small, how is it then that when we look at a word, we have the impression of seeing the whole word, and not just the few letters being fixated directly? One factor is certainly the fact that eye movements can occur in the word. This will be considered later. Another factor is lexical knowledge. When characters form words, lexical constraints may help to disambiguate letters that cannot be properly seen, and the total span of perception may increase. The effect of lexical knowledge on word perception has been known since the work of Cattel (1885) and Erdman and Dodge (1898), who showed that while only a few letters could be reported in tachistoscopic presentations of random letter strings, whole words and sometimes groups of words could be reported. It is thought now that the effect of lexical knowledge is a truly perceptual effect, not just an effect of conscious guessing. Excellent reviews of recent theories can be found in Carr (1986) and Henderson (1982). The following example illustrates the effect: if you fixate at the arrow in the top sequence of letters you will only be able to report about 3 letters on either side. But in the same sequence of letters written in reverse order, you have the impression of seeing all the letters clearly!

YCNADNUDER
↑

REDUNDANCY
↑

The importance of knowledge and context in recognition creates the need to distinguish what can be seen without its help from what can be perceived with it. I will call what can be seen without making use of lexical knowledge and contextual constraints the 'visual span', and what can be perceived by additionally making use of them the 'perceptual span' (the idea is that 'perception' is 'vision' plus knowledge). The perceptual span will be larger than the visual span by an amount which will depend on the strength of the lexical constraints: for example, the internal statistical structure of the individual words, and, at a higher level, the predictability of the words within the surrounding text.

Exactly how much bigger will perceptual span be than visual span? For the purpose of the argument to be made below, I do not need to know the exact answer; rather, it will be sufficient to make the reasonable assumption that for a given reader, reading a given text, on average, the relation between visual span and perceptual span is a fixed monotonic function such that perceptual span is greater than visual span. The simplest such function would assume that perceptual span is a constant multiplicative factor k times visual span, where k is greater than 1. The exact function is unimportant; what is important is that the function is a measure of the disambiguation power of linguistic and knowledge constraints, and so depends only on the text being read (which may provide stronger or weaker constraints) and the reader (who may be better or worse at making use of these constraints), but which cannot depend on the physical characteristics of the text such as its typography, the letter spacing, or the reader's distance from the page.

2.6. No simple relationship between perceptual span and saccade size in reading

In this section I return to the question of the relationship between perceptual span and saccade size. As implied in previous eye movement work, a tempting hypothesis to make about saccade size in reading is that the eye moves in such a way that (at least on average) the right edge of each perceptual span just coincides with the left edge of the next span (or overlaps with it by a constant amount). Under this 'perceptual span control' hypothesis about eye movement guidance in reading, manipulations in perceptual span should provide analogous changes in saccade size. Certainly in the literature on perceptual span (see sections 2.1, 2.2) changes in window size have always provoked approximately the expected changes in saccade size, with the smallest windows provoking the smallest saccades. But are the changes exactly those which would be expected under 'perceptual span control'? Given that we now have a way to estimate visual span and perceptual span, we can now test this more precisely by manipulating perceptual span in a known way, and seeing whether saccade sizes change in the expected manner.

The data in Fig. 6A estimate the visual span under conditions of different viewing distance, and for two different typographies, which I call 'normal' and 'double' spaced. If saccade size is proportional to perceptual span, and perceptual span is proportional to visual span, then saccade sizes should follow curves similar to the visual span curves. Fig. 6C shows saccade sizes for exactly the same subjects reading texts from the same viewing distances and with the same typographies. The curves for normal and double typographies are separated by 2–3 letters, which is consistent with the two-letter difference in visual span between these two conditions. However, the curves do not have the expected dependence on viewing distance: they are approximately flat, rather than changing by 4 letters over the range 60–120 cm as do the visual span curves.

It might be thought that the data could be explained if the relation between perceptual and visual span were a more complex function than simple proportionality. But this is not so. Any function relating visual span to perceptual span must be single-valued; that is, a given visual span must always give rise to the same perceptual span (if the reader and the text content is kept constant as was done here). Yet in the data there are cases where the same visual span provokes very different saccade sizes: for example, visual span is similar for the double-spaced typography at 60 cm and for the normal-spaced typography at 90 cm, yet the associated saccade sizes in reading are very different.

To account for the lack of correspondence between perceptual span and saccade size, we have previously suggested (O'Regan et al., 1983) that perhaps saccade size is determined partly also by linguistic factors. However, it is difficult to imagine how linguistic factors could have been the cause of the differences in saccade sizes that occurred when there were no visual span differences, since the subjects and texts (and therefore linguistic and context factors) were strictly the same.

Further experiments also discount linguistic factors as a sole explanation. In these experiments (Lévy-Schoen et al., 1984), we reasoned that if linguistic factors were the explanation for the incompatibility between visual span and saccade size changes, then, in tasks where linguistic factors were reduced to a strict minimum, visual span and saccade size should fall into step with each other. We used a task of searching for a target letter 'B' hidden in lines of random nontarget letters – assuredly a task requiring minimum linguistic processing. Fig. 6B shows the measured visibility span for letters in three spacing conditions (0, 1 and 2 blank characters between letters). Fig. 6D shows the saccade sizes observed in the similar conditions in the search task (note that only spacings 0 and 1 were common to both experiments). There is no correspondence between the two sets of graphs. The results seem again to show that something is wrong with the perceptual span control hypothesis, but we cannot be absolutely sure here, since the saccade sizes were not sensitive at all to the manipulations of spacing in this experiment: this time we cannot exclude the possibility that the relation between visual and perceptual span is more complicated than simple proportionality. However, in a third set of experiments, Jacobs (1986a,b) also directly adressed the question of the validity of the perceptual span control hypothesis in visual search. Although he concludes that overall there is a correspondence between perceptual span and saccade size, closer examination of his data shows exactly the same difficulties as in the earlier experiments we did: whereas changing visual span by one kind of manipulation (in his case by changing target-background similarity) creates a given change in saccade size, changing visual span by the same amount but through a different manipulation (e.g., by changing viewing distance or letter spacing) may give no change at all in saccade size. Similar observations apply to a study by Heller (1987), who varied letter size and spacing.

Since linguistic factors do not account for the incompatibility between saccade size and perceptual span, what other possibility exists to salvage the perceptual span control hypothesis? One possibility might be to take into account fixation durations: perhaps the amount of material that can be processed depends in a combined way both on the perceptual span and also on the time the eye stays at each fixation. For example, there might be an inverse relation between perceptual span and fixation duration: perceptual span might be smaller when fixation duration is short (see Jacobs, 1986, for other possibilities). It is certainly true in the studies discussed above that when changing the perceptual span produced no effect on saccades (e.g., for viewing distance changes), then fixation durations were affected (e.g., in Lévy-Schoen et al., 1984). However, as shown in a further study we did (Jacobs and O'Regan, 1987), this still leaves open the question of why under some circumstances saccade size reacts, under some circumstances fixation durations react, and under some circumstances both react to perceptual span changes. Also, in that study we found no evidence for an inverse relation between span and fixation duration. If there were such a trade-off on average in reading, one would expect that saccade size would be inversely correlated with preceding fixation duration. Neither we nor several other authors have found such correlations over large bodies of text (Andriessen and de Voogd, 1973; McConkie and Zola, 1984; Rayner and McConkie, 1976), although locally they may be found (Pollatsek et al., 1986).

The conclusion is that perceptual span does not determine saccades in reading and search in any simple way. So what does? In the strategy-tactics theory to be presented in section 6, the eyes are guided by a general scanning strategy, based mainly on gross visual characteristics of the text (not on perceptual span). To simplify: in reading, the eye moves from word to word, independently of how well words can be identified in parafoveal vision. Changing viewing distance thus changes nothing in this strategy, and no effect on saccade size is expected. Changing spacing, however, can have an effect on the visibility of the inter-word space, and thus may render inter-word aiming more or less difficult. This probably accounts for the fact that saccade sizes were smaller (measured in letters) in the double-spaced conditions of O'Regan et al. (1983).

2.7. Letters are the right units to measure saccades

One noteworthy point concerning all the experiments just discussed, as well as the results of Morrison and Rayner (1981), Javal (1878), Lamare (1893) and Huey (1908), is that viewing distance and letter size (cf. Heller, 1987; Tinker and Paterson, 1955) always has almost no effect on saccade size (when this is measured in letters). As explained above, this result is *approximately* predicted from perceptual span measurements and theoretical calculations. But unfortunately it is not *precisely* predicted, nor is it consistent with the results of other visual span manipulations. Nevertheless the result is a good reason for measuring saccades in letters rather than in degrees. It is amusing that ever since Javal, researchers have justifiably measured saccades in letters, but all the time without being aware of the underlying mystery.

3. Oculomotor constraints: spatial factors

Oculomotor constraints of different kinds may affect the way the eyes behave in reading. There may be spatial constraints, determining the accuracy with which the eye can attain a target, and temporal constraints, determining the latencies preceding saccades, and there may be interactions between the two. Temporal constraints in the oculo-motor system have received some attention in the reading literature (cf. Russo, 1978; McConkie, 1983) because there has been doubt about whether the apparently ponderous machinery necessary for saccade programming could actually leave any time for higher-level linguistic processing to influence the parameters of the immediately following saccade. Section 4 will consider the temporal constraints. However, recently, with the discovery of the 'center of gravity' effect to be described below, it has become apparent that spatial constraints can also be quite stringent in determining eye guidance in visually complex scenes.

3.1. The 'center of gravity' effect and a conceptual model of saccade programming

It is frequently said that saccades tend to undershoot a target, typically by about 10% of the target's eccentricity (Frost and Pöppel, 1976; Henson, 1978; Deubel et al., 1986). But this classical assertion applies to saccades made to an isolated target, that is, a target which can easily be seen within its surroundings. Recent work has shown that if a target is surrounded by other material in the visual field, then the eye's landing position will be deviated to a sort of 'center of gravity' of the the whole visual configuration around the target (Coren and Hoenig, 1972; Findlay, 1981, 1982, 1983; Ottes et al., 1984; Deubel et al., 1984, 1988; Coëffé, 1986; Coëffé and O'Regan, 1987). Thus, in Fig. 7A, the eye will have no trouble saccading to the target letter marked by crosses when it is present alone, but it will overshoot or undershoot it in the other examples because of the influence of the adjacent letters.

The phenomenon, which has also been called the 'Global Effect' (Findlay, 1983), can be conveniently explained by a model of saccade target selection which was proposed by Findlay (1983, 1987) and Deubel et al., (1984) and has been made most explicit by Coëffé (1987). There are two ideas behind these models. The first is that the visual processing which determines saccades must pass through the same stage of relatively slow spatio-temporal filtering that determines visual pattern recognition in general. The second is that two independent processes determine saccade generation: saccade triggering and saccade computation.

Saccade *triggering* is done by an external event which is independent of the saccade computation mechanism. At any moment, if a triggering signal occurs, the saccade will depart to the target location indicated by the current state of the ongoing saccade computation. Triggering can occur on the basis of visual information such as the visual transient produced by target onset, by visual recognition of some aspect of the target, but also on the basis of a non-visual event which is not related to the target onset, such as an auditory signal, the completion of some kind of cognitive processing of simply a voluntary decision. If (as for anticipatory saccades) the triggering signal occurs very early, before visual information has been properly analysed, the saccade will depart to an incorrect position or to a position determined by prior expectations.

Saccade *computation* is done continuously and automatically on the basis of the available visual information (Deubel et al., 1984), but is also modulated from moment to moment by attentional mechanisms (Coëffé, 1987). The saccade computation process is going on continuously without supervision, so that if a triggering signal occurs at any moment, the saccade will depart to the endpoint which is currently active. The visual information used in updating the saccade endpoint computation is assumed to come from low-level visual spatio-temporal filtering operations (possibly also involving texture-sensitive mechanisms; cf. Deubel et al., 1988), so its spatial extent and time course depend on the spatial and temporal characteristics of the

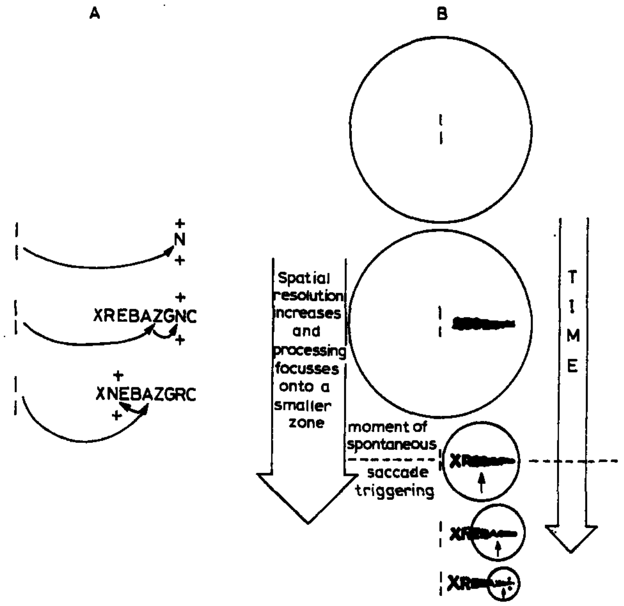

Fig. 7. A. Typical eye behavior observed by Coëffé and O'Regan (1987) on attempting to saccade to a target letter marked by crosses. If the letter is alone, the eye attains it after the primary saccade. If the letter is in a string of other, non-target, letters, the primary saccade will generally go to near the center of gravity of the whole string, and a correction movement will occur, bringing the eye on to the target.

B. Example of the course of excitation in a hypothetical sensory map of the visual field when saccading to a target as shown in A. The top circle is the zone of 'attention', which is initially large, and centered on the fixation mark. A moment later, a stimulus string appears on the right, but, because of spatio-temporal filtering in the early stages of the visual system, only a crude, low spatial frequency representation is at first available, so the letters cannot be distinguished. The representation is also distorted by cortical magnification, so the more peripheral parts of the stimulus are smaller and less clear. A moment later, the attentional circle has shifted and narrowed down to the general region of the stimulus. But since information as to the position of the crosses (indicating the target location) has not yet become available, the attentional circle can do no better than move to somewhere near the center of gravity of the whole configuration. With time, the crosses become visible, and the attentional circle can shift further rightwards and narrow down further to the region of the crosses, and the target letter becomes identifiable. As these processes occur, saccade coordinates are being continually calculated and updated. The endpoint being calculated at any moment is assumed to be the center of the attentional circle. If a signal to trigger a saccade happens to be given at the moment indicated by the horizontal dotted line, then the saccade will go to the place in the string shown by the small arrow. But if saccade triggering occurs later, the saccade will go further into the string, as shown by the arrows in the bottom two circles. The moment of saccade triggering is determined by independent processes, not shown on this diagram. They may depend on visual, but also cognitive processing, as well as on expectations, or even auditory or other stimuli. (From Coëffé, 1987)

filters. For example, immediately after target appearance, the information available about the target will be perturbed by transient phenomena, and accurate representation of the target will only appear after a certain integration period. Information of high spatial frequency will be available later than information of low spatial frequency. The temporal impulse response of the filters has been determined by Deubel et al. (1984), and shown to extend over a relatively long period of over 200 ms. The attentional mechanisms modify the way visual information is extracted, accelerating processing in the zone which the viewer is interested in. If the viewer has expectations about the target location, target extraction will be easier in the expected zone.

To illustrate how this conceptual framework explains the center of gravity effect, consider its operation in the situation of Coëffé and O'Regan (1987), where the eye starts at a central fixation point, and a string of letters appears in the left or right parafovea, at different eccentricities. The observer's task is to make a saccade to the letter in the string which is marked above and below by crosses, as shown in Fig. 7A.

Fig. 7B shows the sequence of events that will occur. The figure depicts successive states of excitation in a hypothesized sensory map in the brain. Before the stimulus appears, the sensory map is empty except for the fixation point, and the region being attended to, indicated by the large circle, is evenly distributed around it (top of figure). When the stimulus appears in parafoveal vision, activation builds up in the part of the map corresponding to the stimulated retinal location. The build-up of activation is represented by the increasing resolution of the image, with the idea that high spatial frequency information becomes available later than low spatial frequency information. In order to show the effect of reduced resolution in parafovea, the

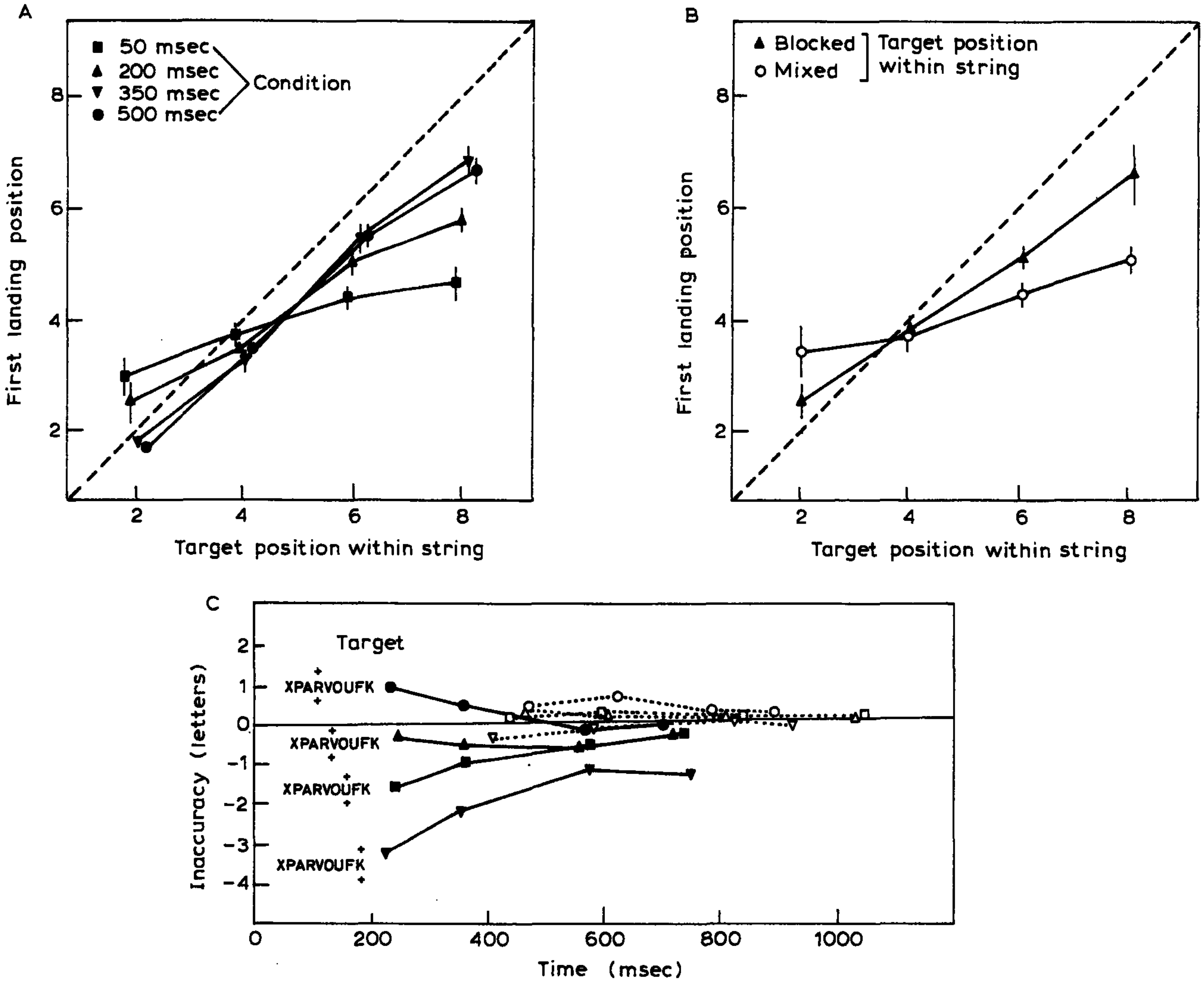

Fig. 8. A. Accuracy of primary saccades, meaned over 4 subjects, in attaining a target letter marked by crosses in a string of 9 letters, as shown in Fig. 7A, lower two examples. The task was to determine whether the target letter was a vowel or a consonant. The crosses appeared in random order at the 2nd, 4th, 6th or 8th letter position, the 8th being the most eccentric. The target string could occur in the left or the right visual field, with its least eccentric end starting at 8 or 16 letter spaces from the fixation mark. The ordinate gives the landing position in the string of the primary saccade, as a function of the target position on the abscissa. Data points with perfect accuracy would lie on the dotted diagonal line. The four curves correspond to four different latency conditions, in which the eye was detained at the intial fixation mark for varying amounts of time before being allowed to make the saccade. The eye was kept at the fixation position, despite the fact that the target string was already visible, by asking subjects not to make their saccade until the target mark disappeared. Disappearance occurred either 50, 200, 350 or 500 ms after the onset of the stimulus string. (From Coëffé and O'Regan, 1987)

B. The same as A, but comparing two conditions, one in which the crosses appeared randomly in one of the four positions in the string (mixed condition), and one in which the location of the crosses was always the same, so that at each trial, once the subject had located the side and eccentricity of the whole stimulus string, he knew where to look within it to find the target letter (blocked condition). (From Coëffé and O'Regan, 1987)

C. Solid curves: position that the eye has reached after a primary saccade at various moments following stimulus onset, on abscissa. Data points with perfect accuracy would lie on the horizontal line at ordinate 0. Dotted curves: position that the eye has reached after a primary and secondary saccade at different moments following stimulus onset. It can be seen that for target letters at positions 4, 6 and 8 within the stimulus string, after 400 ms the eye is closer to the target if it makes two saccades than if it makes only a primary saccade with 400 ms latency. (From Coëffé and O'Regan, 1987) stimulus is shown as deformed according to cortical magnification. As time progresses, higher- and higher-quality information becomes available in the sensory map, and the crosses become distinguishable: attention begins to direct itself onto this target region of the string. It is assumed that during this process of 'zooming in' and improving the resolution of information at the target location, potential saccade parameters are being continuously updated so that if the triggering command for a saccade is given, the saccade will go to the current center of attention, shown at the center of the circles in the figure. If triggering occurs early, accuracy will be poor, and the eye will go to the center of gravity of the whole visual configuration. If triggering occurs late, accuracy will be good, and the eye will go very near to the target.

The moment at which the saccade will be triggered will depend on processes independent of the 'zooming in' process. It may depend on cognitive processing of the visual information gathered, but it may also be determined by some other event necessitating little or no processing of the visual field, such as a tone that is heard or a rhythmic strategy adopted by the subject. It is seen from the figure that if the moment of saccade triggering occurs at the instant indicated by the dotted line, then the saccade will not attain the target accurately, but will go to the center of gravity of the (distorted) configuration. The center of gravity effect is explained.

It is important to stress two points about this model. The first point concerns the 'attentional' mechanism. Attention is a topic which has recently been accumulating an immense literature in experimental psychology. However, saccadic eye movements are rarely incorporated into this literature (though see Engel, 1971; also Groner, 1988, for a review, and Ch. 1 of this volume). The present rudimentary model has obvious similarities with 'zoom-lens' models (Eriksen and St. James, 1986) and 'spot-light' models (Norman, 1968; Posner, 1980; Shulman et al., 1979), but its details must be further developed before a comparison would be of interest. Meanwhile the model has constituted a sufficient framework from which to predict certain latency and expectancy effects that modulate the center of gravity phenomenon, as shown below.

The second point concerns the resemblance of the present scheme to the WHEN and WHERE mechanisms of Becker and Jürgens' (1979) often-cited model. However, the similarities are misleading, because Becker and Jürgens actually have two WHERE mechanisms: one that decides which side the target is on, left or right, and one which calculates the saccade amplitude. This latter mechanism is also not independent of the decision to move, since it is assumed to contain a temporal averaging window that only starts averaging after the decision to move has occurred. Further, the WHEN decision is determined purely by the retinal error signal, which is after all another kind of WHERE information. Thus, in Becker and Jürgens, WHEN and WHERE mechanisms are actually somewhat intertwined, whereas we suggest that they are completely independent. Another difference between the models is that in our case the spatial averaging that explains inaccurate saccades in the center of gravity effect (and also in double-step paradigms) comes not from a mechanism specific to the saccadic system, but simply from the early stages of the visual system, which is assumed to be continuously and automatically spatio-temporally filtering information as it falls on the retina. Finally, unlike Becker and Jürgens, in our model we assume that the WHEN decision is not triggered by the retinal error signal, but is based on a variety of kinds of information, including in particular non-visual information and voluntary decisions.

3.2. Latency and expectancy effects on the center of gravity phenomenon

The above model explains the data on the center of gravity effect, that is, the fact that the eye tends to be deviated towards the center of gravity of the visual configuration. In addition, two predictions can be made.

First, the deviation towards center of gravity should diminish when latency increases, since visual processing then has time to 'zoom in' closer to the true target position, and is less affected by the surrounding material. Indeed, Findlay (1981) has already shown that the center of gravity effect became less pronounced for longer-latency saccades, but the effects were weak owing to the fact that only a small range of latencies generally occur naturally. Coëffé and O'Regan (1987) and Jacobs (1987) therefore artificially increased the range of latencies by asking subjects to voluntarily delay their saccades until a central signal disappeared, or by giving subjects a simple perceptual task to do at the fixation point. We confirmed that saccade accuracy considerably improves at long latencies (see Fig. 8A).

It is also interesting to consider the literature on eye movement speed-accuracy trade-off in the light of the present model. Cohen and Ross (1978), Viviani and Swensson (1982), Findlay (1983), Kapoula (1984) and de Bie et al. (1986) have sometimes observed speed-accuracy trade-offs, but they have been weak for another reason. The reason is that the effect of latency on saccade accuracy will depend on the visual complexity of the target configuration. A single, isolated target has the same center of gravity when it is seen at low resolution in the early stages of processing as later, when higher resolution is available. This is not true of a target embedded in other material, since at early low-resolution stages of processing the target will not yet be isolated from its surroundings, and the center of gravity will include the whole configuration. Speed-accuracy trade-offs will thus only be strong for complex stimulus configurations.

A second prediction made by the present model is that the center of gravity effect should be weaker if visual processing can determine the target location rapidly: this would occur if the target is easy to isolate from the surroundings, but particularly also if its position is predictable in advance from coarse visual information, for example if it always occurs in the same place relative to some mark that can be localized using just coarse cues (e.g., the 'blob' constituted by a string of characters).

We have indeed confirmed that saccade accuracy improves in conditions where the subject knows in advance within the string where the target letter could occur (even if the string itself can occur at different places in the visual field) (Fig. 8B; Coëffé and O'Regan, 1987).

Apart from our study, evidence in the literature of the effect on saccade accuracy of prior knowledge about target position is scarce. Instead, work has concentrated on the effect of number of target alternatives or prior knowledge of target position on saccade latency, where no coherent picture emerges (cf. Heywood and Churcher, 1980). However, this is to be expected from the present theory, since we postulate that the time needed for target extraction will depend not just on the visual configuration, but also strongly on non-visual, task and strategy-specific factors.

3.3. Implications of the center of gravity phenomenon for saccade accuracy in reading

The importance of the center of gravity effect for reading will become apparent later in this chapter, after it is shown that each word has an 'optimal viewing position' where it is best to fixate. The question then arises of whether the eye will be able to accurately land on this optimal position: in particular do the surrounding words create a visual configuration that will deviate the eye from the desired position? How much time will be required before moving in order to get the eye accurately to the desired position?

With respect to the first point, note the following. In order to explain the Coëffé and O'Regan (1987) data, we found it necessary to assume that the sensory map is distorted in such a way as to give greater weight to stimuli that are near the center of the visual field. This is consistent with the concept of cortical magnification (Rovamo et al., 1978; Schwartz, 1980; Levi et al., 1985; Cavanagh, 1978), according to which the cortical area attributed to visual processing continuously diminishes as we move away from the center of the field. The implication of this for reading is that when the eye attempts to attain a target in the next word, the presence of words beyond that word will not strongly affect the saccade's accuracy (unless the current word is very short). I have confirmed this in my laboratory, by comparing saccades towards isolated words versus saccades towards pairs of words. I find that the presence of a word beyond the target word increases saccade size by at most half a letter, and only for the shortest (5-letter) words that I used. However, further work needs to be done on even shorter words, and also to explain some effects observed by McConkie et al. (1988) concerning the influence of the eye's starting position (see section 7.2).

With respect to the second question, namely of the time needed to accurately attain the 'optimal viewing position', an indication can be obtained from Fig. 8C, taken from Coëffé and O'Regan (1987), which concerns the accuracy of attaining a marked target letter in a string of non-target letters. The *x*-axis indicates time after stimulus onset. The solid curves give the deviations with respect to the target position of the endpoints of the saccades made to the target. The four curves correspond to four different target positions in the string of 9 letters. It can be seen that good accuracy is achieved only if the latency of the saccade is about 500–600 ms. Even then, targets which are far from the center of gravity of the string (target position 8) are not accurately attained (undershoot of 2 letters). The dotted curves in the figure give the position where the eye arrives after making a second, correction saccade, as a function of the arrival time after stimulus onset. A very interesting thing appears: at a moment 400 ms following stimulus onset, accuracy is better when two saccades have been made (dotted curves) than if only a single saccade with delayed latency has been made. It therefore seems that it is more efficient to make two saccades with short latency than to extend the latency of the primary saccade in order to increase its accuracy. Jacobs (1987) has reached a similar conclusion.

4. Oculomotor constraints: temporal factors

In the following sections I will review a number of factors that are known to influence saccade latency. These factors may presumably also act during reading, so they must be kept in mind when trying to understand eye movements in reading. In the discussion of these factors, I will pay particular attention to the question of whether some kind of incompressible motor latency period must precede each saccade. The question is important for reading, since if such a motor latency period exists, then only a portion of visual and linguistic processing done during a fixation can influence the following saccade, namely, the portion that occurs before the beginning of the latency period. This would limit the extent to which eye movements in reading could be under the direct control of the information extracted at each fixation. Note that McConkie (1983) has also considered this question in detail.

4.1. Minimum latency and oculomotor programming

It is generally said that saccades take a long time to program (cf. Carpenter, 1981). In simple tasks, saccade latencies are rather longer than the approximately 45–95 ms that would be expected from 35–60 ms afferent (Creutzfeldt and Kuhnt, 1974; Mohler and Wurtz, 1976; also Russo, 1978) and 10–35 ms efferent (Robinson, 1972) propagation delays (although these values, which are for animals, should probably be somewhat increased for humans). Saslow (1967b) says that the fastest latencies shown classically (Westheimer, 1954; Ginsborg, 1953) of 120–180 ms contain anticipatory saccades. When these are removed, fastest latencies of around 180 ms are found. The fastest values quoted by other authors are usually around 150 ms for latencies and about 180–220 ms for fixation durations in tasks where the fixation is preceded and followed by a saccade (Salthouse and Ellis, 1980; Rayner et al., 1983; Kapoula, 1983; although see later for 'express saccades' and the 'gap' condition).

These values represent the times necessary for saccades to be generated to a simple peripheral dot target. In addition to afference and efference, the processes involved are presumably as follows: building-up of visual information; recognition of the stimulus; selection of the saccade target; preparing the saccade characteristics; and triggering the saccade. Because making a saccade to a simple dot target seems to involve little in the way of recognition and target selection processes, it is often assumed that most of the time is taken in motor programming. It is thought that there is some kind of oculomotor programming delay which is necessary to get the motor apparatus ready to send the saccade onto target. Vaughan and Graefe (1977), Salthouse and Ellis (1980) and Rayner et al. (1983) estimate this oculomotor preparation to require 150–200 ms.

However, in fact, there is no firm evidence proving that the main portion of saccadic latency involves a preparation of the oculomotor apparatus. In the model I sketched above, all the latency comes from visual (stimulus localization) or decisional (saccade target selection) processes. This is not incompatible with current theories: in fact Young (1981), in his sampled data model, explicitly notes that the delay element may equally well be in the visual component. Becker and Jürgens (1979) explicitly refer to the delay of about 200 ms as being due to 'central decision and computation'. In the following brief overview of effects on saccade latency, while sometimes it may seem more natural to suppose that a factor acts via some motor mechanism, as far as I can see, alternative visual or attentional mechanisms are also feasible and have certainly not been empirically ruled out.

4.2. Factors affecting saccade latency

Factors affecting saccade latency and which are attributable to attentional effects include factors such as practice (Heywood and Churcher, 1980), warning signals (Saslow, 1967a; Becker, 1972), the number of stimulus alternatives or spatial uncertainty (Saslow, 1967b; for a review see Heywood and Churcher, 1980). Zingale and Kowler (1987) and Inhoff (1986) have also drawn attention to the extensive literature on the planning of sequences of limb movements, and compared this to planning sequences of saccades (see also Lévy-Schoen, 1977). It was found that the latencies of a pre-planned sequence of saccades depends on the number of saccades in the sequence.

Factors which may be visual in origin are target luminance (Wheeless et al., 1967; Prablanc and Jeannerod, 1974) and target-background similarity (Jacobs, 1987). An interesting, presumably visual or attentional effect, and which will be referred to later, is the 'gap' phenomenon, in which saccade latencies are significantly reduced when the central fixation point is extinguished before saccade occurrence (Saslow, 1967a; Deubel et al., 1982; Ross and Ross, 1983; Fischer and Ramsperger, 1984; Mayfrank et al., 1987; Kalesnykas and Hallett, 1987).

We shall see later that the effect of target eccentricity will be important in understanding within-word fixation durations in reading. Findlay (1983) cites a number of studies showing that for saccades larger than about 10–15 degrees, latency is often positively correlated with eccentricity. However, an interesting recent finding shows a strong effect on latency of the eye's final position in the orbit (Accardo et al., 1987). For large saccades this will often confound eccentricity measures, and so this renders most previous studies dubious.

For reading, we are more interested in saccades smaller than a few degrees. Wyman and Steinman (1973) found that for saccades of less than about 0.5–1 degree, latency was inversely correlated with amplitude, with very small saccades having longer latencies than larger saccades. More recently Kowler and Anton (1987) have observed a similar inverse correlation. The finding is also consistent with incidental observations on the latencies of corrective saccades, which are small and inversely correlated with saccade size (Becker and Fuchs, 1969; Prablanc et al., 1978; Robinson, 1964; Cohen and Ross, 1978; Viviani and Swensson, 1982; Deubel et al., 1982). There may be a relationship between this finding and the concept of saccadic dead-zone (cf. Rashbass, 1961; Wyman and Steinman, 1973; Young, 1981), or the idea that there are different modes of saccade programming depending on their size (Becker, 1976). The effect of eccentricity might naturally be considered a motor factor, but, since saccade size and target eccentricity are confounded in most experiments, it is impossible to rule out a visual explanation. In fact, I have found, in the conditions of an experiment to be mentioned in section 5.5, that the explanation must be perceptual not motor: it is not because small saccades are difficult to execute that their latencies are long.

A debate in the literature on saccade generation has concerned the question of whether there are separate mechanisms involved in deciding the amplitude and the direction of a saccade. This could be relevant to reading research, since it may determine how hard it is to make different kinds of modifications to a previously programmed saccade. Young (1981) has compiled data from various experiments concerning the latest moments before the saccade when certain types of modification of the target position can still just be taken into account. Young claims that inhibiting the saccade requires the least preparation and can be done almost up to the moment of occurrence of the saccade. Decreasing the saccade's magnitude can be done up to 50 ms before the saccade. Increasing the amplitude requires greater preparation and must be done at least 80 ms before the saccade. Reversing the saccade's direction must be done more than 100 ms before the saccade. Deubel et al. (1982) also find that correction saccades which change direction with respect to the primary saccade require about 30 ms more latency. However, there is some debate about the chronology suggested by Young, and about whether there exist separate amplitude and direction mechanisms (cf. Lévy-Schoen and Blanc-Garin, 1974; Becker and Jürgens, 1979; Hou and Fender, 1979; Findlay and Harris, 1984; Aslin and Shea, 1987; Deubel, 1987). But again it should be noted that all these effects may have either a visual or motor source.

The preceding discussion has shown that there is no need to postulate that the main portion of saccadic latency is an incompressible time delay needed for preparation of the oculomotor apparatus. But how can we then account for the fact that saccadic latencies to simple targets are so long?

Perhaps the visual, attentional and decisional mechanisms involved in attaining a simple target are not so simple after all. In fact the model outlined above suggests that even in the case of a simple target, before triggering saccade execution, the 'circle of attention' must have time to disengage from the region currently fixated (cf. Mayfrank et al., 1987), and move to the region where the target appears, otherwise gross undershoot will occur. Without prior knowledge of where to move attention, and particularly in cases where a central fixation point remains visible and thereby retains attention, an appreciable time may be necessary. Indeed, using a task where the central fixation point is extinguished before the saccade ('gap condition'), Kalesnykas and Hallett (1987) showed that accurate, visually guided (i.e. non-anticipatory) saccades can have latencies as low as 100–120 ms, a value which in humans is probably very close to the sum of the times for afference and efference.

4.3. Constraints on fixation durations in reading

Fixation durations in reading differ from saccadic latencies in simple step-tracking tasks in a number of ways. First, fixations are preceded and followed by saccades. There may be some basic oculomotor refractory period, perhaps needed for repotentiation of the muscles of their command centers, which prevents saccades occurring in rapid sequence. However, in fact this is not the case, as shown by the existence of 'back-to-back' saccades, that is, saccades with an effectively zero-duration fixation separating them, first observed by Lévy-Schoen and Blanc-Garin (1974) and now often found in the 'double-step' paradigm (Becker and Jürgens, 1979). Chapter 8 of this volume also shows examples of saccadic trajectories that slow down or stop briefly in the middle. In a task where subjects scanned sequences of crosses, and by investigating the effect on saccade latencies of delaying the onset of crosses with respect to the eye's arrival time upon them, Rayner et al. (1983) deduced that there was no oculomotor refractory period.

Another difference with saccadic latencies is the existence of the 'clearing-up period' suggested by

Dodge (1907). This period of poor vision after the saccade may be caused by forward masking following the smear created by the saccade, or by mechanical oscillation of the eye, dynamic overshoot (Kapoula et al., 1986), saccadic suppression (Volkmann et al., 1968) or vergence adjustments (Stromberg, 1938). Using computer-controlled, eye-contingent displays, the duration of the clearing-up period can be estimated by observing modifications in fixation durations when, at different moments following the end of the saccade, a mask is displayed which replaces the text being read. In evaluating such work it is important to bear in mind the possibility that if gross visual changes are involved, fixation durations may be determined not by visual processing, but simply by the warning signal created by the occurrence of the change itself (cf. Vaughan, 1983). Keeping this in mind, analysis of studies by Morrison (1984), Rayner et al. (1981) and Wolverton and Zola (1983) leads to 30 ms as the likely value for the clearing-up period – although its duration might also depend slightly on the size of the preceding saccade.

What conclusions can be reached about saccade control in reading? Even though, as shown above, there is actually no evidence for it, several previous authors had started from the (probably false) supposition that there is an irreducible oculomotor programming delay of about 150–200 ms preceding the saccade, to which must be added 30 ms of clearing-up period. Noting in addition that the average fixation in reading is 250 ms, they have argued that this leaves a time of only 20–70 ms at the beginning of each fixation during which saccade decisions must be made. In reading, these authors argue, saccades and fixation durations must therefore be predominantly governed by some simple pre-programmed strategy based on low-level visual information, and not on ongoing linguistic processing (Morton 1964; Bouma and de Voogd, 1974; Shebilske, 1975; Vaughan, 1978). Moreover, in an attempt to find some way of explaining how more time might be available for cognitive processing in reading, Salthouse and Ellis (1980) and Rayner et al. (1983) wondered whether the sequential, rhythmic, predictable nature of eye fixations in reading might reduce the difficulty of saccade programming in reading. But in a very elegant series of experiments they concluded that this was only minimally the case, and that even in reading there existed a 'minimal saccadic latency' of the order of 180–200 ms.

However, all these arguments are rendered unnecessary, given that the 150–200ms minimum saccadic latency may actually be part and parcel of the visual and attentional decision mechanisms that determine saccades. Nothing in the results of Salthouse and Ellis or Rayner et al., is incompatible with this idea. It is possible that in reading, visual and linguistic processes are at work, and require attention to be directed at various parts of the text. If a saccade is triggered at any moment, the eye will go to near the current focus of attention. The question is, when is the saccade triggered? Presumably different strategies may exist, depending on the reader, his attitude and abilities. McConkie (1983) and McConkie et al. (1985a) consider in detail the temporal characteristics of processing in reading, and suggest that it may be more efficient to trigger the eye before processing is complete; in that way additional visual information becomes available quickly, and processing need rely less on linguistic knowledge. This may be the case at some times. At other times it may be better to trigger saccades later, when processing has proceeded further.

4.4. Conclusion on visuo-motor constraints

An initial conclusion to be drawn from the above sections is that the visual or visuo-motor processing that determines saccade accuracy and latency is susceptible to a number of influences which will probably be present in normal reading, and which will contribute to variation in fixation durations and saccade lengths. We shall see later that some of these, in particular the center of gravity effect and the effect of eccentricity on the latency of small saccades, will be important in the strategy-tactics theory.

A second point concerns the time needed for accurate saccades. Even in the case of an isolated target, but certainly in a complex field, the processes of extracting target location and disengaging attention from the preceding fixation point are time-consuming. It is quicker, instead of attempting to make a single, accurate saccade, to use a strategy of successive approximations: make a quick, approximate saccade, followed by a correction movement. This suggests an explanation for the findings in section 2.6, where it was shown that in reading, saccade size is not a simple function of perceptual span. For if at each saccade in reading the eye were to attempt to move to the edge of the zone of perceptibility, this would require a lot of processing: first using visual and linguistic information to process what can be processed around the fixation point, then determining the location where no further processing can be done, then disengaging attention from the current fixation point and making the saccade. Just as was the case for the isolated target, a more efficient strategy may actually be not to attempt to extract the location of the edge of the zone of perceptibility, but use crude, easily extractable visual cues such as the spaces between words, to move forward by some approximate amount that has a good chance of bringing the eye somewhere useful, and make local adjustments in the eye's position if necessary. If this were the strategy being used, then saccade size in reading would be mainly influenced, not by perceptual span, but by the crude cues being used in the eye guidance strategy. Perceptual span would only influence the probability and nature of the correction movements that occur when the general strategy fails to allow processing to continue.

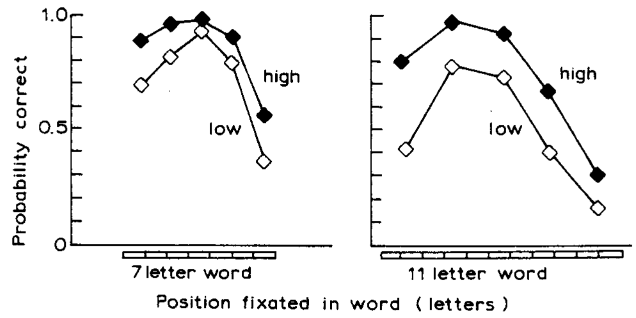

Fig. 9. Probability of correctly reporting words that appear at different positions with respect to the eye's fixation point. By use of a computer-controlled, eye-contingent display, the word was made to disappear if the eye attempted to move. The small rectangles on the abscissa represent the letters of the words where the eye could start fixating. 'high' and 'low' refer to words with high and low frequency of occurrence in French. Data points represent means over 10 words and 10 subjects. Fifty words contribute to each curve (latin square design).

A final point concerns the question of whether there is time for cognitive processing of information gathered at the fixation to influence its duration or the target of the next saccade. At present the question remains open. No firm evidence in the literature points to the existence of an incompressible motor programming period. In fact several models of oculomotor programming place most of the delay in initiating saccades at the visual and decisional levels. If this is true, then eye movements in reading may perfectly well reflect ongoing processing. However, reading strategies in which saccades are triggered before all processing is done at each point in the text may turn out to be more efficient. This may be the explanation, rather than oculomotor programming time, for the fact that many recent theorists suggest an appreciable lag between eye movements and cognitive or linguistic processing in reading.

5. The optimal viewing position phenomenon

Can words be recognized without eye movements? Psychologists using tachistoscopes have studied word recognition for almost a century now, and have never doubted that they can. But in their experiments the eye's fixation point is always placed near the middle of the word, where, even with visual resolution dropping off very rapidly, a maximum number of letters can be seen. Given the results in section 2.4 showing that visual span is very small, one can ask whether words can still be recognized when they are not fixated at their middles. It might be that word recognition depends critically on the position within a word that the eye fixates.

5.1. Optimal viewing position with the eye stationary

In an experiment I did to investigate this question, isolated words were presented displaced laterally by different amounts with respect to the eye's fixation point, so that on the appearance of a word the eye would be fixating one of five positions in the word. The subject's task was to read the word aloud. However, by the use of online eye-contingent control of the computer display, whenever the subject attempted to move his eye, the word being fixated disappeared and was replaced by x's. The subject was thus forced to attempt to identify the word from a single fixation point in the word, but he could keep his eye there as long as he liked.

Fig. 9 shows the probability of correctly reporting the words as a function of the position the eye was fixated. Note first that subjects cannot perfectly recognize the words. Especially in rare or long words, recognition can drop to 30–40% if the eye is fixated at an eccentric position in the word. Also interesting is the fact that frequent words were easier to report than rare words.

A second point is that there is an optimal viewing position where recognition is best. This was to be expected from the fact that visibility span is rather small, so fixating at the middle of the word would allow the most letters to be seen: the middle letters could be seen, but also the end letters, since they are not masked by flanking letters. However, contrary to expectations, the optimal viewing position is not at the middle of the words, but just left of the middle, especially for long words. We will see below that this shift is partially related to the internal informational structure of words, and partially to the mental processes responsible for word recognition.

5.2. Optimal viewing position when the eye is free to move

The finding that words cannot always be recognized from a single fixation raises the question of what happens in normal word recognition, when the eye is free to move. Obviously the word can now always be identified. But is there a penalty incurred when the eye must refixate the word because it started from a non-optimal place? A large number of experiments from my laboratory have addressed various aspects of this question, and they form the basis

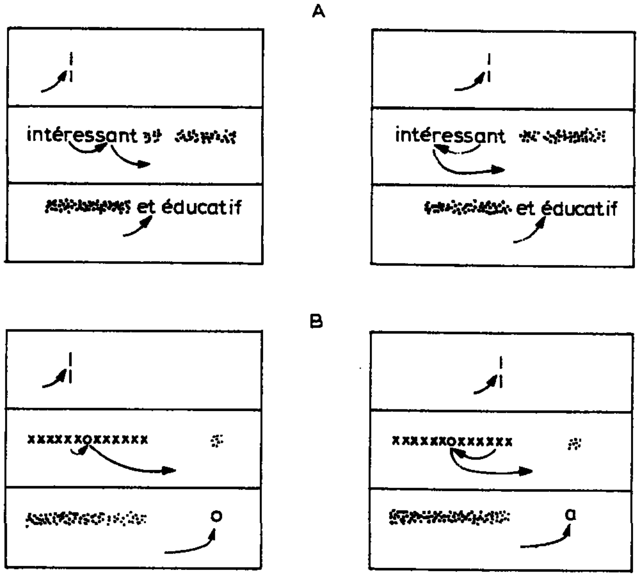

Fig. 10. A. Example of the technique used in experiments demonstrating the optimal viewing position effect. The eye fixates in the gap between two short, vertically aligned line segments. When the computer detects accurate fixation in the gap, it extinguishes the fixation marks and displays a short phrase in such a way that the eye initially fixates a certain position in the first word of the phrase, which is the word being tested. In the left hand example, this is the fourth letter, and in the right hand example it is the ninth letter. The words beyond the test word are initially masked off with random dots. The eye remains in the test word for a certain time (in the two examples it makes a second fixation in the test word, but it may make any number in the experiment), and then it makes a saccade to the next word. When the eye crosses the (imaginary) boundary between test word and remaining words, the dots are removed from the remaining words, and descend upon the test word so the eye cannot go back to re-examine it. The subject continues reading the phrase and then must make a decision as to whether it makes sense. In this case it does. An example of a phrase that does not would be: 'concombre de la solidité'.
B. The same technique as in A, but applied to a task in which the subject must fixate the middle letter of a string, and then move to a comparison letter on the right which may or may not be the same. His task is to respond 'same' or 'different'. The test string can be displayed in different positions with respect to the eye's initial position, so that on appearance the middle letter of the test string is at different distances from the fixation point.

of the strategy-tactics theory to be described later. The main finding, which I call the 'optimal viewing position phenomenon', is that the total time the eye spends on a word before moving out of the word depends very strongly on the position where the eye starts fixating in the word.

The experiments use a method in which the eye's initial position in a word is varied, and the total time the eye spends on the word before moving on to other words is measured. The paradigm is the following (Fig. 10A). For each trial, the subject fixates a small fixation mark. When the computer detects an accurate fixation at the mark, it displays a word. The word can be displaced by varying amounts with respect to the eye, so that initially the eye may be fixating at one of several positions within the word. At the same time as the test word appears on the screen, an additional word or words is also displayed, starting at a position two letters to the right of the test word. The subject reads the test word, and then moves on, as in normal reading, to look at the remaining word or words. In one task a single non-test word is used, and the subject must decide whether it is identical to the test word. In a task more similar to normal reading, the test word plus several non-test words form a whole phrase, and the subject's task is to decide whether it is meaningful or not. In both tasks, in order to prevent processing of the non-test word or words while the eye is still on the test word, the non-test words are initially masked out by random dots so they are illegible. Only when the computer detects fixation upon them are the dots removed.

Typical data are shown in Fig. 11A. The graph shows the gaze duration on the test word, that is, the total time the eye stays on the test word before moving on to the remaining word or words. There is an optimal position, where the gaze duration on the test word is shortest. The position is at the middle or left of middle of the word, depending on its length, frequency and lexical structure, as we shall see later. The penalty for not starting to fixate at the optimal position is rather large: gaze duration increases by about 20 ms for each letter of deviation from the optimal position.

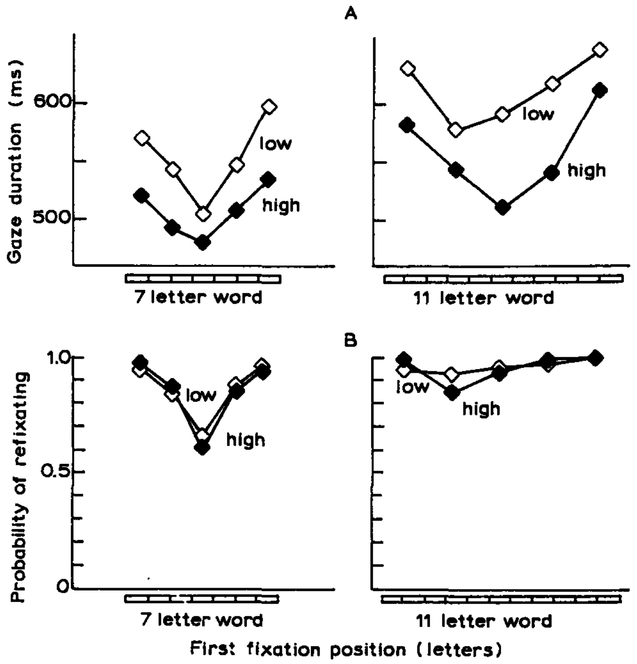

Fig. 11. A. The optimal viewing position phenomenon. The curves show the total time the eye spends on a word (gaze duration) before leaving it to read the remaining words displayed (see Fig. 10A), plotted as a function of the eye's initial fixation position in the test word (the small rectangles on the abscissa represent letters of the word). 'high' and 'low' refer to words of high and low frequency in French. Each data point represents a mean over 10 subjects reading 10 words, and 50 words contribute to each curve (latin square design).
B. For the same experiment as in A, the probability of making more than one fixation in the word as a function of the position initially fixated by the eye.

The optimal viewing position phenomenon has now been replicated in many different experiments. It is the main inspiration for the strategy-tactics theory to be presented later. I will now consider several aspects of it in detail.

5.3. Influence of lexical structure on optimal viewing position

What determines the optimal position in a word? If acuity and lateral masking were the only factors operating, it is clear that the most letters would be seen by fixating the middle of the word. However, the internal statistical structure of words may modify the situation: for example, consider a word like

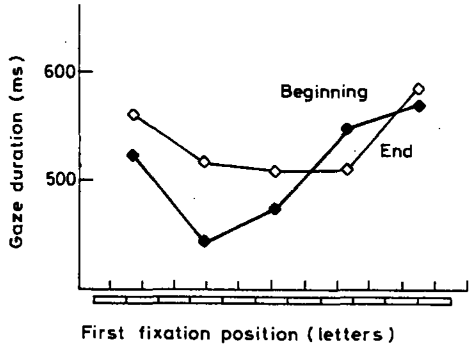

Fig. 12. Optimal viewing position curves for two types of word: words selected in the French dictionary in such a way that knowing their first six letters and approximate length allowed them to be uniquely determined ('beginning' words; examples: 'coccinelle', 'gladiateur'), and words such that knowing their last six letters and approximate length allowed the word to be uniquely determined ('end' words; examples: 'interview', 'transversal'). The words were matched for length and frequency. Each data point corresponds to 50 subjects and 2 words, with 10 words contributing to each curve in a latin square design. (From O'Regan and Lévy-Schoen, 1987)

'interview', where the first letters of the word are a commonly occurring prefix. These letters may provide less help in identifying the word than the last letters of the word. The optimal viewing position may therefore be located more to the right. The opposite might be true for words like 'elucubration', where most of the information is contained in the first half of the word. Here the optimal viewing position might be shifted towards the beginning of the word.

Fig. 12 shows the results of an experiment which attempted to verify this prediction. Whereas for words with information at the beginning, the optimal viewing position is near the beginning as expected, for words with information at the end, the optimal viewing position is not so clearly marked, and is certainly not located near the end of the words. The explanation for this asymmetry is undoubtedly related to how word-recognition processes operate. It seems that while information at the beginning of a word can be made use of efficiently, this is not true of information at the end of a word. If I give you the last few letters of a word, even if they uniquely determine the word's identity, the word may be hard to guess. It seems that the internal lexicon is organized in a left-to-right fashion, and that people cannot recognize words easily by their ends. Another point is apparent from the previous figure (Fig. 11A). Long words and rare words tend to have their optimal viewing position slightly left of the middle, whereas short words' and frequent words' optimal viewing position is closer to their middles (O'Regan and Lévy-Schoen, 1987). These differences could be related to differences in the distribution of information in words of different length and frequency, or to differences in lexical access processes. A review of the extensive psycholinguistic literature on lexical access can be found in Henderson (1982). Researchers are only now beginning to investigate the relationship between lexical structure, lexical access, and the optimal viewing position phenomenon (Holmes and O'Regan, 1987; O'Regan and Lévy-Schoen, 1987; Underwood et al., 1987, 1988).

The important point to note from all these results is that the optimal viewing position is not fixed: it is determined by the way visual constraints and internal word structure combine, and so may be different for each word. There is an unfortunate consequence for reading: the eye cannot know in advance, before landing in a word, where the optimal viewing position will be. I will come back to this problem in section 6.2.

5.4. Within-word eye movement tactics

Because it will turn out to be the 'tactics' in the strategy-tactics theory, I will now consider in detail the eye movement behavior that underlies the optimal viewing position phenomenon. For example, when the eye lands in a non-optimal position, where does the extra time needed to recognize the word come from? Presumably partly from extra fixations being made – but where and of what duration? How long does the eye stay in the non-optimal position before deciding to move? On what basis is the decision to move taken?

The natural hypothesis to make is that the eye's behavior is governed directly by the lexical processing occurring from moment to moment while the word is being recognized. At first sight all the evidence will appear to suggest that this is true. But it will turn out that in fact the situation is more complicated, with lexical processing only having an influence fairly late in the course of the scanning of a word.

Suppose that the eye lands at the optimal position. All lexical processing can be done from there, so the eye should saccade out of the word after making only a single fixation ('single-fixation tactic'). However, if the eye lands a little way from the optimal position, lexical processing will begin, but may not be able to terminate, since information about certain letters in the word is lacking. The eye would then have to refixate in the word to complete the recognition process. The probability of this 'two (or more) -fixation tactic' occurring should be higher if the initial fixation location is further from the optimal position. This indeed appears to be the pattern found (see Fig. 11B): (note by the way that even at the optimal position, the probability of refixating the word is quite high, especially for long words).

Where does the eye refixate in a word? Fig. 13 shows that when the eye is on one side of the word, it goes to the other. When it is near the middle, it goes to either one or other end. In other words, the eye is not attempting to get to the optimal viewing position. Rather, it is attempting to spread its fixations evenly over the word. This makes sense, given that once one fixation has occurred the best place to refixate will probably be on the other side of the word, where little information has as yet been gathered. This suggests that the eye's behavior is governed by lexical processing, but we shall question this later.

Things continue to look good for the hypothesis that the eye's behavior is governed by lexical processing when we examine the pattern of fixation durations in the two-fixation tactic. We expect the following: when the eye initially lands far from the optimal viewing position, very little processing can be done, and the fixation duration at this position should be very short. The eye then moves to another

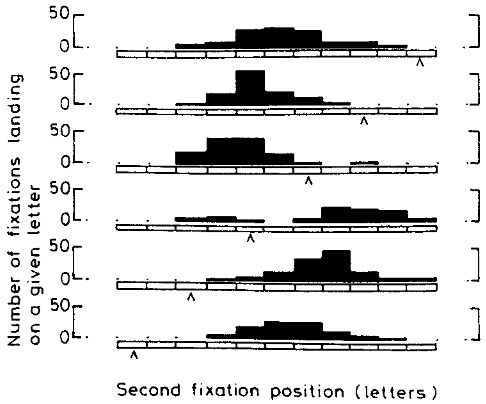

Fig. 13. Analysis of the subset of the data from O'Regan et al. (1984) when exactly two fixations were made in 11-letter words: histograms (unnormalized) showing the positions in the word where the second fixation occurred. A different histogram is plotted for each position where the first fixation could be (shown by arrows under each histogram). (Adapted from O'Regan and Lévy-Schoen, 1987)

position in the word, and there most of the processing can be done: fixation duration there should be long. On the other hand, if the eye lands near the optimal viewing position, more processing can be done on the first fixation, and less need be done on the second. There should be a trade-off between the durations of the first and second fixation in a word. Processing not done on the first fixation can be done on the second. This is also the pattern observed. To show this, Fig. 14A has been plotted in a special way. The solid curves represent first fixation durations as a function of the position where these fixations occurred. However, the dashed curves indicate the durations of the second fixations, NOT as a function of where they occurred, but as a function of where the preceding first fixations were. This was done in order to indicate for each abscissa position both the duration of the first fixation that occurred there, and the duration of the second fixation that followed that first fixation, even though it occurred somewhere else in the word. The expected trade-off between first and second fixation durations is found: when the first fixation is short because it occurs far from the optimal viewing position and little processing can be done, then the second fixation that occurs is long. Conversely, when the first

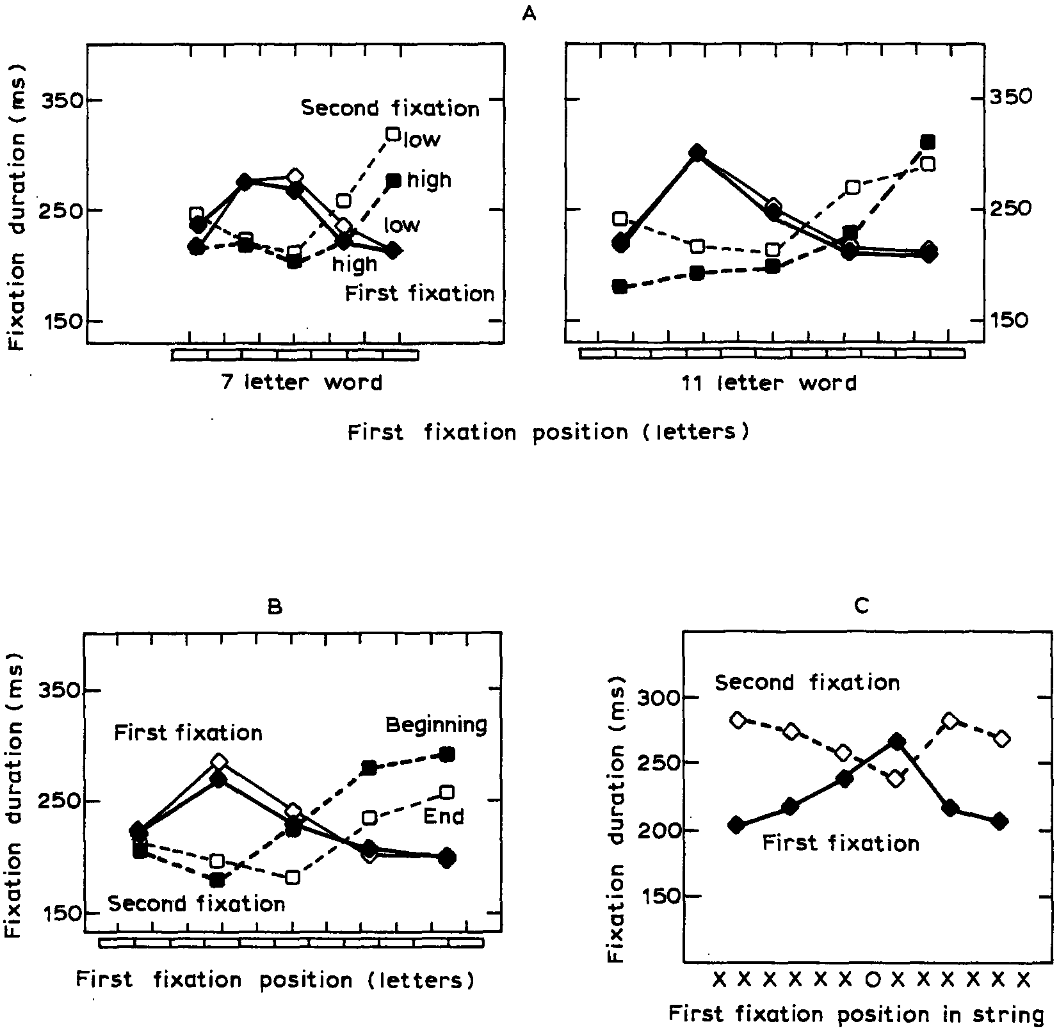

Fig. 14. A. Subset of the data of the experiment described in Fig. 12 when exactly two fixations were made: fixation duration as a function of the position of the first fixation, that is, the position of the eye at the moment the word appeared. The second fixation durations (dotted lines) are plotted at the abscissa positions where the corresponding first fixation (solid lines) occurred. In this way, the total time spent on the word as a function of the position that the eye initially fixated can be obtained by summing the data points aligned vertically at that position in the word. The thick lines (solid or dotted) correspond to high-frequency words, the thin lines (solid or dotted) to low-frequency words. (Adapted from O'Regan and Lévy-Schoen, 1987)
B. First and second fixation durations in the subset of the data of the 'beginning–end' experiment (Fig. 12) in which exactly two fixations occurred, plotted in the same way as in A. (From O'Regan and Lévy-Schoen, 1987)
C. Subset of the data of the string experiment (Fig. 10B) in which exactly two fixations occurred, plotted in the same way as in A.

fixation falls nearer the optimal viewing position, and its duration is long because more processing can be done, then second fixation duration is correspondingly shorter. In fact when the first and second durations are summed, the result is constant, independent of the position where the eye started fixating in the word. This suggests that the total amount of processing done is the same, wherever the eye starts fixating, it is just distributed differently over the word.

The above findings are again compatible with the idea that the eye's behavior is being governed by the moment to moment demands of lexical processing. But a problem appears when we consider the dif-

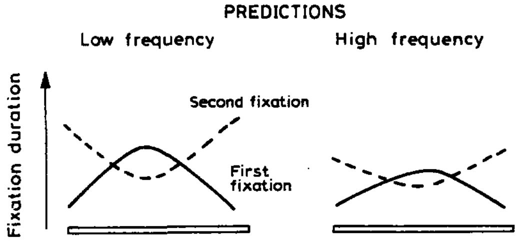

Fig. 15. Predictions that would be made for the subset of the data in which exactly two fixations occurred. For 'easy' words such as high-frequency words (a) the slopes of the first and second fixation curves should not be steep, and (b) the two curves should be fairly close together. This is because there is little processing to do, so (a) the advantage in fixating near the optimal position should not increase strongly as the eye's initial position approaches this position, and (b) the sum of the first and second fixation durations should not be great. The opposite should be true for 'hard' words like low-frequency words.

ference in behavior for words of different frequencies or different lexical structures. We would have expected that these differences would be reflected in the durations of first and second fixations. An easy word would require a smaller total time than a hard word. Fig. 15 shows the predictions: the trade-off between first and second fixation durations should continue to exist, but the curves would be flatter since their sum should be less. The thick solid or dotted lines in Fig. 14A correspond to high-frequency words, and the thin solid or dotted lines to low-frequency words. Curiously, for first fixation durations, the curves for high-frequency and low-frequency words are identical. The expected differences only appear for second fixation durations. Similar problems arise when considering words whose informational structure is manipulated. Again, virtually no difference appears on first fixation durations, only on second fixation durations (Fig. 14B).

5.5. Visuo-motor factors in the two-fixation tactic

An interesting experiment elucidates the mystery. I attempted to remove linguistic processing altogether, to see if the first/second fixation trade-off curves would become completely flat. To do this, I repeated the experiments above, but instead of having to recognize words, subjects had to simply look at a letter 'o' inserted in the middle of a string of 10 x's. Just as in the word experiments, the string appeared on the screen in a position that was displaced laterally with respect to the eye, so that subjects had to make a saccade to the 'o' at the center of the string before moving out of it. There was thus always a first fixation in some non-central string position, followed by a fixation in the middle of the string (cf. Fig. 10B). I observed that fixation durations followed exactly the same trade-off relation as for words, despite the fact that the processing involved in the task was virtually minimal, requiring only the (extremely easy) extraction of the central letter 'o' in the string of x's (Fig. 14C).

This result suggests that the hump in the first fixation duration curve, and the dip in the second fixation curve, may be caused by some mechanism other than perceptual or lexical processing. It may be that they are linked to purely visuo-motor phenomena.

One possibility to explain the hump in first fixation curves might be the eye's starting position. It is known that saccadic latency depends on the presence or absence of visual material at the fixation point (see the gap phenomenon of section 4.2). Perhaps latency also depends on how this material is arranged at the fixation point. The model presented in section 3.1 suggests that if the center of gravity of the material is at the fixation point, making a saccade to leave it might be harder than if the center of gravity is not there. We have done pilot experiments to check this hypothesis, but it appears not to be confirmed. The size and position with respect to the fixation point of a string of characters do not influence the latency of saccades made to leave the string.

Another possibility to explain the hump in the first fixation curve is the dependence of saccade latency on eccentricity: small saccades take longer to prepare than large saccades (for saccades less than about 1 degree, see section 4.2). However the simple suggestion that it is the angular size of saccades that influences their latency is not supported by an additional experiment we performed, similar to the experiment using strings of x's (Fig. 10B), but in which we doubled the subject's distance from the display. The saccades that occurred in this version of the experiment were all half as large, in angular terms, as those in the previous version. Yet their latencies did not increase in the expected way. In fact, when plotted using number of letters as abscissa, the curves for first and second versions of the experiment were exactly superposed. This shows that what is determining the latency is the number of letters the eye is moving over, irrespective of their angular size. A similar state of affairs was found in the study of perceptual span, above, where we showed that number of letters rather than angle determined perceptual span. It may be therefore that the hump in the first fixation duration curves has a perceptual and not a motor origin. In fact, more generally, the inverse correlation found for small saccades between saccade size and latency may also have a perceptual rather than a motor origin (cf. section 4.2).

One possibility might be that a target which is very easy to see does not serve as such a salient stimulus for a saccade as one which is hard to see. I have indeed confirmed that if a very visible target is used, the hump in first fixation duration curves is not so pronounced. In the case of words, where no particular visual target is present, the difficulty of judging where the eye is relative to the middle of the word may be less when the eye is near one end of the word than when it is already quite near the middle (it is easiest to tell that you are off-center when you are far off-center).

I now turn to the question of the dip in the second fixation curves. I will consider the case of the x-experiment first. Perhaps an explanation for these might be in terms of a kind of scanning rhythm in which the subject preprograms the moment at which he will make the large saccade out of the string of x's, irrespective of the moment when the first saccade in the string occurs. Preprogramming of spurts of saccades has been suggested before (Lévy-Schoen, 1981; Becker and Jürgens, 1979; Zingale and Kowler, 1987; cf. also Vaughan, 1983; Inhoff, 1986; Morrison, 1984). Another possibility might be that there is some oculomotor constraint that makes a short fixation more likely to be followed by a long one and vice versa. Yet another possibility is related to the size of the preceding saccade: when this is small, it might be easier (quicker) to make the next saccade than when the preceding saccade is larger.

We are only just beginning to study the visuomotor component, and have not yet looked at aspects such as the effect of word length, density of contours (though see Coëffé, 1985), character size and brightness, nor possible dependencies between the sizes, directions and durations of succeeding saccades or fixations. Nevertheless the finding that fixation duration trade-offs were found even in strings, where no lexical processing is involved, shows that the purely visuo-motor component in within-word tactics is important and must be further elucidated.

5.6. Conclusion on within-word eye movement tactics

Curves similar to those in Fig. 14A,B showing a trade-off between first and second fixation durations in the two-fixation tactic are very systematic and have now been observed in many different experiments performed in my laboratory. While initially we had thought that they reflected the way lexical processing is distributed over a word during recognition, closer examination showed that the fixation durations have an additional component related to visuo-motor phenomena. In fact, the lack of difference observed for words of different frequency in Fig. 14A suggests that the hump in the first fixation duration curves is probably related primarily to visuo-motor mechanisms. The dip in the second fixation duration curves also has a visuo-motor component, as suggested by the results of the experiment using strings of x's. However, in words, lexical effects are also apparent on the second fixation curves.

Similar conclusions can be reached from analysis of first and second fixation duration curves for words with different morphological or informational structure (Holmes and O'Regan, 1987; Lévy-Schoen and O'Regan, 1987): in the case of two-fixation tactics, first fixation curves are sensitive only to visuo-motor factors. Lexical processes become apparent only at the second of the two fixations that occur.

An obvious explanation for the fact that lexical processes act only on the second of the two fixations in the two-fixation tactic is that lexical processes take time, and so cannot determine the first stages of eye movement behavior. When the eye arrives in a word, its initial behavior must therefore be based on some tactic that requires no lexical knowledge. A reasonable tactic would be one that ensures that if the eye arrives in a place near one or other end of the word (from which the whole word is likely not to be visible), an additional fixation is programmed in the word. But if the eye lands near the position just left of center which is generally optimal for word recognition in French (and probably English), then no such additional fixation would be programmed. The eye would then remain in place until word recognition has been achieved. The length of time this takes would depend on the word's structure and frequency. In the case of very difficult words, a third fixation might be programmed. Their occurrence and durations could be under control of lexical processing. However, the duration of the first fixation (when several occur) would be determined purely by a visually based tactic depending only on the eye's position in the word.

This suggestion for eye movement control within words therefore consists of a superposition of two processes: a first, low-level visuo-motor process checks whether the eye is reasonably placed. It is driven by gross visual information and so can act rapidly. A second, linguistic analysis process slowly catches up on the visuo-motor process. Once it has, it can extend or shorten the currently occurring fixation.

There is an interesting consequence of the idea that, at first, only visuo-motor processes are driving the eye movement tactics within words. If this is true, then the decision as to whether or not to make a second fixation, as well as where to go, must also be based on a visuo-motor and not a lexical criterion. This is rather counter-intuitive for the following reason. One would have expected to find that the probability of making a second fixation should depend on how close the eye is to the optimal viewing location, with the likelihood of having to refixate being smallest at the optimal position. But the argument made here shows that this cannot be true, because the optimal location depends on the word's lexical structure. The decision whether to move can only be based on some purely visually definable cue, such as the closeness to the generally optimal position. That this may be true is suggested by the fact that even though high-frequency 11-letter words have their optimal viewing position near the middle (Fig. 11A), the probability of making more than one fixation in these words is actually lower near their third or fourth letters (Fig. 11B). Another prediction that must be made from the idea that lexical processing cannot influence the probability of refixating is that this probability should not be affected by a word's frequency or lexical structure. Fig. 11B shows that, as expected, there is little difference in the probabilities of refixating for high- and low-frequency words, although a small difference does appear in the middle of 7-letter words and near the 3rd or 4th letter of 11-letter words. This difference might arise because at this position, which is generally the optimal position, the eye will generally stay for a long time, so lexical processing may actually have a chance of being able to influence the probability of refixating after all.

5.7. Optimal viewing position versus 'preferred viewing position'

Up until now, studies on optimal viewing position have been done in conditions where a word appears at the eye's fixation point, and the subject must read the word and move on to a second word. This situation is different from normal reading in a number of respects, and we should ask whether in normal reading there still exists an optimal viewing position. Several studies in the past have looked at where the eye tends to land in words in normal reading, and

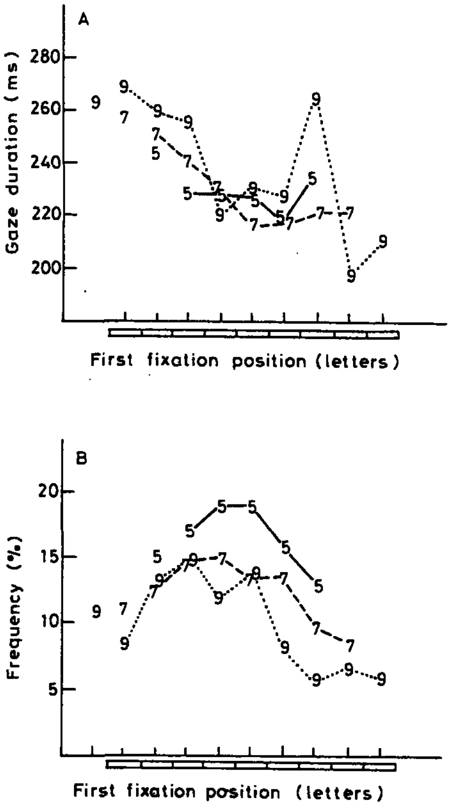

Fig. 16. Graphs plotted from data on continuous reading of texts, provided by Blanchard and McConkie (personal communication). The top graph gives the total gaze duration on words of length 5, 7 and 9 letters as a function of the first position the eye fixates in the word. The middle position on the abscissa corresponds to the middle of the words. The first point of the graph for each word length is not connected to the other points because it corresponds to a fixation occurring in the space preceding the word. For word lengths 5, 7 and 9, the data are derived from 2578, 1642 and 623 fixations, respectively. The last 3 data points for the 9-letter case are noisy because there were very few observations per data point. The lower graph gives histograms of the positions where the first fixations fell, expressed as a percentage of the total number falling on the word or in the preceding space. (From O'Regan and Lévy-Schoen, 1987)

have observed that this position is at the middle or left of middle of words (Rayner, 1979; Dunn-Rankin, 1978). But this position, where the eye 'prefers' to land (the 'preferred viewing position') need not logically be the same as the 'optimal' position, which is the position where recognition is most efficient. In fact, analysis of a large corpus of reading data I have obtained from Blanchard and McConkie shows that the position where the eye tends to land is in fact different from the generally optimal position, that is, the position where recognition was quickest, as measured from the same data. The generally optimal position is near the middle of words (Fig. 16A), while the 'preferred' landing position is nearer the third letter of words (Fig. 16B).

5.8. Optimal viewing position in normal reading

Research on the optimal viewing position in normal reading requires investigation of the total time taken to recognize a word as a function of where the eye happens to land in the word in reading. At present no published work exists on this question, but again the preliminary data from Blanchard and McConkie (see Fig. 16) show that the optimal viewing position continues to exist. However, two differences with my data on isolated words appear. First, the optimal viewing position is at the center of words, even for long words, whereas I have always found that for long, low-frequency words the optimal position is slightly left of middle (Fig. 11). This difference is not serious, because it is likely that in the (elementary) texts read by Blanchard and McConkie's subjects, mainly frequent words were used. A second difference is more serious: in Blanchard and McConkie's data, the penalty for not fixating at the optimal viewing position is about 10 ms per letter of deviation from the optimal position. This is half the value I have systematically found on the first words of short phrases, and some explanation for the difference is required.

Vitu and O'Regan (1988) tested two possibilities. The first explanation is that in normal reading, parafoveal information gathered during the fixation preceding the eye's arrival in each word allows processing of the word to begin. This might lessen the need to refixate the word when the eye lands in a non-optimal position. We found no evidence that this was happening. Preprocessing did in one experiment (but not in a more recent experiment) increase recognition speed, but it did not modify the penalty for not fixating the optimal viewing position (interestingly it also did not displace the optimal viewing position rightwards, as might have been expected).

A second possibility which might explain the lesser penalty in normal reading is the idea that in normal reading, a rhythmic fixation strategy which drives the eye onwards is used, suppressing many refixations in words. However, in another experiment where a reading rhythm was simulated by having subjects successively fixate two separated asterisks before fixating the target word, we found no evidence for this idea (Vitu and O'Regan, 1988).

It may be that the forward-going strategy suggested here could not be used in the simulated reading task. In normal reading, subjects can take the risk of now and then not successfully identifying a word, since context will generally help out. Adopting this risky tactic was perhaps not possible in our task, where no context was available. Context may also help in improving the ability to extract parafoveal visual cues (McClelland and O'Regan, 1981), thereby reducing the probability of refixation. Further work on the influence of context on the optimal viewing position phenomenon is needed.

More evidence in favor of the existence of the optimal viewing position in normal reading is provided by McConkie et al. (1989). These authors analysed the probability that a word will be refixated as a function of the position where the eye initially falls in the word. They found very clear evidence that the probability of refixating the word depends on the eye's landing position in the word, with an optimal position near the center of words.

6. A strategy-tactics theory of eye movements in reading

6.1. Summary up to now

I began this chapter by arguing that the perceptual span control hypothesis is false: sizes of saccades in reading do not correspond to estimates of the amount of material that can be seen at each fixation. An explanation for the discrepancy came from the findings in sections 3 and 4, showing how eye movements are restricted by visuo-motor constraints: aiming the eye accurately is a time-consuming process involving extraction of the target location and needing attention to be disengaged from the current fixation point. If the desired target location were defined as the edge of the perceptual span, determining its position would require not only visual, but also perceptual and perhaps preliminary lexical processing: saccadic latencies would have to be much longer than the 250-ms average fixation duration observed in reading. I therefore suggest that in reading a different strategy must be used in which eye movements and perceptual and linguistic processing are not so intimately yoked, but proceed autonomously. The proposal is that first, a global, preprogrammed scanning routine driven only by coarse visual cues guides the eye across the text; second, perceptual, lexical and linguistic analysis of the text is done continuously, and this can intermittently regulate the scanning routine by delaying the triggering of a saccade or by triggering it prematurely if the rate of information intake is too fast or too slow.

Similar proposals for eye movement guidance had been made by some early authors who also believed that saccade programming required long latencies. Thus, Buswell (1937), Morton (1964), Kolers and Lewis (1972), Andriessen and de Voogd (1973) and Bouma and de Voogd (1974), believed that the eye moved forward with a reading 'rhythm' which was adjusted in such a way that the rate of information intake kept approximately in step with the rate of linguistic processing. A minor difference between this old 'oculomotor' kind of theory and the theory I now wish to outline is that before, researchers thought that the necessity for long saccade programming delays came from an incompressible oculomotor programming delay, whereas it now seems more likely that the delay is due to the difficulty of extracting the target from its surroundings and disengaging attention from the present eye location. But the essential difference between the old 'reading rhythm' theory and the 'strategy-tactics' theory I will now present will be the fact that our greater knowledge about visuomotor constraints, and about the optimal viewing position phenomenon, allows much more precise predictions to be made about exactly where the eye goes in reading, and how long it stays where it does. Thus, although both the old oculomotor theories and the strategy-tactics theory postulate an autonomous scanning routine, in the strategy-tactics theory, because of visuo-motor constraints and the optimal viewing position phenomenon, this routine turns out not to be a rhythm, nor to have saccades of constant amplitude. The precise characteristics will be set out below.

6.2. A scanning routine for 'careful word-by-word' reading

In the proposal I wish to present, I will make the assumption that in reading the reader proceeds in a word-by-word fashion, completing recognition (or some stage of recognition) of each word before going on to the next word. I will call this 'careful word-by-word reading'. This kind of reading may not actually exist, but it will be a starting point which can be improved upon so as to correspond to more normal kinds of reading.

The existence of an optimal viewing position in words, and the large penalty in recognition time incurred when the eye fixates in a non-optimal position, suggests that in careful word-by-word reading it would be advantageous to aim the eye accurately to the optimal position in each word. In fact, if the penalty for not fixating the optimal position is the same in normal reading as for isolated words, then an error of only two or three letters in aiming precision would lead to a 40 or 60 ms increase in recognition time. Given that normal fixation durations in reading are 250 ms on average, this penalty would give rise to a 15–25% decrease in reading rate, which is considerable.

Of course there are probably differences between optimal viewing position in reading and optimal viewing position in isolated words. Parafoveal preprocessing or linguistic context might modify the phenomenon, perhaps by diminishing the penalty for not fixating the optimal viewing position, or by modifying its location in words (though see Vitu and O'Regan, 1988). Further, the notion of optimal viewing position in words should perhaps be generalized to groups of words: particularly groups of two or three very short words may be recognized in a single fixation if this fixation is appropriately placed. I will leave these issues for future work, and assume provisionally that in careful reading the optimal viewing position in each word is used, and that an efficient strategy for careful reading would be to move the eye from optimal viewing position to optimal viewing position.

But unfortunately, as we have seen in the preceding sections, the exact place where the optimal viewing position is located in each word depends on characteristics of the particular word (such as its informational or morphemic structure, frequency and length) and so cannot be known in advance. If the eye were to attempt to calculate, from poor-quality peripheral information, where this optimal viewing position might be, then we would be back to the situation of the perceptual span control hypothesis, where eye movements would be guided by the result of some time-consuming perceptual or linguistic calculation. If this were true, then we should have found a direct relationship between perceptual span and saccade size, which we didn't.

Instead of using the true optimal viewing position, an effective scanning routine must therefore somehow use coarse visual clues to take a bet on where in each successive word the optimal location generally is. Now, from the data available for French words of various length, frequency and structure, the 'generally optimal' position is at the middle or a little left of the middle of words. A reasonable bet for a scanning routine would therefore be to aim the eye to this 'generally optimal' position, i.e. to the middle or left of middle of each successive word (for French).

But can the eye attain this position accurately, and what happens when it misses? The section on visuo-motor constraints showed that even when the target position is defined in coarse visual terms, in the case of a complex visual field, as found in reading, accurate aim may still be quite time-consuming. In the 250 ms of an average fixation in reading, can the eye determine the location of the word's boundaries, estimate the middle of this region, and send the eye there? Evidence from studies with series of isolated crosses to fixate, which is presumably simpler than estimating the middle of a word, show that with fixation durations around 300 ms accuracy is far from perfect, and many correction saccades are made (Rayner et al., 1983; Kapoula, 1984). Thus, in reading, not only is it better not to wait for the edge of the perceptual span to be extracted, it may also not even be a good idea to wait for such an apparently easy-to-extract location as the generally optimal position to be located. It may be more efficient instead to program an approximate saccade quickly, and have a 'rescue tactic' ready when the eye arrives in the wrong place.

What exactly would the appropriate rescue tactic be? Presumably precisely the one I have observed in word recognition in the preceding sections, and which gives rise to the optimal viewing position phenomenon. That is, when the eye lands beyond a critical distance from the generally optimal viewing position, it rapidly makes a saccade bringing it to the other side of the word from where it is. (It might have been thought that an appropriate rescue tactic would be to make a correction movement bringing the eye accurately to the generally optimal viewing position. This would be analogous to the correction saccade that occurs when saccading to a target in a visual scene. However, the data (Fig. 13) for isolated words suggests that actually a more effective tactic is to move to the other side of the word – presumably even though the initial fixation was in a non-optimal place, some lexical processing would have started there, and it is better to move the eye somewhere where the most processing remains to be done.)

In summary: reading involves two fairly autonomous processes: a process of lexical and linguistic analysis which occurs on the basis of the available visual information; and a pre-programmed scanning routine which uses only coarse, easy-to-extract visual cues to guide the eye, but does so in such a way that (1) the eye quite frequently falls near the generally optimal viewing position of each word, but (2) when it does not, rescue tactics are engaged which allow the word still to be recognized. A suitable scanning routine would be the following (but see later for other possibilities).

Between-word strategy: When leaving a word, attempt (within the possibilities of visuo-motor constraints) to move to the 'generally optimal' viewing position (for French and probably English: middle or left of middle of the next word).

Within-word rescue tactics: If the landing error relative to the generally optimal position is greater than some critical value (to be defined), immediately make a saccade to the other side of the word from where you currently are. Then return to the between-word strategy.

6.3. Temporal aspects of the scanning routine, and cognitive intervention

As yet I have not discussed the temporal aspects of this scanning routine. What determines WHEN the between-word or within-word saccades occur? The hypothesis that can be made for 'careful word-by-word reading' is that the eye only moves to the next word when the word has been 'recognized' (i.e., some well-defined stage in the word recognition process has been attained – see later for other possibilities). Triggering the between-word saccades would thus be under the control of the ongoing lexical and linguistic processing. Triggering the within-word rescue saccades would be under the autonomous control of the scanning routine, and would occur automatically when the generally optimal position had been missed.

There is an interesting consequence of the idea that between-word saccades are triggered by word recognition. Consider the case when the fixated word is highly predictable or easy to recognize. Saccade triggering will occur very rapidly: in fact it may occur well before an accurate target can be determined for the saccade. The saccade may therefore be very inaccurate. This seems most likely to occur when the eye lands on a short, predictable word, or a word that was already partially processed in parafoveal vision before the eye landed on it. The consequence of this is that in reading easy text, it may often happen that the eye doesn't manage to land anywhere near the generally optimal viewing position of the next word, and may even land somewhere outside the next word. In particular, when the next word is a short word, because of the center of gravity effect, the word following the short word may exert an influence on the saccade, and the eye may tend to skip over the short word. But this is not a catastrophe, because if reading is easy, then there may be less need to land accurately at the generally optimum position.

An implication of this is also that despite the fact that I have called this kind of reading 'careful word-by-word' reading, the eye actually may not move from word to word. When the currently fixated word is easy to recognize, saccade size variability becomes greater.

6.4. Lexical influences on saccade size and fixation duration

A number of points about this proposition for eye movement guidance should be made. The first point concerns which kinds of information influence saccade size.

Saccade size is assumed to be determined only by coarse visual information concerning the inter-word spaces. The justification for this is the idea obtained from the section on visuomotor constraints that saccade size computation is difficult in a complex task such as reading. If the eye were to take account of perceptual cues such as letter or word identity, this would require even more time than taking account of coarse visual clues, and I concluded that doing this was difficult enough given the 250-ms fixation durations found in reading. Linguistic processing is, therefore, very unlikely to affect saccade sizes unless the prior fixation is unusually long.

The idea that saccade size generally does not depend on lexical or linguistic information implies that the eye cannot usually jump over a predictable word, or a word that is easy to recognize in parafoveal vision. In addition, when within-word tactics occur, the position the eye goes to when refixating a word cannot be determined by the identity of the word and, a fortiori, it cannot depend on where the true optimal viewing position of the word is, only on where the 'generally optimal' position is, since only this can be determined from coarse visual information about inter-word spaces.

Another point concerns what the present proposal predicts about fixation durations. Whereas saccade sizes are assumed to be exclusively determined by inter-word spaces, fixation durations are governed in two different ways, depending on whether they precede between-word saccades or within-word saccades. Between-word saccades are triggered by the completion of some stage of lexical processing. Fixation durations preceding them should be influenced by the difficulty of this processing, and therefore should reflect aspects of the word such as its frequency, length or morphemic structure. Within-word saccades, however, are governed by the autonomous scanning routine's detecting that fixation in the word is insufficiently near the generally optimal position. The visual processing necessary to detect that this has happened is probably in general more rapid than lexical processing. I therefore predict that when the eye lands far from the generally optimal viewing position and two fixations occur in a word, then the duration of the first of the two fixations will be determined purely by visuo-motor constraints. In particular, we have seen in the study of 2-fixation tactics in the case of isolated words that the duration of the first fixation of the two will depend on the position in the word where it occurs.

Another interesting aspect of the present model concerns the probability of making two fixations in a word. Again, the model supposes that a rescue tactic will be invoked when the eye misses the generally optimal viewing position. This is not dependent on the word's lexical structure and, in particular, it does not depend on where the optimal viewing position in the word really is, only on where the eye lands with respect to the 'generally optimal' position.

6.5. Alternative scanning routines for different occasions

The present proposition of 'careful, word-by-word' reading is only an idealized step towards more realistic models, and can be modified in various ways.

One possible modification concerns the moment at which between-word saccades are triggered. The suggestion made above that saccades leave a word after some phase of 'recognition' has occurred leaves open the question of exactly what phase of recognition is involved: is it the identification of the word's constituent letters, the generation of some preliminary access code, the completion of some phonological recoding process, access to knowledge of the word's presence in the internal lexicon, or the access to the word's meaning? These are open questions, but I suspect that the various intermediate stages of word recognition cannot normally generate 'signals' that can be used to trigger saccades, and attending to the covert stages of word recognition would require additional processes which are alien to normal reading. One candidate for a saccade-triggering signal might be the generation of an articulatory or 'pre-articulatory' response, as when one sub-vocalizes a word to oneself or 'hears' it while reading.

But this is only one of a range of other possibilities that might trigger between-word saccades. At the most 'motor' level, each saccade could serve as the warning stimulus to trigger the next saccade. This would lead to a very fast sequence of saccades, but they would be rather inaccurate, and frequently miss the generally optimal viewing position. In addition, there would be little time for the visual percept to clear up after each saccade. This kind of scanning can be experienced by moving the eyes in a very rapid series of saccades (not a smooth pursuit movement, which is impossible to make without a moving target) across the lines, so that the words seem to glide past the eye and appear blurred, and reading is impossible except at the ends of the lines where the eye stops for longer.

Another possibility for an event that might be used to trigger between-word saccades might be some visual event, such as detection of the retinal image becoming immobile or cleared up. Another possibility would be to trigger the saccade when the eye's position in the word can be ascertained (e.g. 'I am about in the middle of the word, I am on the left edge of the word, etc.').

These different possibilities would require varying amounts of time, and would therefore lead to latencies of different durations and saccades of varying degrees of accuracy, and so to different styles of reading. It would be the reader's choice which of such styles he or she wished to adopt, as a function of the amount of time he or she wished to assign to lexical processing and text-understanding, and of the risk he or she was willing to take of having to reread.

A further modification of the strategy-tactics model suggested here is certainly necessary to account for the way children or very slow readers read. For these readers, word recognition perhaps cannot usually be done in one or two fixations, and the simple, visually based within-word scanning tactics I proposed for normal reading would not apply. Instead, such readers may use some form of more extensive within-word scanning. Since, as seen in section 4.2, making small saccades is difficult, these within-word fixations will have to be long. This purely visuo-motor factor may be important in understanding children's eye movements. Other factors, such as an increased need to reread sentence portions, would of course also contribute.

Another place where the strategy-tactics model presented here might be modified is in its spatial characteristics. I have suggested that the eye should attempt to aim at the 'generally optimal' viewing positions in successive words. But an almost equally viable strategy might be to aim say three characters beyond the next space. It might equally be feasible simply to move forward a fixed number of letters. The reader might also adopt the riskier strategy of not fixating each word at all, and attempt to jump only to every other word. Different readers may have evolved different strategies. Certainly different strategies will have to be used in alphabetic languages where spaces between words are not marked, such as Thai, or in Chinese, where spaces between words and between within-word morphemes are not distinguished. In Japanese, function and content words can be distinguished on the basis of visual density (content words end in denser kanji symbols), and this may sometimes help to direct the eye. However, all these strategies will have to comply with the constraints of visuo-motor programming. In particular, inter-word strategies requiring precise aiming are probably unrealistic.

Another question concerns the within-word tactics. According to the suggestions made above, these were triggered by the eye's arriving 'too far' from the 'generally optimal' viewing position. Now different readers may use different definitions of the generally optimal position, and different definitions of 'too far', and in fact the adequacy of their definitions may explain part of the differences in their reading speeds. One factor contributing to the difference between fast and slow readers might be that fast readers have evolved an aiming strategy that tends to get their eyes more accurately on the generally optimal viewing position. A given reader could induce different reading styles by modulating the criterion used for refixation: for fast reading, a tactic of making no within-word refixations at all might be used.

7. Evidence for and against the strategy-tactics theory

Despite various modifications that might be made to the between-word strategy and within-word tactics to accommodate different reading styles, different readers, different languages and different tasks that the reader sets himself or herself, the main characteristics of the strategy-tactics proposal remain invariant and are amenable to testing. Since the theory is new, little work has as yet been done to test it directly. In the following sections I will review what already existing evidence is relevant.

7.1. Evidence on saccade size

An essential premise of the strategy-tactics theory is the idea that saccades are hard to aim accurately, so neither between-word saccades nor within-word saccades should generally show influences of ongoing lexical processing. The only variables that should influence saccade sizes in reading should be variables related to crude visual information such as the lengths of words or the position of spaces in the text, and center of gravity effects should be

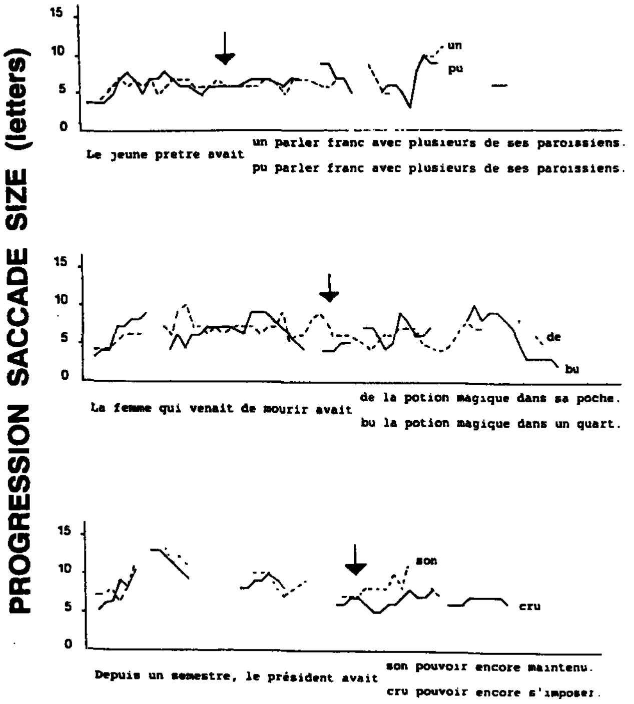

Fig. 17. Progression saccade size for saccades leaving each letter of the sentences shown on the abscissa. Each data point is a median over saccades made by 22 subjects leaving that letter and the two adjacent letters. The solid curves correspond to sentences containing the verb, the dashed curves to sentences containing the article. Gaps in the curves are places where there were fewer than six saccades contributing to the data. The arrows show the critical location where differences in saccade sizes should occur if the eye is making use of parafoveal information about word identity to aim saccades. The top sentence is an example where no differences appeared. Seven out of 10 of the sentences in this experiment gave data like this. The middle sentence is an example where a difference did appear in the critical region. However, this may have been noise, because similar differences appeared in other regions (see saccades leaving the word 'qui' at the beginning of the sentence). The third sentence is an example where the difference did appear to be significant. Further analysis showed the difference to occur only in those saccades which were preceded by long fixations.

strong. However, an exception to this principle might occur when the fixation duration before a saccade is particularly long (this might happen if the eye lands at the generally optimal position and the word is difficult to process). In that case, there would be time for the computation of the following saccade to take into account lexical factors.

Crude visual clues certainly influence saccade size: I have found that saccades leaving or going into long words are longer (O'Regan, 1979, 1980). More recent evidence comes from the careful study by McConkie et al. (1988), to be described in the next section. My interpretation of the experiments using moving windows of different sizes is also that crude visual clues influence saccade size (cf. section 2.2).

A more critical test of the strategy-tactics theory concerns the assertion that saccade sizes must generally not be affected by lexical factors. A potentially excellent test of this was my 'THE-skipping' experiment (O'Regan, 1979). In this experiment, I had constructed pairs of sentences which had a common beginning, but which could end in one of two ways, one with a segment beginning with the word THE and one with a segment beginning with a three-letter verb. Under the strategy-tactics theory, there should be no difference in behavior when saccading into the THE or the three-letter verb. The only exception to this would be cases when the fixation before the saccade was unusually long. This would allow parafoveal processing to be influenced by the frequency or the lexical category of the THE or three-letter verb, and a difference in saccade size might appear, presumably with the eye skipping over the THE more readily than over the three-letter verb.

At the time, I had found that saccades were longer when saccading towards the THE than towards the verb. The effect was weak, amounting to a difference of only 1–2 letters. Was the effect weak because in fact, as predicted by the strategy-tactics theory, THE-skipping was occurring only when the eye happened to make a long fixation in the previous word? Unfortunately at the time I did not test for this prediction, and the data are no longer available to check it. I have therefore repeated the experiment recently, using French readers, and sentences containing either the French definite and indefinite articles 'le', 'un', 'du', 'de' and 'des' (highly frequent), or the (less frequent) verbs 'bu', 'du', 'lu', 'vu', 'été', 'ri', 'cru', 'pu', 'va'. For seven out of the ten pairs of sentences, there was no difference between the saccade size approaching the article and the saccade size approaching the verb (an example is shown in the top graph of Fig. 17). For the remaining three sentence pairs, differences appeared (bottom two graphs in Fig. 17) similar to those found in my 1979 experiment. Analysis of the durations of the fixations preceding the saccades that are influenced by the article/verb distinction shows that differences only appear when preceding fixations are of particularly long duration. This is precisely as predicted by the strategy-tactics theory.

A number of other authors have also considered whether or not lexical or linguistic factors can influence the probability of skipping a target word. Some studies found no skipping (Zola, 1984; Ehrlich and Rayner, 1981, second experiment). Other studies found skipping (Pollatsek et al., 1986; Just and Carpenter, 1980; Ehrlich and Rayner, 1981, first experiment; Balota et al., 1985; Schustack et al., 1987). Of these, Pollatsek et al. (1986) analysed fixation durations prior to the word being skipped, and found, as predicted by the strategy-tactics theory, that these were longer than when no skipping occurred. Unfortunately the other studies did not check whether skipping occurred predominantly when prior fixation duration was long. Also, when skipping was found, it may have been caused by purely visual factors. This is because it is very difficult to design an experiment where visual factors are kept completely constant, and yet lexical factors change. For example, if you notice that function words tend to be skipped more often than content words, this may merely be because function words tend to be shorter (cf. Kliegl et al., 1982, 1983). As another example, suppose you want to manipulate the predictability of a word to see if this influences its probability of being skipped. To do this, you have to change the word itself, or the context in which the word appears. These changes will almost inevitably be accompanied by visual changes. In fact, even in my THE-skipping experiment mentioned above, the effects might be due to something about the overall shape of the word THE rather than on its lexical category.

Another test of the strategy-tactics theory was provided by experiments in which perceptual span was modified. According to the theory, since saccades from word to word are determined only by crude visual parameters, such as word length, so long as visibility is sufficient to see the block-shapes formed by words, word-to-word saccades in reading should be unaffected even in conditions of a small perceptual span. This is counter to the idea that saccade size might be approximately adjusted to perceptual span size. Evidence relevant to this issue has already been presented in section 2.6, where it was indeed noted that changes in perceptual span provoked by changing viewing distance did not affect saccade size in reading. A further study by Lévy-Schoen and O'Regan (1987), in which perceptual span was very strongly reduced by blurring the retinal image, also showed stability of saccade sizes, as predicted. However, in both this and the O'Regan et al. (1983) experiments, fixation durations did rise significantly when perceptual span decreased. This can be explained by invoking changes in the within-word tactics, which are sensitive to lexical processing and thus perceptual span.

7.2. Evidence on landing position

The strategy-tactics theory suggests that the eye in reading should ideally be aiming at the 'generally optimal' position in words, but that visuo-motor constraints, in particular the center of gravity effect, would prevent it from accurately attaining this position, particularly when preceding fixation durations are short.

Dunn-Rankin (1978) and Rayner (1978) had investigated the position in words where the eye tends to land, and found that this position, called the 'preferred landing position', is near the middle or left of middle of words. This certainly suggests that the eye is not moving randomly, and is aiming somewhere definite. But the result does not tell whether the position actually attained is the position being aimed at. In fact Blanchard and McConkie's data mentioned in sections 5.7 and 5.8 (Fig. 16) showed that the position the eye tends to attain is in fact different from the generally optimal position.

This is compatible with the pattern observed recently by McConkie et al. (1988), who examined landing positions in words of different length in reading as a function of the eye's launch site in the preceding word, and came to the conclusion that the eye was indeed attempting to aim for a particular location in words (which they called the 'functional target location'), but that it does not accurately attain it. When the eye starts very close to the next word it tends to overshoot this location, and when it starts very far from it it tends to undershoot the location. This kind of spread in landing positions is similar to the range effects observed by Kapoula (1985). It is compatible with the center of gravity effect, and is expected from the strategy-tactics theory when fixation durations are short.

7.3. Evidence on fixation durations

The predictions of the strategy-tactics theory concerning fixation durations are as follows.

A. (i) Gaze duration, that is, the sum of fixation durations on a word in reading, should be strongly dependent on the first location where the eye fixates in the word, and show an optimum viewing position curve as found in the experiments on individual words described in section 5. (ii) Gaze duration should also depend strongly on lexical processing.

B. (i) When a single fixation occurs in a word, its duration should not depend strongly on the eye's position. (ii) However, it should depend strongly on lexical processing.

C. When two fixations occur in a word, the duration of the first should depend strongly on its location in the word, but not strongly on lexical factors. The duration of the second should depend strongly both on the position of the first fixation and on lexical processing (with the trade-off curves as found in Fig. 14).

These predictions have never been tested in the literature, but in some cases partial evidence can be gleaned from existing work. Prediction A(i), the dependence of gaze duration in a word on the eye's initial fixation location in a word, is the cornerstone of the strategy-tactics theory. It has of course been confirmed for the first word of short phrases, since this is the optimum viewing position phenomenon described in section 5. In normal reading it has been confirmed in the unpublished data provided to me by Blanchard and McConkie (see Fig. 16, and discussion in section 5.8). However, further verification is necessary. In particular, it would be interesting to do a reading experiment in which words only become visible when the eye lands upon them. This would prevent parafoveal processing of upcoming words from modifying the optimum viewing position phenomenon, and similar optimal viewing positions should be found as in the experiments reported in section 5.

Prediction A(ii) that gaze duration should depend on lexical processes was confirmed in multiple regression analyses by Just and Carpenter (1980), although Kliegl et al. (1982, 1983) noted that most of the effects might not be lexical but merely related to word length. An explanation of the weakness of lexical effects on gaze duration may be the existence of a very strong effect of initial fixation location expected from the strategy-tactics theory, which might swamp lexical effects on gaze duration if first fixation location is not factored out. Further work must be done similar to Carpenter and Just's and Kliegl et al.'s, but in which initial fixation location is also used as a factor in the multiple regression.

An extremely interesting study by Hogaboam (1983) came very close to being a test for the strategy-tactics theory's predictions concerning the effect of initial fixation location on the duration of single, first of two, or second of two fixations (predictions B and C). Using a reading task, Hogaboam classified patterns of saccades into various classes, including within-word and between-word saccade sequences. He then applied multiple regression analysis to attempt to determine what factors influenced which fixation durations in the particular patterns. Of interest here is his analysis of the influence of lexical factors such as word frequency and length on fixation duration in the case where a single fixation on a word occurred, and in the case when two fixations occurred before the eye left the word. Hogaboam found that when a single fixation occurred, this fixation's duration was affected significantly by lexical factors. This is as predicted from the strategy-tactics theory. When two fixations occurred on the word, Hogaboam distinguished two patterns: a regressive one, where the second fixation was in the word, but to the left of the first fixation, and a progressive one, where the second fixation was in the word but to the right of the first. For the regressive pattern, lexical factors affected the second fixation duration, but not the first. This is expected from the strategy-tactics theory. However, for the progressive pattern, lexical factors affected the first fixation duration, but not the second. This result is not expected from the strategy-tactics theory. However, one of the stepwise regressions performed by Hogaboam in this case only showed a marginally significant contribution of lexical factors. It is possible that some of the progressive patterns were cases where the progressive saccade was aimed to the following word and undershot. The first fixation would have been at the generally optimum position and therefore reflected lexical processes. Further work must be done to check this. In addition, a better test of the strategy-tactics theory would have been possible if the initial fixation point in the word had been included as a factor in the multiple regression analysis.

Some other studies in addition to Hogaboam's are relevant to the question of the effects of lexical factors on the duration of fixations. But unfortunately these studies did not distinguish within-word tactics in which single fixations were made from tactics when two fixations were made. Authors have used the measures 'average fixation duration on a word', which may include contributions from first and further fixations, or 'first fixation duration', which means 'first' independently of whether there were one or more fixations in the word. Since both these measures include cases when a first and single fixation was made, I predict that both will reflect lexical processing somewhat. But because both of these measures are diluted by the presence of first fixations when there are two in a word, and these first fixations are not expected to depend on lexical factors, the composite measures will not be as sensitive as they could be to lexical factors. The eye's initial fixation location in a word will also influence these measures and increase their variability. Nevertheless, the strategy-tactics theory predicts that lexical processing should affect these measures, albeit weakly because of the confoundings.

Rayner (1977) studied eye behavior in sentences of the form 'The + subject + verb + the + object + prepositional phrase'. He found that 'average' fixation duration on the verb was longer by about 20–30 ms than on the subject or object. Ehrlich and Rayner (1981) tested the effect of context on fixation durations, and found that 'average' fixation duration on an unexpected word was longer than on an expected word. However, the authors did not use item statistics to verify that the effects were not due to one or two peculiar items in the experimental material. Zola (1984) showed that the 'first' fixation duration on a noun preceded by an adjective was 16 ms shorter if the noun was strongly rather than weakly constrained by the adjective (e.g., moviegoers desire 'buttered popcorn' vs. 'adequate popcorn'). First fixation duration was also longer if the noun was misspelled. However, again no item statistics were done. Underwood and McConkie (1985) did a study in which, during reading, the eye sometimes fell on a word in which several letters were replaced by dissimilar letters, so that the word could not be recognized. The authors observed that the duration of the affected fixation increased by 12 ms. Rayner and Duffy (1986) studied the effects of various lexical variables (frequency, lexical complexity and ambiguity) on eye movements. They found that 'first' fixation duration on a high-frequency word was shorter than on a low-frequency word by about 37 ms. Inhoff (1984) attempted to determine whether in word recognition during reading, lexical access and word interpretation are two separate processes or not. He studied the effect of word frequency and contextual constraint on first fixation and gaze duration in cases when there was or was not a small (1 or 3 letter) foveal mask that moved with the eye. Inhoff observed weak effects of frequency but stronger effects of predictability (contextual constraint) on 'first' fixation duration. On the other hand, Balota et al. (1985) observed that the 'first' fixation duration on a word was influenced by whether the parafoveal preview of that word was visually similar to it, but not by whether the word was predictable from its context.

All these findings, which generally show weak but consistent effects of lexical variables such as word frequency, contextual constraint, lexical category, are consistent with the strategy-tactics theory. But it is likely that stronger data would have been obtained if the effects on single and multiple fixations had been analysed separately, and if initial fixation location in words had been taken into account.

7.4. *'Immediacy'*

The question of how tightly eye movements are yoked to perceptual and cognitive processing in reading has been called the 'immediacy' question, and has been a central issue in eye movement research over the last fifteen years. For an excellent treatment of some of the issues involved, see McConkie (1983). Ehrlich and Rayner (1983) also discussed the problem clearly, and distinguished between three groups of theorists: those who think that there is a cognitive or eye-mind delay between eye movements and processing (Kolers, 1976; Bouma and de Voogd, 1974; Morton, 1964), those who think eye movements reflect some but not all linguistic processing done on the fixated word or words ('process-monitoring hypothesis', Rayner, 1977, 1978), and those who think eye movements (at least gaze durations) reflect all the linguistic processing done at the point fixated, that is, the eye-mind delay is zero (Just and Carpenter, 1980).

The strategy-tactics theory has a compromise status with respect to these theories in the sense that it considers all of them to be right in some way. Thus, because of the difficulty of accurately extracting a saccade target, the strategy-tactics theory proposes that it is often more efficient for the eye to move on the basis of crude visual clues rather than on the basis of lexical or linguistic processing. There will thus appear to be an eye-mind delay between eye movements and processing. On the other hand, the idea that there should be a scanning routine which is modulated by ongoing processing is also comparable with the 'process-monitoring' view. Finally, since the strategy-tactics theory assumes that the eye moves on from one word to the next when some stage of lexical processing has been reached, the gaze durations on words should reflect that lexical processing. This is compatible with the idea that, for gaze durations, the eye-mind delay is zero.

The advantage of the strategy-tactics theory is that it makes precise predictions about which text factors should affect which eye movement variables and when. Crude visual clues should always act immediately on eye movements, since they determine where each between-word and within-word saccade goes. They also partially determine the duration of fixations when there are two fixations in a word. Lexical information, however, has a more subtle influence: it does not determine saccades (unless the prior fixation duration is long for some reason), and it determines fixation durations only sometimes: it determines the duration of single fixations in a word, and the duration of second fixations when there are two. Lexical information does determine gaze duration, but the influence is complicated by the simultaneous influence of the position of the first fixation in the word: when this is not at the optimal viewing position, a substantial penalty of 20 ms per letter of deviation from the optimal position is added to gaze duration.

Past studies concerned with immediacy have of course not been designed to test the predictions of the strategy-tactics theory, and so they do not make the distinctions the theory requires between single and multiple fixation tactics within words. What past studies have been concerned with is determining whether information gathered at the current fixation can immediately influence the next saccade or the current fixation duration. Unfortunately, however, the methodology that was used leaves open the possibility of alternative explanations.

For example, while there is no doubt that saccade sizes are affected by the length of the currently fixated word and that of the next word, (e.g., O'Regan, 1979, 1980), no one has up to now excluded the possibility that the word length effect occurs on the basis of word length clues extracted in peripheral vision *several fixations before* the eye gets to the current fixation. Another example concerns the effect of lexical processing of the currently fixated word on the current fixation duration. Several of the studies mentioned in the preceding section show effects of the currently fixated word's lexical properties on the 'first' fixation duration on the word, but in all but one of these studies parafoveal processing of the currently fixated word could have occurred on prior fixations, so there is no guarantee that lexical processing of the word was having a truly immediate effect on the current fixation duration. The study where no parafoveal processing of the word could have been done is that of Underwood and McConkie (1985), who looked at what happens when the eye falls on a misspelled word. In this study, by use of eye-contingent computer display, the misspelling appeared only when the eye landed on the word, so no prior parafoveal information was available about the error. Perhaps this is why the authors observed a much smaller lexical effect (12 ms) than the other studies (20–40 ms) cited above.

Another point concerns the use of the measure 'average fixation duration'. Three of the studies mentioned in the preceding section show lexical effects on average fixation duration. But since in some cases several fixations will have been made on a word, changes in average fixation duration may have come about because of changes not of the first fixation, but only of the second fixation in a word. These studies cannot be used as evidence for true immediacy of fixation durations.

Rayner and Pollatsek (1981) set out to give a definitive demonstration of the moment-to-moment influence on saccade size of the information gathered at the current fixation. The idea was to restrict parafoveal vision by means of a moving window whose size was changed from fixation to fixation. If saccade size adapts from moment to moment to the size of the window, this would be a good demonstration of moment-to-moment control of saccades as a function of locally gathered information. The authors did indeed demonstrate such immediate adaptation. However, the question arises of what information was driving the adaptation. If it was anything other than gross visual cues, then the strategy-tactics theory would be in trouble. But in fact the theory has no difficulty explaining the result, since the window used by the authors was a moving 'grating' that filled the spaces between words, and spaces are of course precisely the kind of gross visual cue that the theory proposes can be used to guide saccades on a moment-to-moment basis.

7.5. What eye movement measure for psycholinguistics?

Eye movements are being used increasingly often as an index of readers' cognitive processes during sentence comprehension. Excellent examples can be found in the reviews by Rayner and Pollatsek (1987) and Frazier (1987). In all this work, linguistic factors are generally manipulated, and the resulting changes in eye movements are used to make inferences about linguistic processing. The problem is that the changes in the text that must be made to manipulate linguistic structure are inevitably accompanied by changes which have visual correlates, such as changes in word length or number of words. Researchers have therefore attempted to use eye movement measures which are insensitive to these visual influences. Unfortunately no completely satisfactory measure has been developed as yet, and workers resort to using a range of measures: generally 'gaze duration', 'average fixation duration', 'time per letter', 'probability of fixation'. However, the strategy-tactics theory suggests that all these measures are strongly influenced by visuo-motor factors related to the scanning routine. The following paragraphs give a few examples of how this can occur.

The use of gaze duration as a measure of processing has already been criticized in section 7.3: because of the optimal viewing position phenomenon, this measure will depend strongly on initial fixation location in the word. Gaze duration has also been criticized by Blanchard (1985), who pointed out that the principle underlying this measure is what he calls the 'trade-off' assumption, which is the idea that multiple short fixations are equivalent to one long one. This principle, he says, has not been proven. And indeed, evidence from my experiments shows (i) that when two fixations are made in a word, the sum of their durations is about 75–100 ms longer than when a single fixation is made (cf. O'Regan and Lévy-Schoen, 1987), and (ii) that two fixations occur for visuo-motor reasons, not for lexical processing reasons (when the eye fixates too far from the generally optimal position). Thus when two fixations occur, there will be a penalty of 75–100 ms linked to visuo-motor mechanisms, not to lexical processing. Coherent with this is Blanchard's (1985) finding, in a heirarchical regression analysis of eye fixations in text reading, that the number of fixations made in a word correlates only with word length, not with word frequency, whereas their durations correlate with word frequency, not with word length.

Frazier and Rayner's study (1982) is one example of a number of studies which use total time per letter as a measure of processing time. To test theories of sentence parsing, Frazier and Rayner considered sentences where an ambiguous noun phrase leads the reader's eye 'down the garden path' before it reaches a disambiguating region. An example is: "Wherever Alice walks her shaggy sheep dog will follow", compared with "Wherever Alice walks her shaggy sheep dog men follow". They observed differences in the total time per letter spent by the eye in critical regions of the sentences and used these differences as arguments to distinguish between possible theories of sentence parsing. They used the variable 'time per letter' in order to compensate for the fact that some of the sentence portions they wanted to compare were not of the same length. For example in the above case, what they called the 'disambiguating region' of the sentences was 'will follow' for the first and 'men follow' for the second sentence (one letter difference). More drastic differences in the length of the disambiguating region occurred in other sentences when they compared 'she laughed' to 'were laughing', or 'all the' to 'was running', or 'her history' to 'will be'.

Now it is not clear whether the variable 'time per letter' adequately compensates for the differences in length. By superimposing the high-frequency curves for words of 7 and 11 letters in Fig. 11 (and this is also true if 5- and 9-letter words are added: cf. O'Regan and Lévy-Schoen, 1987), it would be seen that the increment in gaze duration on these words when length is increased depends on where in the word the eye was fixated (there is virtually no increment if the eye fixates near the end of the word, whereas there is if the eye fixates near the beginning of the word). There is also an effect of the word's frequency (there is more increment for low-frequency words). These are confounding factors which will interact with the 'time per letter' measure. They will certainly have increased the variance of the data. Also, they may have appeared on particular sentence pairs and given rise to an apparent overall effect in the Frazier and Rayner experiment. (Unfortunately the authors did not verify this possibility by doing item statistics. This would have also allowed them to discount the possibility that the observed effects were due to other differences in the regions being compared, such as word frequency and semantic effects.)

Like many authors, Frazier and Rayner also used another measure of processing, namely average fixation duration over a given region. But this measure is also not wholly satisfactory. According to the strategy-tactics theory, when two fixations are made in a word both tend to be shorter than if a single fixation is made. Two fixations tend to be made for visuo-motor (not linguistic) reasons, when the eye's position is too far from the generally optimal position. This occurs primarily in long words. Thus, sentence portions with long words will tend to have shorter average fixation durations. Thus, as before, if average fixation duration is used to compare processing across sentence parts, these must contain words of identical length. Similarly, since word frequency may also affect fixation duration and the probability of making additional fixations, this factor should also be controlled when making comparisons. Ideally, sentence portions to be compared should be identical, and item statistics should be used.

As another example that suffers from similar problems, consider one experiment in a study by Ferreira and Clifton (1986). These authors attempted to verify the 'modularity' of syntactic processing by showing that prior contextual bias does not change the reader's low-level parsing strategy. One source of evidence for this view came from their finding that while prior context changed nothing in the 'reading time per letter' measure, a syntactic difference did change reading time per letter: in particular, when the syntactic ambiguity in: "Sam loaded the boxes on the cart..." was removed by reading the following sentence portion, 'onto the van', times were longer on this disambiguating region than on the purportedly easier 'before his coffee break' disambiguator. But this difference could have been caused by the fact that the 'before his coffee break' type disambiguators were always longer than the 'onto the van' type disambiguators. If (as is probably the case) the 'time per letter' measure does not actually compensate adequately for word length, then some of the effects observed in this experiment could be due to these systematic length differences.

What would be an appropriate measure of cognitive processing? O'Regan and Lévy-Schoen (1987) suggested a possibility in which gaze duration would be 'corrected' by subtracting an approximately 75–100 ms 'visuomotor penalty' for each additional fixation made after the first. But this suggestion is an extrapolation of data from studies on isolated words, and empirical justification in normal reading is still required. Also, other problems with this measure have still to be studied. For example, the penalty may not be the same going from the first to the second as going from the second to the third fixation in a word. There is also some suggestion that a better correction 'formula' should contain a small term depending on the eye's initial location in the word and on the word's length. Finally the 'formula' would probably be valid in what I have called 'word-by-word' reading, in which no parafoveal preprocessing of upcoming words is done, but it is unclear whether modifications must be made for normal reading. However, there is hope, if the strategy-tactics theory is right, that in future work a purer index of linguistic processing can be found than the measures that have been used up to now.

8. Conclusion

For the last fifteen years an impressive body of work has accumulated on the subject of eye movements in reading. Within this, one of the most intensively studied topics has been 'perceptual span', probably because of the underlying assumption that in reading the eye moves from span to span. This chapter started by reviewing a number of recent studies of perceptual span, and by showing that in fact something other than perceptual span must be determining where the eye goes at each saccade, and how long it stays at each fixation. This led to the conclusion that it might be necessary to give up the hope that instantaneous eye movement variability is purely caused by sensory or cognitive processing, and consider some of the low-level visuo-motor constraints that might also be active. It may be that eye movements have a life of their own that must be respected before they can be used as an indicator of cognitive processing.

An inventory of possible spatial and temporal visuo-motor constraints on eye movements then provided two important ideas which would help to understand eye movement behavior in reading. First, it appears that long latencies are necessary to aim the eye accurately, so it is usually better to program many quick, inaccurate saccades, based on crude visual cues, rather than few accurate ones based on fine cues. Second, visibility, even in the fovea, drops off catastrophically, and so even short words may need several fixations to be recognized.

The drastic drop-off of visibility even in the fovea led me to discover the optimal viewing position phenomenon: depending on its length, frequency and lexical structure, each word has a (possibly different) optimal viewing position, where the eye must first land in order to recognize the word most quickly. A study of the eye movement tactics underlying this very strong and reliable phenomenon provided the basis for a preliminary theory about eye movements in reading, the 'strategy-tactics' theory. In the final sections of the chapter I compared the predictions of the theory with the available evidence. Though the theory withstood the test successfully, more work needs to be done, since up to now its detailed predictions have not been tested.

A difference between the strategy-tactics theory and previous work on eye movements in reading is that the strategy-tactics theory is a 'mechanistic' model that attempts to describe as precisely as possible where the eye will go next and how long it will stay at each point in a text. In the past, workers have been concerned with studying the effects of various typographical or linguistic variables on eye movement parameters without trying (or at least without succeeding) to pin down the rules governing the behavior of individual saccades and fixations. I think the strategy-tactics theory is a breakthrough in this direction, because it sets out a preliminary testable set of rules, and thereby opens new lines of research, even if it turns out to need radical modifications. The breakthrough has come about, I believe, by giving greater respect to low-level constraints in the visuo-motor system.

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