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Reading Unspaced Text: Implications for Theories of Reading Eye Movements

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According to current theories of reading, the reader's saccades are guided primarily by spaces between words, clearly the most prominent visual feature in most modern texts. This belief was investigated by recording eye movements with unprecedented accuracy and precision while subjects read spaced and unspaced passages both silently and aloud. Modest increases in fixation durations and decreases in overall reading speed were observed when unspaced texts were read. However, subjects read unspaced texts with the same level of comprehension and percentage of regressions as they read spaced texts. The only global eye movement parameter that changed appreciably when spaces were removed was progressive (rightward) saccade length. Progressive saccades were shorter in unspaced texts. However, unspaced texts were denser and narrower because they were constructed so as to contain the same number of words/line as the spaced texts. This meant that unspaced texts contained more informational characters/degree of visual angle. The observed decrease in progressive saccade length tended to be proportional to this increase in text density. Therefore, the number of saccades/line of text remained approximately the same in both spaced and unspaced texts. Furthermore, a detailed examination of local eye movement properties, i.e. where within words the subjects fixated and how many times they fixated words of different lengths, suggested that the same oculomotor strategy was used for reading spaced and unspaced texts. This was true for both silent reading and reading aloud. Thus, a model that could explain reading spaced texts could also explain reading unspaced texts with only a change of a single global parameter, namely, saccade length. We conclude that the current tendency to emphasize spaces as guides to reading eye movements must be reconsidered. Words, not spaces, may serve as the perceptual units that guide the line of sight through the text.

Reading Saccades Regressions Optimal viewing position Word recognition

INTRODUCTION

Today, we take spaces, punctuation and capitals in text for granted. So much so that modern theories of reading eye movements treat spaces between words as highly visible markers that guide the line of sight from one position in the text to the next. However, for much of Western history, text was written with letters strung together, without spaces, punctuation, capitals, or paragraphs. It was not until late in the eighth century that an English monk, Alcuin, acting on an edict by Charlemagne, introduced punctuation into Latin writing. Around the same time, with the Carolingian script reforms, scribes began to separate words by empty spaces. Capital letters at the beginnings of sentences did not become common until the twelfth century. In some books printed as late as sixteenth century, one can see words incorrectly divided by spaces, or running from one line to the next, a leftover from the days when spaces between words were not common. [This brief summary is based on Boorstin (1983). See his book for a very readable account of the history of Western writing and for additional details.]

Does this mean that the ancient and medieval scholars read very laboriously or used different reading eye movement patterns than are in use today? For that matter, does reading modern languages like Thai, which does not separate words with spaces, or German, which often runs several nouns together to produce very long, unspaced words, require different oculomotor patterns than reading Romance languages in which compound nouns are rare? According to contemporary theories of reading eye movements the answer to these questions should be "yes" (e.g. O'Regan, 1990; McConkie, 1983; Morrison, 1984; Pollatsek & Rayner, 1990; Rayner & McConkie, 1976; Jacobs, 1987; Rayner & Morris, 1992; Vitu, 1991a, b; Rayner, 1993). Our study challenges this widespread belief by showing that reading text without spaces is relatively easy and that there are no important differences in eye movement patterns or strategies when spaced and unspaced passages are read. In essence, our study asks a simple question and seeks its answer in a very straightforward way. The significance of what we did and found, however, can only be appreciated within the broadest context of contemporary approaches to

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research on reading eye movements. For this reason, our experimental report will be preceded by a relatively detailed review of the relevant literature. Our findings have broader implications that might not be apparent if this review were not provided.

Background

Reading eye movements have been the topic of many studies for more than 100 yr beginning with Javal (1878, in O'Regan, 1990), who placed a stethoscope-like device on the eyelid and heard the clicks produced by the eye scraping against the eyelid when reading saccades were made (see O'Regan, 1990 for a particularly insightful review of the large body of research on eye movements during reading). In the last 20 yr, most research on reading eye movements has concentrated on how visual factors affect the moment-to-moment programming of reading saccades. These factors are studied by manipulating the physical features of the text (e.g. font, case, spacing, color, contrast, etc.) and observing changes in the oculomotor pattern. Current understanding of how cognitive and perceptual factors affect reading eye movements is relatively poor. This is probably because the reader's internal processes are more difficult to monitor than eye movements and context and semantics are more difficult to manipulate than the physical features of the text. Perceptual components of reading include perceptual span (O'Regan, 1990) and identification of letters and letter patterns (words). Cognitive components of reading include word recognition, semantic and syntactic processing, hypothesis testing based on the subject's expectations about the grammatical structure and informational content of the text, as well as on the reader's schemata and mental models of the subject matter of the text (e.g. Just & Carpenter, 1980; Frazier, 1983).

Early studies of reading assumed that the eye movement patterns observed reflected the reader's cognitive processes directly and could, therefore, be used to understand their nature (e.g. Judd & Buswell, 1922). Viviani (1990) recently expressed grave doubts about this assumption. He pointed out a number of dangers inherent in attempting to infer mental operations solely by observing eye movements. One reason for his pessimism was that high level mental operations critical to reading (as well as to other tasks such as visual search or playing chess), unlike eye movements, are not likely to be sequential in nature (McClelland & O'Regan, 1981; Ehrlich & Rayner, 1983; Just & Carpenter, 1980). This makes it difficult, if not impossible, to find a simple correspondence between an observed series of reading eye movements and a series of internal mental operations that affect or result from these eye movements. Another problem arises from the need to assume that the part of the visual field currently being processed coincides with the fixation locus. This assumption ignores the possibility that attention and fixation need not coincide, noted by James (1890) and supported by psychophysical experiments (e.g. Reeves & Sperling, 1986; Khurana & Kowler, 1987). Once such concerns are identified it becomes easy to understand why contemporary studies of reading eye movements concentrate heavily on visual, rather than cognitive, factors. Spaces between words, arguably the most salient visual factor, have received special attention. While there is evidence that syntax and semantics affect how long the reader looks at a region of text (Ehrlich & Rayner, 1981; Frazier & Rayner, 1982; Just & Carpenter, 1980; Henderson & Ferriera, 1990), spaces are believed to play a crucial role in guiding the line of sight from one position in the text to the next (e.g. O'Regan, 1990; McConkie, 1983; Morrison, 1984; Pollatsek & Rayner, 1990; O'Regan, 1979; Rayner & McConkie, 1976; Jacobs, 1987; Rayner & Morris, 1992; Vitu, 1991a, b; Rayner, 1993). Rayner and Morris (1992) concluded from their review of recent literature that "landing position in words is determined by low-level visual information" (p. 165), namely spaces. The current opinion on the relative roles of visual and cognitive factors in programming reading eye movements was summarized in a recent review by Rayner (1993) who said that "Where to move next is based primarily on word length information and when to move is based on the ease or difficulty associated with processing the fixated word". In other words, it is believed that the durations of reading fixations (*when* to move the eye) are determined on the basis of cognitive factors, whereas endpoints of saccades (*where* to move the eye) are programmed by detecting spaces, since it is widely believed that word length information is obtained from spaces between words, rather than from word meaning. It is important to note that the theories that assume that visual factors guide the reader's eye movements do not restrict themselves to spaces. General terms like "low-level visual factors", or "physical features of the text" are often used. However, since word length information plays a key role in such theories, spaces and to a much lesser degree capitals and punctuation marks, are the only plausible candidates for the role of these low-level visual factors.

The theories of reading eye movements that do invoke cognitive components are usually limited to lexical access in the most primitive sense. For example, Rayner and Morris (1992) defined lexical access as the process of retrieving a word from a mental lexicon and making available the information about its properties, such as meaning, syntactic class, sound and spelling. They made no further hypotheses about what this process might be like or how it might interact with reading eye movements. Lack of information about the precise nature of cognitive processes involved in reading has led researchers to design experiments to minimize their significance. In many experiments, for example, the subject read individual words, short phrases or unrelated sentences, rather than coherent passages (e.g. O'Regan & Jacobs, 1992; Vitu, 1991a, b; Inhoff & Rayner, 1986). This kind of reading is quite different and not as efficient as the ordinary reading of everyday life. For example, it is known that anticipation of grammatical construction increases comprehension and reading speed (Wishner, 1976) and that sentences embedded in coherent paragraphs are read faster than single, unrelated sentences (Bader, Pierce & Thompson 1980).

It is helpful to consider the variety of approaches and explanations favored in prior reading research before details of our study are described. A discussion of these approaches, which can be divided into four categories, follows [see O'Regan (1990) for a different, but complimentary, treatment of these approaches].

Text-independent eye movements. The simplest approach to reading eye movements is that they represent a highly overlearned, automatic motor pattern. According to this text-independent, or "random control" approach (Haber, 1976), reading is similar to walking, in that the line of sight progresses in rhythmic steps of approximately equal size across the text. Just as walking can be adjusted to accommodate road conditions or the walker's skill, parameters of reading eye movements such as the average size of progressive (rightward) and regressive (leftward) saccades and the average duration of reading fixations can be adjusted by the reader from one reading session to the next on the basis of global features of text such as the size of the type and its intellectual difficulty. The extraction of information from the text occurs in parallel, independently of this automatic oculomotor process. In other words, moment-to-moment saccadic programming is completely independent of the text being read. The appeal of the text-independent approach is in its simplicity and the fact that it relies solely on observable behaviors, rather than on complex mental or visual factors, to explain reading eye movements.

The simplest version of the text-independent approach is the constant-step strategy which assumes that the eye moves the same number of characters at every saccade. It is unlikely that any reader actually uses this simple strategy because the variability in the size of reading saccades typically observed is large. The standard deviation of progressive (rightward) saccade size is typically around 50% of the mean, but can vary from subject to subject. For example, in Fig. 2 of O'Regan (1990, p. 399), which shows saccade size distributions for seven subjects, standard deviations range from 36 to 76% of the mean. Such variability seems too large for the constant-step strategy to be a good description of the data. However, highly variable saccade size does not preclude the text-independent model altogether. This variability can be explained by assuming that the size of each saccade is determined by sampling randomly from a normally, or otherwise, distributed population.

A study by Bouma and de Voogd (1974) supported the text-independent model by showing that the exact locations and durations of reading fixations are not important for correct and timely reading. In their study, the subjects were asked to keep their line of sight stable, while a line of text was moved from right to left at a rate and step size determined by the experimenter. Even under these unnatural conditions the subjects were able to read both silently and aloud with reading speeds and error rates comparable to those observed when they read normal text. From these results Booma and Voogd concluded that saccadic programming need not depend on cognitive processing of the text. They theorized that visual information acquired during each reading fixation is stored in a buffer and that processing this information can continue after the eye has moved to the next location in the text.

Another line of evidence supporting text-independent reading eye movements is the failure to find a significant correlation between the size of the reading saccade and the duration of the reading fixation just before or just after this saccade. The failure to find autocorrelations in either saccade-size or in the durations of reading fixations also supports the text-independent approach (Andriessen & De Voogd, 1973; Heller & Müller, 1978; Rayner & McConkie, 1976; Just & Carpenter, 1980).

On the other hand, it has been observed that reading eye movements are not completely independent of the text. Buswell (in Kolers, 1976) observed that the readers with little technical background fixate technical words more often than the readers who are familiar with those words. More recently, Rayner and McConkie (1976) found that the average number of fixations within a word is not proportional to the number of letters in the word. They called the number obtained by dividing the average number of fixations in words of particular length by word-length, the "probability of fixating a letter". If saccade sizes were independent of word length, we would expect that there would be, on average, twice as many fixations in 10-letter words as in 5-letter words, assuming that the words of different lengths are distributed randomly in the text. Rayner and McConkie found this not to be the case. Rayner and McConkie showed that very short and very long words received fewer fixations than a text-independent theory predicted. However, if words of different lengths were not distributed randomly in the text, e.g. if short words and long words tended to alternate, a text-independent eye movement model could still produce these results. This possibility will be considered later.

Another line of evidence against the text-independent approach to reading eye movements is the demonstration of what has been called the "preferred viewing position". This preferred viewing position has been inferred from the observation that the first saccade into a word tended to fall just to the left of the word's center (Rayner, 1979). The only way this pattern of results could occur within the text-independent eye movements approach is if the distribution of words of different lengths were not random in the text.

The dependence of reading eye movements on local characteristics of text observed in the research just described does not, however, preclude the operation of random factors. The next section describes a probabilistic model of reading eye movements that emphasizes such factors.

Suppes' probabilistic eye movement model. A step up in complexity from the minimal control, text-independent approach to reading eye movements, is the "text-dependent probabilistic control" (TDPC) model proposed recently by Suppes (1990). This model assumes that moment-to-moment saccadic programming depends in specific ways on local characteristics of the text and at the same time stresses the importance of probabilistic factors. According to Suppes "the phenomena [involved in reading] are too complicated and the movements involved are too unstable ever to hope to have anything like a complete deterministic account. Not only now but a 100 yr from now, probability distributions will be an important part of the best fundamental account of eye movements in reading" (p. 472). After examining the results of many experiments, Suppes concluded that at every reading fixation, the reader must choose one of several types of eye movement operations. These operations included staying within a word, going to the next word, going to the previous word, and skipping the next word. The probability of selecting a particular operation at a given time varies, depending on local visual, syntactic and semantic properties of text, such as word length, word frequency or grammatical structure, as well as on the status of the reader's cognitive processing of the region in the text currently fixated. Global eye movement characteristics can be adjusted for reading skill, types of reading (silent vs aloud), difficulty of the text, type size, etc. A similar model of eye movements, while doing arithmetic, worked well in simulating experimental data (Suppes, 1990; Suppes, Cohen, Laddaga, Anliker & Floyd, 1983), but no new data, collected specifically to test the model for reading, was available. (Suppes' type of probabilistic analysis was run on our reading eye movement data with interesting results, reported below.)

Unlike Suppes, most other reading researchers implicitly assume that a deterministic explanation of the reading eye movement pattern will be possible given a sufficient number of experiments on all of the many factors that may operate when saccades are programmed during reading. For example, McConkie (1983) published a table, which lists 35 "local influences" which have been shown to affect the reading eye movement pattern. Theories dealing with some of these influences are discussed in the next two sections.

Visually-guided eye movements. Both the existence of the preferred viewing position and the differences in the probabilities of fixating a letter in words of different lengths (described above) suggest that the lengths of the word currently fixated and the word to the right of the line of sight have an effect on the programming of reading saccades. These phenomena may be explained by assuming that the reader uses spaces to the right of the line of sight to extract information about word length. The word-length information is then used to calculate the endpoint of the next saccade. This strategy should be fairly fast and easy for the reader because detecting spaces in text does not require discriminating fine detail, which is required to disambiguate some common letter pairs (e.g. "l" and "i").

Recently, O'Regan (1990) proposed a "strategy-tactics" theory of reading eye movements, which places great importance on the role of local physical features in the text, specifically, spaces between words. According to his theory, the goal of each reading saccade is to bring the line of sight as close as possible to a position near the center of a word, which allows for the fastest recognition of the word (Grainger, O'Regan, Jacobs & Segui, 1992; O'Regan, Levy-Shoen, Pynte & Brugaillere, 1984; O'Regan & Jacobs, 1992). O'Regan calls this position in the word the "optimal viewing position" (OVP). However, aiming each saccade accurately enough to reach this exact location is time consuming, so O'Regan proposed that a more efficient strategy is used to hasten word recognition. Namely, reading saccades are aimed in the general area of the OVP and if the line of sight lands too far from the OVP, a "rescue tactic", taking the line of sight to the opposite side of the OVP is used. According to the strategy-tactics theory, spaces, which are easy to detect, are used for aiming the saccades to fall next to the OVP and for programming the rescue tactic. O'Regan's theory is based mainly on experiments in which the subjects read isolated words or short phrases. However, it has been shown that when the subjects read coherent text (even when only a single line is displayed at a time), the effect of not landing near the OVP was less detrimental than with isolated words (Vitu, O'Regan & Mittau, 1990). Therefore, it is not known whether O'Regan's strategy-tactics method is used when normal texts are read, or, even whether the endpoints of reading saccades are calculated primarily on the basis of the location of spaces to the right of fixation, as his strategy-tactics theory proposes (O'Regan, 1990; Vitu, 1991a, b).

In many other studies, spaces and letters to the right of fixation were manipulated in order to determine how such changes would affect the reading eye movement pattern (e.g. McConkie & Rayner, 1975; McConkie, Underwood, Zola & Wolverton, 1985). One class of these experiments used a computer display of text that was changed dynamically as the line of sight moved along a line of text. Using this paradigm, Morris, Rayner and Pollatsek (1990) found that when both letters and spaces to the right of the word being fixated were replaced by Xs, reading performance suffered more than when only letters were Xed out and the spaces were left in. However, it is difficult to interpret experiments in which the text was perturbed during reading. O'Regan (1990), for example, suggested that the effects found in such "perturbation" experiments may be explained most parsimoniously not by the nature of the changes in the text, but rather by the blurring and luminance changes related to display screen persistence and/or by changes in the subject's reading strategy imposed by such perturbations. This issue, raised recently by O'Regan (1990), has attracted the attention of other researchers. Normally, the effects of the perturbations themselves are largely ignored or it is claimed that subjects were not aware of them (e.g. Sereno & Rayner, 1992). But, no one has published the psychophysical data that would rule out the importance of these perturbations during reading. Without such data, it is difficult to argue convincingly that the subjects were unable to detect and/or were not influenced by the perturbations in their visual field.

In other studies on the role of spaces in reading, subjects read texts with spaces replaced by random letters, gratings, random numbers, letter-like symbols or colored blocks, or with the visibility around fixation location degraded (e.g. Fisher, 1976; O'Regan, Levy-Shoen & Jacobs, 1983; Malt & Seamon, 1978; Pollatsek & Rayner, 1982; McConkie & Rayner, 1975). In all of these studies, reading performance was quantitatively different (shorter reading saccades and longer reading fixations) than was observed with normal texts. However, it is not known from these experiments whether the deterioration in performance was caused by the removal of the spaces, or by the introduction of the extra, irrelevant, information. A proper control experiment would be to insert extra letters, numbers or colored blocks in the text without removing the spaces. These control experiments have not been performed, so the significance of this type of research is not clear. A more meaningful study was attempted by Fisher (1976), who showed that even first-grade children were able to read texts with spaces removed. Fisher missed the significance of his finding, however, probably because of the widely-held opinion that spaces guide reading eye movements.

Although there is evidence that the lengths of the words at and to the right, of the fixation location influence saccadic programming, the importance of spaces in determining word length cannot be known unambiguously from the experiments performed to date. Spaces, however, are not the only cues for word length, although they are arguably the easiest to isolate. Semantic and syntactic cues can also be used to estimate word length. The role of these high-level properties of the text in the programming of reading saccades will be considered next.

Meaning-guided eye movements. The purpose of reading is to extract meaning from visual information. It is not unreasonable to suppose that as the meaning is extracted, it is used to program the next saccade. An influential theory of reading eye movements, based mainly on semantic and syntactic features of the text, was proposed by Just and Carpenter (1980). The dependent variable these authors correlated with cognitive functioning was "gaze duration", defined as the total time the subject looked at a particular word. Just and Carpenter reported that gaze duration was proportional to the number of syllables in the word and inversely proportional to the frequency of the word in the language. However, Kiegel, Olson and Davidson (1982, 1983) showed very clearly that the only variable in Just and Carpenter's data that correlated highly with gaze duration was word length, which can be obtained from spaces between words as well as from cognitive factors. Inhoff and Rayner (1986) showed that when word length was kept constant, word frequency did influence gaze duration by about 30 msec. But, unlike Just and Carpenter, who used coherent paragraphs, Inhoff and Rayner used short sentences and kept context cues to a minimum. Based on these experiments the relative importance of word frequency and word length on gaze duration during normal reading is not clear. Furthermore, Just and Carpenter's theory deals mainly with gaze durations and does not address the question of how the endpoints of saccades are programmed.

Other experiments seemed to link semantic variables to saccadic programming. For example, O'Regan (1979) found that short but informative verbs like "eat" are fixated more often than short grammatical words like "the". Subsequently, O'Regan (1990) reinterpreted this result and suggested that it may have been caused by rare cases where the duration of the reading fixation that preceded the saccade was long enough to allow extra processing. It is difficult to evaluate these claims because it is not known how long it takes to program a reading saccade or to process a particular portion of the text [Kowler and Anton (1987), note that the estimates of the time required for saccade programming range from 30 to 200 msec in the current literature]. Therefore, it is impossible to determine which reading fixations were "long enough" and which were not.

Another line of evidence supporting meaning-guided eye movements involves long words in which information is not distributed evenly. For example in the word "extraterrestrial", the second half is more informative than the first half, whereas in the word "evaporation" the first half is more informative. Recent studies suggest that the distribution of information in the word to the right of fixation can influence the initial landing position of the saccade into that word. For example, when more information was located in the second half of the word, the initial saccade into that word went farther than when more information was located in the beginning of the word (Hyona, Neimi & Underwood, 1989; Underwood, Bloomfield & Clews, 1988; Underwood, Hyona & Niemi, 1987). This kind of reading eye movement pattern should improve reading efficiency because O'Regan and Levy-Shoen (1987) showed that the distribution of information within a word affects the location of the OVP.

The question to be answered by any theory in which word meaning is claimed to affect eye movements, is whether there is enough time in an average reading fixation, lasting only 200–300 msec, to process the meaning of the next word and also to program the saccade to move the line of sight to the appropriate location within it. This question is difficult to answer because estimates of the time required for saccadic programming can vary greatly and because moment-to-moment semantic processing, unlike sequences of reading saccades, cannot be observed directly.

Novel features of our study

Most recent theories described above assume that visual factors, particularly spaces between words, play an important role in determining the landing positions of reading saccades. The most straightforward way to test this hypothesis is simply to remove the spaces between words. This avoids the possibility of introducing perturbation artifacts by changing the display while the subject reads. It also prevents extraneous low (visual) and high-level (cognitive) interference, which must occur when extra characters are inserted into a text. Given these considerations, we simply removed spaces from texts and asked our subjects to read them.

We also wanted an unambiguous and continuous measure of reading competence. This was done by asking the subjects to read aloud in our main condition. Reading aloud provides an efficient as well as reliable measure of reading performance, that is, the reader's speech can be scored for accuracy and intonation (Legge, Pelli, Rubin & Schleske, 1985; Legge, Rubin & Luebker, 1987). Reading aloud also forces the subjects to read the text carefully, rather than to skip ahead, hoping to pick up the information required to answer questions about the passage after the text is read. In most prior experiments on reading, eye movements were studied only during silent reading, probably because most reasonably sensitive eye movement recording equipment requires the subject's head to be stabilized with a biteboard or a chin rest. Since most reading is done silently, both in the lab and in everyday life, we studied silent reading as well. The results of both types of reading will be presented.

In both silent and reading aloud conditions, our subjects read paragraphs displayed in their entirety rather than short sentences, or longer passages, displayed one line at a time, as is the common practice in much prior research (e.g. O'Regan & Jacobs, 1992; Inhoff & Rayner, 1986; Hyona *et al.*, 1989). Reading coherent paragraphs and having the entire paragraph available throughout the trial allowed our subjects to establish expectations about its subject matter and, if necessary, to refer to portions of text already read. Establishing expectations and being able to reinspect the text improves reading speed and comprehension and could have an effect on the eye movement patterns as well (Wishner, 1976; Bader *et al.*, 1980; Kennedy & Murray, 1984). In other words, reading paragraphs is more natural than reading short phrases, unrelated sentences, or even longer segments displayed one line at a time.

Another relatively novel aspect of our study was that a small number (five) of subjects participated. The performance of each of these subjects, however, was analyzed in detail and will be reported individually. In short, we followed the practice common in visual psychophysical and basic oculomotor research. This practice, however, differed from most research on reading where, typically, a dozen or more naive subjects participate and only their averaged performance is reported. We chose the "psychophysical" approach, in part, because large individual differences in reading styles have been known at least since Buswell's important early studies [see Kolers' (1976), description of this pioneer's work and its significance]. Because of these individual differences, averaging data across subjects is likely to produce misleading results.

Our recording instrumentation was also novel. An unusually accurate eye movement recording apparatus was used and this, combined with frequent behavioral calibration trials, allowed two-dimensional reading eye movements to be studied with unprecedented precision and accuracy on both horizontal and vertical meridians.

We anticipated one of two outcomes. Specifically, if spaces between words guide reading saccades, large differences in both global and local characteristics of reading eye movements during reading of spaced and unspaced texts should be observed. If, however, such large differences between the two types of texts were not observed, other factors, such as cognitive processes or text-independent oculomotor patterns must be more important than spaces between words for the control of reading eye movements. The latter outcome would be contrary to widely-held beliefs. It turned out to be correct.

METHOD

Subjects

Five researchers, who were working in our laboratory on other oculomotor research, served as eye movement/reading subjects. RS, ME and JE read spaced and unspaced texts in English. RS and ME were native English speakers. JE's first language was Russian, but she learned to speak and read English fluently by 12 yr of age and has been fluent in both languages for more than a decade. The other two subjects, CE and ZP were not native English speakers. They learned English as a second language as adults. These subjects read spaced and unspaced texts in both their native language (Dutch for CE and Polish for ZP) as well as in English.

In addition to these five eye movement subjects, four subjects, whose eye movements were not recorded (BG, CL, SS and AG), were also studied. All were native in English. They read spaced and unspaced English texts aloud.

Eye movement recording

The Maryland revolving magnetic field-sensor coil instrument (revolving field monitor or RFM) was used to record horizontal and vertical eye positions (Collewijn, Erkelens & Steinman 1988a, b; Erkelens, Steinman & Collewijn 1989a, b). The fundamental principle behind this recording method is that when a coil of wire is placed in an alternating magnetic field, an alternating voltage is induced in the coil. The amplitude of the induced voltage is proportional to the sine of the angle between the plane of the coil and the magnetic field vector. In the amplitude-detection method, introduced by Robinson (1963), a coil is attached to the eye and the voltage amplitude is used to compute eye position. Alternately, if the magnetic field vector is made to revolve around the eye coil, the phase of the alternating voltage induced in the coil is linearly related to the coil's angular orientation. The phase-detection method for recording eye movements was described by Collewijn (1977), who used it first in his work with the rabbit, by attaching the sensor coil directly to the rabbit's eye. Presently, this technique is used with human subjects by embedding the coils of wire in a silicone annulus which is inserted in the eye and remains in place because suction is formed between the slightly curved annulus and the surface of the eye (Collewijn, van der Mark & Jansen, 1975). This type of silicone annulus sensor coil is available commercially from Skalar-Delft.

The Maryland instrument is unique in that it uses the phase-detection method on both horizontal and vertical meridians. This is accomplished with two orthogonal pairs of cube-surface coil arrangements (Rubens, 1945). Cube-surface coil arrangements are used instead of Helmholtz coils, customarily used with the amplitude-detection method, to assure homogeneity of the magnetic field, thus virtually eliminating artifacts introduced by eye translations. Frequency coding is used to separate horizontal and vertical eye movement signals. The orthogonal pair of cube-surface coil arrangements, which is used to measure horizontal eye movements, produces an alternating magnetic field revolving about the vertical axis with a frequency of 976 Hz. The other pair, which is used to measure vertical eye movements, produces an alternating magnetic field revolving about a horizontal axis with the frequency of 1952 Hz. Because phase-detection is used on both meridians, the Maryland instrument is insensitive to fluctuations in the strength of the magnetic field and, therefore, capable of absolute calibration on both axes. The instrument's noise level is < 40 sec arc and its linearity is better than 0.01% over its 360 deg recording range. In the present experiments, the output of the RFM was rounded to the nearest minute of arc for convenience of data storage. Sampling frequency was set at 488 Hz (effective bandwidth = 244 Hz).

Although the Maryland RFM is capable of free-headed recordings, we chose to simplify data processing by keeping the subject's head relatively stable because Kowler, Pizlo, Zhu, Erkelens, Steinman and Collewijn (1992) had already used this instrument to study natural reading with the head free, showing that the main characteristics of the reading eye movement pattern were very similar to the pattern observed with the head stabilized. In the sessions in which the subjects read aloud, they leaned their foreheads against the front of a bicycle helmet suspended from above to keep the head relatively stable. The small head rotations, which did occur, were recorded with an annulus taped to the forehead. In some silent reading sessions, head movements were minimized by using dental impression biteboards. Reading was monocular and the non-seeing eye was covered by an eye patch.

Materials

Texts and calibration patterns were presented on the LCD screen of a laptop computer (LCD displays are not distorted by the rotating magnetic fields). Each subject located the forehead rest so that his viewing distance allowed the letters on the display to be seen clearly. These distances varied from 30 to 50 cm, which made the letters subtend from 19 to 26 min arc at the subjects' eye.

English passages were selected from back issues of the *Washington Post* newspaper. They were taken from editorials, reviews, advice and similar columns. Care was taken to assure that the topics and specific content of the passages was not likely to be known to the reader. Dutch passages were taken from the newspaper, *de Vokskrant*. Polish passages were taken from the newspaper, *Nowy Dziennik*.

Procedure

Before the start of each session, the subject positioned the display screen and adjusted the room lights so that the text was clearly visible. Recording sessions did not begin until the subject was sure that a pre-test pattern of unspaced letters could be seen clearly. Throughout the experiment, subjects were told never to start a calibration or reading trial until they could see a fixation target on the screen as clearly as their normal vision permitted. Each session started with a calibration trial and then alternated between reading and calibration trials. Before each reading or calibration trial a fixation target (+) was presented in the upper left corner of the screen. The subject was asked to look at the target and begin the trial, when ready, by pressing a button. Then, in a reading trial, nine lines of text appeared on the screen with the first character of the text appearing at the position previously occupied by the fixation target. In a calibration trial, a nine-element calibration pattern appeared (described below). Trials of both kinds lasted 20 sec. When subjects read aloud, their speech was recorded on an audio cassette located in a mu-metal box in an adjacent room.

Sessions, run on different days, consisted of between 20 and 48 trials (i.e. between 10 and 24 reading trials with a calibration trial before and after each reading trial). Each session lasted about one half hour (the maximum time a sensor coil annulus can be worn safely). Reading silently and reading aloud was done in separate sessions on different days.

For subjects, whose eye movements were not recorded, the procedure was the same, except that the experimental sessions were usually longer (up to 1 hr) and included about 100 trials (calibration trials were run in order to match the pacing imposed on the eye movement subjects).

Reading trials. Text displays were nine lines long and, for spaced passages, about 60 characters wide. For unspaced text, spaces were taken out without readjusting line width. Therefore, the amount of information/line was the same in both types of text. Thus, a line of spaced text was about 15% wider than a line of unspaced text.

In addition to regular texts, subjects RS and ME read aloud unpunctuated spaced and unspaced texts in a separate session. In this condition, punctuation was removed and capital letters changed to lower case in both spaced and unspaced texts.

In all conditions subjects read alternating blocks of three spaced and unspaced passages sandwiched between pairs of calibration trials.

Subjects were instructed to read for meaning and expression when reading aloud. They were asked to read "normally". No other suggestions about how they should read were made. They were not asked to avoid going back to earlier portions of the text or to read quickly as is sometimes done in research on reading. Emphasis was placed on meaning in the sense that the listener should be able to understand what was being said. A question about each text was asked just after it was read. During silent reading sessions, all questions were asked at the end of the session because it was not desirable to have the subject get off the biteboard between trials. This could disturb our calibration sequence.

Calibration trials. The procedure for calibration trials was similar to the reading trials. After the subject pressed the start button a 3×3 grid of pluses ("+") spaced 40 characters apart appeared on the screen. The subject looked at each + for about 2 sec, moving from left to right across each three-element line. A tone, which sounded every 2 sec, prompted him to make a saccade to the next +.

Analyses

Detecting reading saccades and fixations. Saccades were detected from the eye position records by a computer program, which used a two-dimensional acceleration criterion. A different acceleration criterion was established empirically for each subject by examining a large number of eye movement records plotted on a computer display after saccades, which passed the criterion, had been flagged. Once the experimenter established a criterion for each subject, the program was reliable in detecting even the smallest fixation microsaccades (< 12 min arc) known to occur very rarely and only during long (> 500 msec) reading fixations (Cunitz & Steinman, 1969).

Reading fixations were defined as periods of relative stability between saccades. Rarely (< 10% of the time) the program detected fixations of very short durations (< 100 msec). Examination of these fixations showed that in most cases they occurred between the saccade-like eye movements known to be associated with blinks (Collewijn, Van der Steen & Steinman, 1985). In the majority of the remaining cases, they occurred just prior to a long leftward saccade, which took the line of sight to the beginning of the next line of text (a "reset" saccade), or between two smaller leftward saccades ("regressions"). We did not include these short fixations in our analyses because they were very rare and were, in most cases, not reading fixations, but artifacts of our saccade detection method, i.e. they were caused by its inability to distinguish between regular saccades and the fast eye movements associated with blinks.

Locating the position of the line of sight in the text. Eye angles recorded during the calibration trials before and after each reading trial were used to find the intersection of the subject's line of sight with the display screen. To do this, each of the two coordinates needed to locate a point on the screen was expressed as a quadratic function in both the horizontal and the vertical eye angles. The unknown coefficients in these two quadratic functions were determined from a least-square fit to the eye angles recorded as the subject fixated each calibration + and the screen coordinates of the calibration +s. These functions were used to calculate the coordinates of the intersection of the line of sight with the screen as the subject read the text during the intervening reading trial. Since the screen coordinates of the letters of the text were known, the position of the line of sight within the text during each reading fixation was determined. The precision and accuracy of this calibration procedure is shown graphically in Fig. 1. The open rectangles in Fig. 1 are centered at the locations of the calibration +s. The size of the open rectangles represents the size of a character in the texts. Solid rectangles in Fig. 1 are centered at the mean location of the screen coordinates computed using calibration data from all calibration trials for each subject, as outlined above. The distances between the centers of the solid rectangles and the centers of the open rectangles is a measure of accuracy. The heights and widths of the solid rectangles are measures of precision. They show $\pm$ 1SD of the screen coordinates computed using the calibration data from all calibration trials for each subject. If either the subject or recording instrument was unstable during calibration, the solid rectangles would fall outside of the open rectangles (accuracy) and/or be larger than the open rectangles (precision). As shown in Fig. 1, the precision and accuracy of our computation of the position of the line of sight within the text was better than the size of a character in the text.

RESULTS

Subjects found reading unspaced texts easier than anticipated

Our subjects' reaction when they saw the first unspaced passage was that these confusing strings of letters could not be read. However, once the experimenter insisted that they try, all were quite successful, starting with the first unspaced text they saw. Their intonations as they read aloud clearly indicated that they understood what they were reading. They also answered almost all questions about the texts correctly. None showed any measurable improvement in reading unspaced texts between their first and last sessions. The slope of the regression line fitted to reading speed as a function of the sequential number of the paragraph read was not significantly different from zero for any of the subjects in either spaced or unspaced reading, either silently or aloud ($P > 0.4$). After participating in the experiments, all subjects reported that reading unspaced text was much easier than they had thought it would be when they first looked at an unspaced paragraph. Subjects also reported that reading unspaced texts depended on being able to see its individual letters very clearly. If the screen was not illuminated properly, or if the subject's spectacles were not clean or mounted correctly, unspaced texts became very hard to read because individual letters became "fuzzy". The significance of this observation will be considered in the Discussion.

Despite the relative ease with which subjects could read unspaced text, they read spaced and unspaced texts

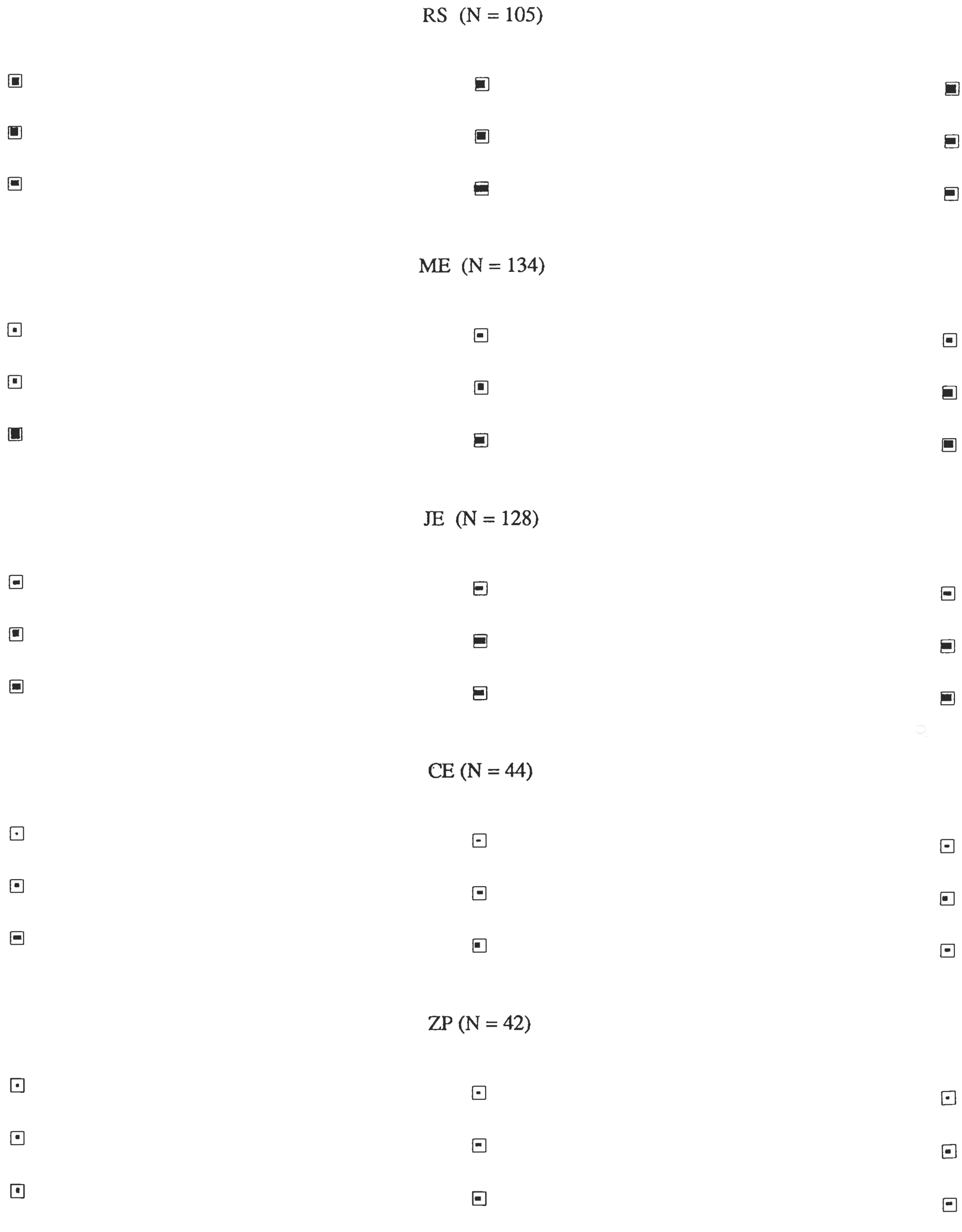

FIGURE 1. Accuracy and precision of calibration trials. Open rectangles are centered at the positions of the calibration targets. The width and height of the open rectangles indicate the width and height of one screen character. Filled rectangles are centered at the mean location of the screen coordinates computed from the eye angles recorded during calibration trials. The width and height of the filled rectangle indicate $\pm 1SD$ of the computed screen coordinates. The distances between the centers of the filled rectangles and the centres of the corresponding open rectangles indicate the accuracy of the calibration procedure. The areas of the filled rectangles indicate the precision of the calibration procedure. The means and standard deviations shown here are taken over all calibration trials for each subject.

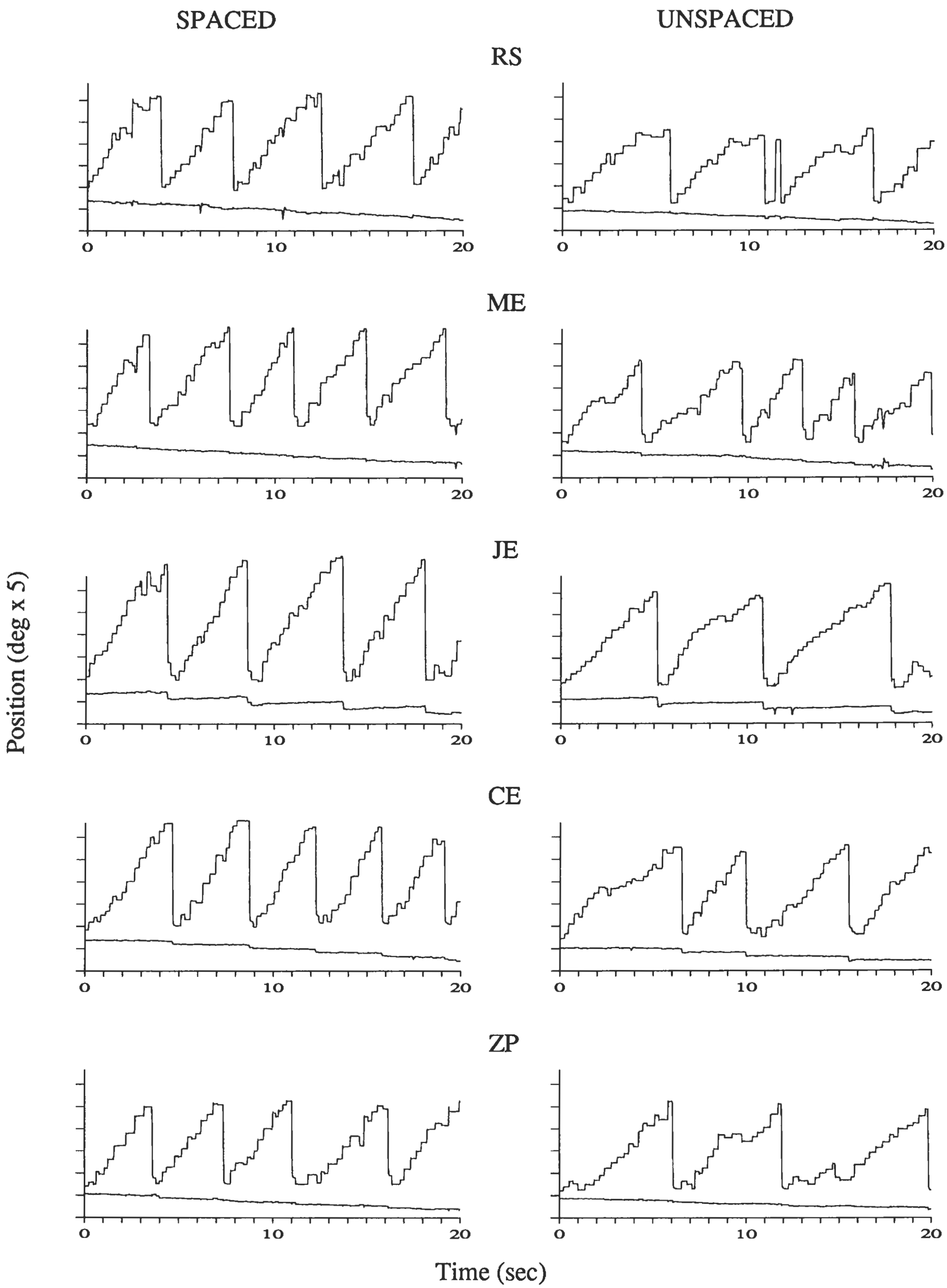

FIGURE 2. Analog records showing representative horizontal (top trace) and vertical (bottom trace) reading eye movements for spaced (left) and unspaced (right) texts while reading aloud. At time 0 traces indicate eye position at the start of each trial (at the upper left corner of the display). Upwards changes in the traces signify rightward eye movements in the horizontal trace and upward movements in the vertical trace. All traces are plotted on the same scale. The sizes of reset saccades are different for each subject because reading distance varied somewhat from subject to subject. The reset saccades were shorter in unspaced texts because the lines became narrower when spaces were removed. Records of all 5 subjects are shown (RS, ME, JE, CE and ZP).

somewhat differently. The following sections report the similarities and differences observed. Global eye movement characteristics, that is, statistics taken over the whole body of text, will be described first. Discussion of local characteristics, i.e. moment-to-moment descriptions of the subjects' eye movement patterns follow.

Global reading characteristics

Eye movement records, while reading both spaced and unspaced texts, look like records of typical reading eye movement patterns. Figure 2 shows representative eye movement records for each of the five subjects while they read aloud spaced (left column) and unspaced texts (right column). The eye movement records for silent reading were similar. Consider first the primary reading meridian, the horizontal. Here, all subjects performed similarly. Their horizontal eye movement traces look like typical reading eye movements. These were some differences between spaced and unspaced reading patterns. Namely, rightward saccades were shorter and reading fixations were longer when unspaced texts were read. Such differences are expected when the difficulty of the text is increased or when the visibility of the text is decreased [see Levy-Schoen and O'Regan (1979), for a review of basic reading eye movement characteristics].

Individual differences in reading eye movement patterns were striking on the vertical meridian. Subjects RS, ME and ZP moved the line of sight *smoothly* downward while they read across each line of text. By the time the end of the line was reached, the vertical position of the line of sight was almost at the level of the next line, so that the "reset saccade" (the long saccade that took the line of sight from the end of one line to the beginning of the next) was almost purely horizontal. These smooth eye movements on the vertical meridian were interrupted periodically by small saccades, but the smooth eye movements continued in the downward direction during intersaccadic intervals. To our knowledge this is the only unambiguous example of voluntary smooth eye movements made under conditions where neither the subject nor the target was moving or was expected to move [see Kowler (1990, 1991), for reviews of these and related eye movement characteristics]. This unexpected eye movement pattern on the vertical meridian, which was exhibited by three of the five subjects, was not reported previously probably because in typical reading experiments, vertical eye movements are either not recorded or ignored.

The other two subjects, CE and JE, did not exhibit such smooth downward vertical eye movements. CE's line of sight was relatively stable along the vertical meridian between saccades, while JE's line of sight drifted slightly upwards. Thus, CE's and JE's reset saccades were actually oblique. NB These individual differences in vertical eye movements during reading were only a matter of oculomotor style. They had no effect on the reading performance of any of the subjects. Furthermore, each subject used his or her individual type of vertical eye movements when both spaced and unspaced texts were read either silently or aloud.

In summary, qualitatively, on the basis of both the subjects' reading competence and on their analog eye movement records, reading unspaced text was similar to reading spaced text, despite the subjects' initial shock when asked to read unspaced text for the first time. Quantitative similarities and differences will be described next.

Unspaced texts were read more slowly than spaced texts, but in most subjects, the difference in reading rates was rather modest. One of the most common measures of reading proficiency is reading speed, usually measured in words/min. In sessions in which subjects read aloud, two options were available for calculating each subject's mean reading speed. One option was to count the words up to and including the last word the subject looked at during each trial. The other option was to count the words up to and including the last word the subject said aloud before each trial ended. These two measures need not be the same as was shown by Buswell (in Kolers, 1976), who found that the line of sight led the voice when good readers read aloud. Buswell referred to this as the "eye–voice span". In our experiments, the position of the line of sight at the end of each trial was, on average, one word past the last word said. The last word looked at, rather than the last word said, was used to calculate reading speed in order to be able to compare reading speeds during silent reading with speeds when reading aloud. For the four subjects, whose eye movements were not recorded and who only read aloud, the last word said was used to calculate reading speed.

Figure 3 summarizes mean reading speeds. First, consider our three main subjects reading aloud (top row). Their unspaced reading speeds were lower than their spaced reading speeds. These differences were statistically significant [$P < 0.005$; $t(29) = 3.5$ for RS; $t(46) = 4.8$ for ME; $t(44) = 15.7$ for JE]. The size of the decrease in reading speed, however, varied quite a bit from subject to subject. The difference was modest (only 18%) for RS, who read spaced text at 149 words/min and unspaced text at 123 words/min. It was also modest (only 21%) for ME, who read spaced texts at 178 words/min and unspaced texts at 140 words/min. JE, on the other hand, had considerably more difficulty reading unspaced texts than RS and ME. She read spaced texts at 166 words/min, but slowed down to 89 words/min (46%) when she read unspaced texts. However, even the decrease in reading speed of almost 50% shown by the poorest subject is surprisingly good in view of current reading theories, which emphasize the importance of spaces for guiding reading eye movements. The very modest decreases in reading speed shown by the other two subjects, RS and ME, leave no doubt that the role of spaces for guiding reading eye movements has been overestimated.

The four subjects, whose eye movements were not recorded, also varied in their ability to read without spaces (Fig. 3, middle row), but all read relatively easily, with good accuracy, intonation and comprehension. Their decreases in reading speed ranged from 16 to 48%

and were statistically significant ($P < 0.001$). One possible reason for the individual differences observed can be found in the performance of subject BG, who showed the greatest decrease in reading speed between spaced and unspaced texts. However, when reading spaced text BG was much faster than the other subjects. He read aloud at 246 words/min, while the reading speeds of the other subjects ranged from 150 to 210 words/min. Furthermore, when we listened to the tape of his reading, we found that he did not articulate clearly when reading spaced texts. He was so unclear that it was difficult to score his reading for accuracy and required stopping the tape and going back many times. When he read unspaced text, BG was slower but somewhat more articulate. This suggests that he did not follow instructions to read clearly, but simply read spaced texts as fast as he could. Although he was able to answer the comprehension questions correctly, he did not read to convey meaning to the listener. He couldn't do the same kind of rushed, uncommunicative reading with unspaced texts. The removal of spaces forced him to change his criterion and read more clearly. Despite these individual differences, all non-eye-movement subjects were able to read unspaced texts aloud reasonably fast (better than 100 words/min). This shows, once again, that spaces are by no means essential for proficient reading.

JE's reading speed for spaced texts was not faster than the speed of the other subjects and she read clearly and with meaning, so her difficulty relative to the other subjects cannot be explained by a criterion change. One plausible reason for JE's difficulty was that RS, ME and all of the non-eye-movement subjects were native English speakers, whereas JE originally learned to read in Russian. Although her reading speed with spaced English texts was within the range of the other subjects, she might have had more difficulty with unspaced texts because she was reading English as a "second" language. This possibility was explored by studying two additional bilingual subjects.

Unspaced reading is somewhat more difficult in a "second" language than in a native language. Subjects CE and ZP were fluent in English, but both had initially

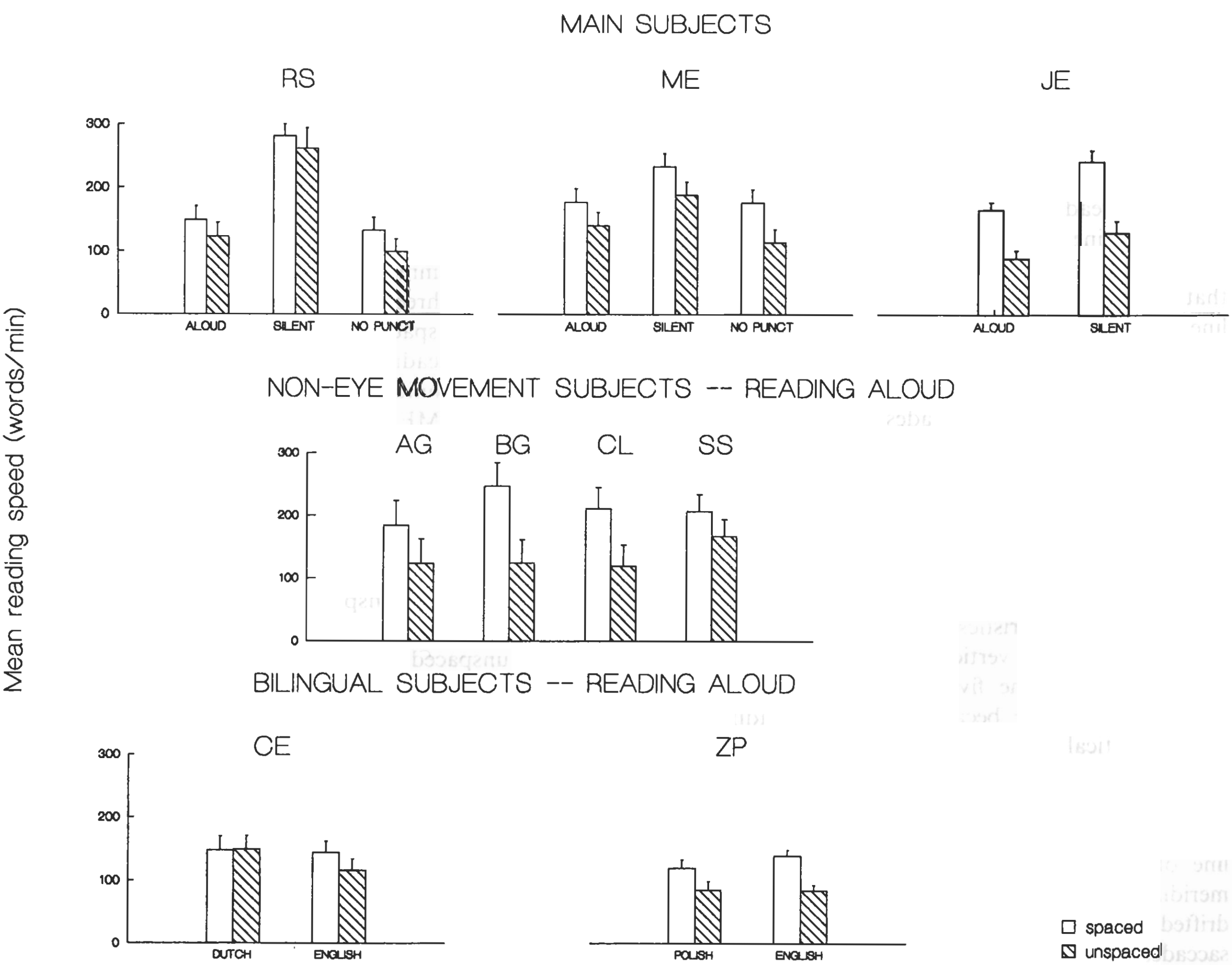

FIGURE 3. Mean reading speeds (words/min) for all subjects in different reading tasks with spaced (open bars) and unspaced (filled bars) texts. The labels on the abscissa indicate different reading conditions, i.e., aloud, silent and no punctuation for the main subjects, and native language vs English for bilingual subjects. Each bar is a mean taken over 9–25 trials for the main subjects, 45–65 trials for non-eye movement subjects, and 5–6 trials for bilingual subjects. Error bars indicate 1 standard deviation.

learned to speak and read in another language (Dutch for CE and Polish for ZP). Their performance is summarized in Fig. 3 (bottom row). CE's and ZP's results supported the hypothesis that reading unspaced texts is more difficult in a non-native language, at least qualitatively. That is, the differences were in the correct direction, but did not reach statistical significance. Namely, both subjects showed greater decreases in reading speed when spaces were removed in English texts than when spaces were removed in texts in their native language. CE read both spaced and unspaced Dutch texts, on average, at 150 words/min [$t(10) = 1.0$, $P > 0.9$]. He read spaced texts in English almost as fast (144 words/min). However, his reading speed for unspaced English texts was 116 words/min, 20% slower than observed with the three other types of text [$t(10) = 3.2$, $P < 0.02$]. For ZP, reading unspaced text was more difficult than it was for CE, both in Polish and in English. Nevertheless, ZP's decrease in speed was greater in English than in Polish. He read spaced English texts at 140 words/min, but slowed down to 85 words/min (39%) when he read unspaced English texts [$t(9) = 3.7$, $P < 0.01$]. ZP's decrease in reading speed was only 28% with Polish texts (from 120 to 86 words/min). This decrease was also statistically significant [$t(9) = 4.6$, $P < 0.01$].

The interaction between spaces and language, however, did not reach statistical significance for either CE or ZP [$F(1,20) = 3.3$, $P > 0.08$ for CE; $F(1,18) = 2.1$, $P > 0.2$ for ZP]. Note also that neither of these bilingual subjects showed as big a decrease in reading speed as JE. This suggests that some factor other than first vs second language is needed to explain her relatively poor performance. It is also interesting to note that CE showed no difference in speed when reading spaced and unspaced Dutch texts and only a very small difference when reading spaced and unspaced texts in English. A possible explanation for CE's excellent performance while reading unspaced texts is that Dutch, like German, has many long compound nouns consisting of several words strung together. Thus, a person reading Dutch always does more unspaced reading than a person reading English or one of the Romance languages.

Reading without spaces was easier for most subjects when they read silently than when they read aloud. As expected from prior research, all subjects read both spaced and unspaced texts faster (25–45%) when reading silently (Huey, 1908). RS, reading silently, showed no significant difference in reading speed between spaced and unspaced texts [$t(22) = 1.8$, $P > 0.05$]. He read both types of texts at about 270 words/min. ME read spaced texts at 232 words/min and unspaced texts at 189 words/min, a decrease of only 18% [$t(16) = 3.2$, $P < 0.01$]. The interaction between spaces and type of reading was not statistically significant for either RS or ME [$F(1,51) = 0.36$, $P > 0.5$ for RS; $F(1,62) = 0.26$, $P > 0.6$ for ME]. JE, however, was still 46% slower when reading unspaced text silently [242 words/min for spaced texts and 130 words/min for unspaced texts; $t(16) = 10.3$, $P < 0.001$]. She was the only subject, who showed a statistically significant interaction between spaces and type of reading [$F(1,60) = 11.8$, $P < 0.002$].

Although subjects could read unspaced texts relatively fast, it was possible that other visible landmarks, such as punctuation and capitals, both much less frequent than spaces between words, could be important guides for reading eye movements. This possibility is considered next.

Removing all punctuation and capitals did not prevent unspaced texts from being read. Punctuation and capitals provide visual, syntactic and semantic cues during reading. Their possible role in guiding reading eye movements was evaluated by requiring RS and ME to read spaced and unspaced texts aloud after all such landmarks were removed. Their results are shown in Fig. 3 (NO PUNCT in top row). The decrease in reading speed between spaced and unspaced texts was somewhat greater when the punctuation marks and capitals, as well as spaces, were removed [25% vs 18% for RS, $t(16) = 4.5$, $P < 0.001$; 35% vs 21% for ME, $t(23) = 8.0$, $P < 0.001$]. However, the interaction between punctuation and spacing did not reach statistical significance for either subject [$F(1,43) = 1.03$, $P > 0.3$ for RS; $F(1,74) = 5.1$, $P > 0.05$ for ME]. It seems reasonable to conclude that punctuation and capitals, like spaces, do not play an essential role in guiding reading eye movements.

Subjects made very few errors while reading aloud. In any discussion of speed, it is important to consider accuracy. A large change in speed can be caused by a small change in the subject's speed-accuracy criterion (see Sperling & Dosher, 1986 for a review of this and related issues). It is possible, for example, that when reading unspaced texts, the subjects were trying to make fewer errors or corrected themselves more often than when reading spaced texts, thus taking more time to read the same amount of text. This was not the case. The percentage of errors (word substitutions or skipped words) was very low for all subjects ($< 5\%$ of the words were missed or replaced with incorrect words). Also, the subjects made more, rather than fewer, errors when they read unspaced texts, showing that they were not slowing down to keep the error rate constant. Many of the errors in unspaced reading occurred near unusual proper nouns or low frequency words. Neither eliminating texts that contained errors from the analyses of reading speed, nor subtracting words that were not read aloud correctly when calculating reading speed, made any notable difference in the results because errors were so infrequent.

Note that in scoring for accuracy, only word errors were considered (i.e. word substitutions and skipped words). Errors in intonation and articulation were not counted. However, all subjects except BG (discussed above), had comparable overall intonation and articulation in spaced and unspaced texts.

These results make it possible to conclude that differences in reading speed cannot be explained by changes in the subjects' speed-accuracy criteria, at least while reading aloud (it was not possible to evaluate reading errors when subjects read silently).

The way in which the differences in reading speed were reflected in global eye movement characteristics will be considered next.

Durations of reading fixations were slightly longer with unspaced texts. Many contemporary theories of reading eye movements hold that *where* the line of sight will move is controlled primarily by visual factors, such as spaces between words, whereas *when* the line of sight will move is controlled primarily by cognitive factors, such as lexical access (Morrison, 1984; Pollatsek & Rayner, 1990; Morris *et al.*, 1990; Rayner, 1993). Figure 4 shows the frequency polygons of reading fixation durations for spaced (dashed lines) and unspaced (solid lines) texts. These distributions look quite similar. The three main subjects had small (11–16%), but statistically significant increases in mean duration of reading fixations when they read unspaced texts [$P < 0.001$; $t(1746) = 6.4$ and $t(1566) = 7.0$ for RS reading aloud and silently; $t(3092) = 7.7$ and $t(1275) = 9.9$ for ME reading aloud and silently; $t(3077) = 9.3$ and $t(1566) = 7.0$ for JE reading aloud and silently]. For the other two eye movement subjects the differences in mean durations of reading fixations were even smaller: CE showed no difference while reading Dutch [$t(807) = 0.57$, $P > 0.5$] and only a 5% difference [$t(786) = 2.0$, $P < 0.05$] while reading English texts. ZP showed no significant differences in the mean duration of reading fixations between spaced and unspaced texts while reading either Polish [$t(733) = 0.43$, $P > 0.06$] or English texts [$t(743) = 1.0$, $P < 0.3$].

Thus, the modest increases in the durations of reading fixations observed do not fully account for the differences in reading speed between spaced and unspaced texts. So, understanding the observed differences in reading speed requires an examination of the characteristics of our subjects' progressive saccades and "regressions" (leftward saccades within a line of text).

Subjects tended to adjust to the size of their progressive saccades to approximate characteristics of the spaced and unspaced texts, keeping the number of saccades/line about the same for both. It has been known since Buswell's early work (described in Kolers, 1976) that as the difficulty of the text increases, the mean size of progressive saccades decreases. Figure 5 shows the distributions of sizes of progressive saccades and regressions (leftwards saccades within a line of text). Table 1 shows their means and standard deviations. All subjects made shorter progressive saccades while reading unspaced text. However, recall that when spaces were removed from the text, the average number of words/line remained the same as it had been in spaced text. This made unspaced texts about 15% narrower than spaced texts. It also made unspaced texts denser, i.e. unspaced texts contained more non-space, information-bearing characters/degree of visual angle. When RS read aloud, his saccades were 18% shorter with unspaced than with spaced texts. This difference was statistically significant [$t(1307) = 6.2$, $P < 0.001$], but note that it was only 3% greater than the percentage by which text width was reduced when spaces were removed. Because his decrease in mean progressive saccade size was proportional to the decrease in text width, RS showed no statistically significant difference in the number of saccades/line of text made with spaced and unspaced texts [$t(118) = 1.4$, $P > 0.1$; see Fig. 6]. ME's progressive saccade sizes did not approximate the decrease in text width as closely. His saccades, while reading unspaced texts, were 27% shorter [$t(2440) = 12.7$, $P < 0.001$]. ME's progressive saccades in unspaced texts were too short by 9% to match the decrease in text width by removing spaces. Because of this, his difference in the number of saccades/line was significant [$t(217) = 5.3$, $P < 0.001$], but this difference was relatively small (14%). This amounts to only 1.5 more saccades/line when unspaced texts were read. The pattern of results was the same for silent reading. It is reasonable to conclude that RS and ME tended to reduce the size of their saccades and keep the number of information-bearing characters/saccade and the number of saccades/line about the same in spaced and unspaced texts. JE, however, did not do this. Her saccades were 47% shorter [$t(2614) = 21.7$, $P < 0.001$] and she made 7 (35%) more saccades/line [$t(158) = 11.4$, $P < 0.001$] while reading unspaced texts. She did this both while reading aloud and silently. There was no significant interaction for saccades/line between spaces and type of reading (silently or aloud) for any of the three main subjects [$F(1,302) = 0.10$, $P > 0.7$ for RS; $F(1,328) = 0.12$, $P > 0.7$ for ME; $F(1,247) = 2.4$, $P > 0.1$ for JE].

Our additional bilingual subjects, once again, reflected both trends evident in our three main subjects. CE, like RS and ME, kept the number of saccades/line approximately the same [$t(49) = 1.3$, $P > 0.1$] for Dutch texts and for English texts [$t(44) = 1.6$, $P > 0.1$]. Once again, ZP was more like JE. He made about 5.5 (33%) more saccades/line while reading both unspaced Polish texts [$t(39) = 6.8$, $P < 0.001$] and unspaced English texts [$t(33) = 8.4$, $P < 0.001$]. CE showed no significant interaction for saccades/line between spaces and language [$F(1,93) = 0.4$, $P > 0.5$]. ZP's interaction between spaces and language, however, was significant [$F(1,72) = 4.2$, $P < 0.05$].

In summary, three of the five subjects (RS, ME and CE) adjusted the size of their progressive saccades when reading unspaced texts just about enough to compensate for the decrease in the width of the text which meant that they adjusted for the increased density of the unspaced texts. The two subjects who did not do this (JE and ZP), were the subjects who suffered much greater reductions in speed when they read unspaced texts.

The considerable variability observed in progressive saccade size makes it unlikely that any of the subjects used a constant-step strategy for reading either spaced or unspaced texts. If spaces were necessary to guide progressive saccades during normal reading, subjects would have to resort to another oculomotor strategy when spaces were removed. One strategy, which does not need any such landmarks, is the constant-step strategy, discussed in the Introduction. In this strategy, the line of sight moves approximately the same number of characters at every saccade. The considerable variability in progressive saccade size, seen in the frequency distributions in Fig. 5 and in the standard deviations in Table 1, rules out the

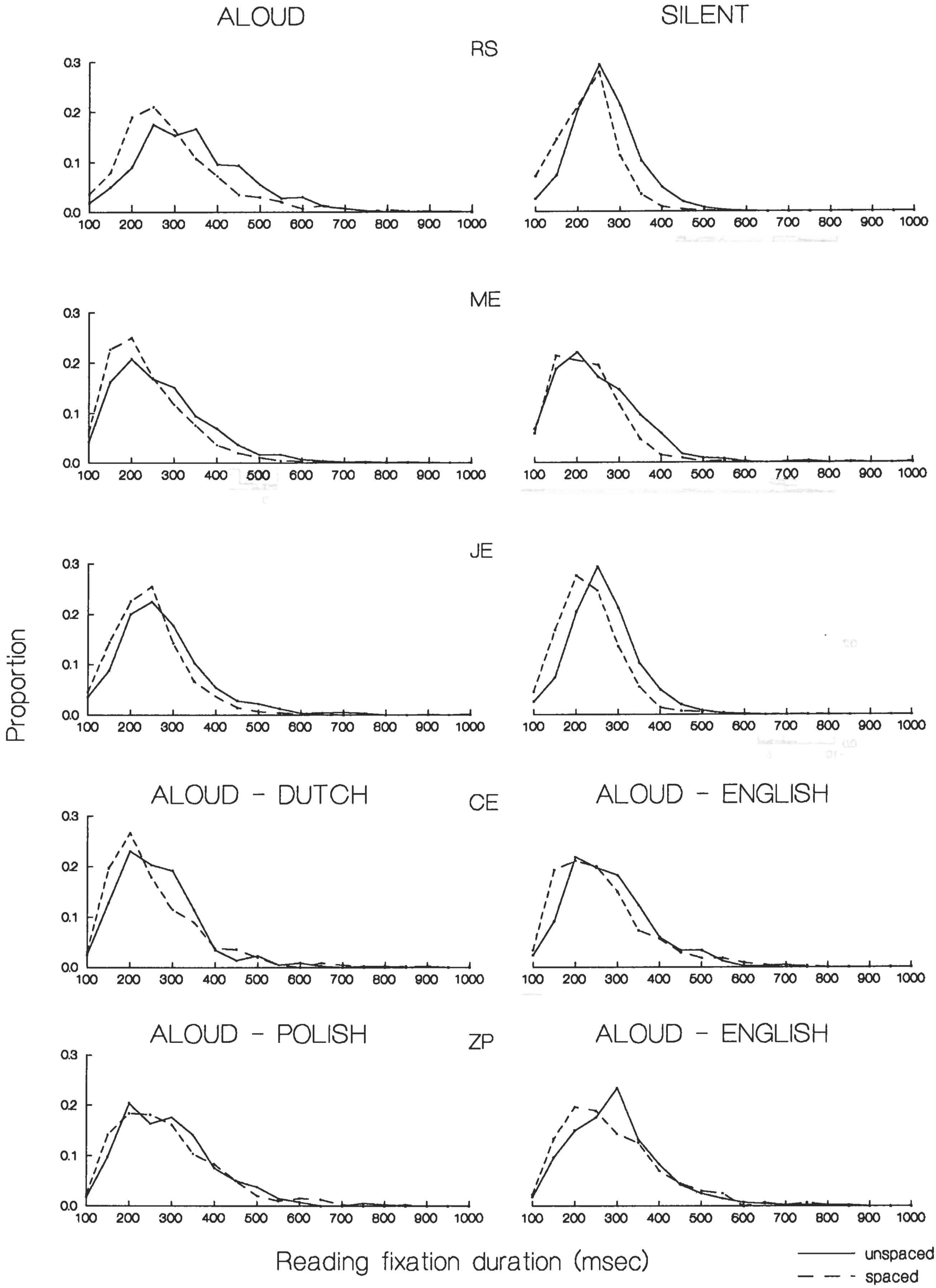

FIGURE 4. Frequency polygons of reading fixation durations for spaced (dashed lines) and unspaced (solid lines) texts for the 5 main subjects reading aloud (left column) and silently (right column). Bilingual subjects reading in their native language (left column) and in English (right column) are shown at the bottom of this figure. Each curve represents 365–1654 reading fixations. Bin-width was 50 msec.

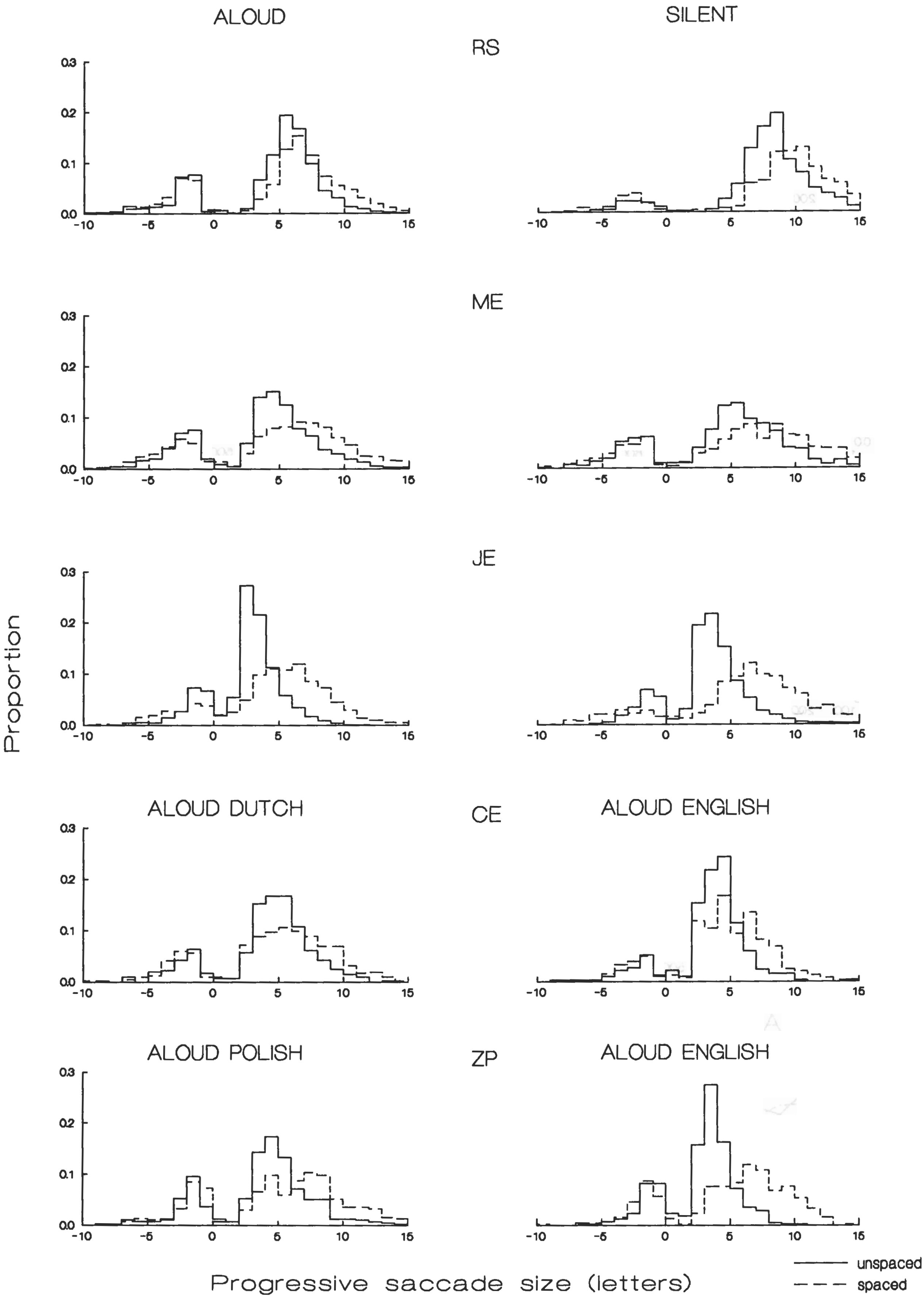

FIGURE 5. Frequency distributions of saccade sizes for spaced (dashed lines) and unspaced (solid lines) texts for 5 main subjects, reading aloud (left) and silently (right). Saccades with positive sizes are progressive. Saccades with negative sizes are regressive. Bin-width is one letter.

TABLE 1. Mean (SD) size (letters) of progressive saccades and regressions

Subject	Condition	SP/USP	Trials	Progressive saccades			Regressions		
				N	Mean (SD)	SD/Mean	N	Mean (SD)	SD/Mean
RS	Aloud	SP	16	709	7.3 (3.6)	0.49	220	3.7 (2.5)	0.68
		USP	15	600	5.9 (3.9)	0.66	181	3.8 (2.8)	0.73
	Silent	SP	12	693	10.6 (4.1)	0.38	99	4.2 (3.0)	0.71
		USP	12	671	8.3 (2.6)	0.31	72	4.3 (3.9)	0.91
ME	Aloud	SP	25	1332	7.2 (4.1)	0.57	449	4.1 (3.3)	0.80
		USP	23	1110	5.3 (3.1)	0.58	403	4.5 (5.8)	1.29
	Silent	SP	9	512	8.3 (4.1)	0.49	166	4.1 (4.2)	1.02
		USP	9	469	6.1 (3.0)	0.49	154	4.5 (5.0)	1.11
JE	Aloud	SP	24	1425	5.8 (3.9)	0.67	354	3.7 (3.7)	1.00
		USP	22	1191	3.2 (2.0)	0.63	311	2.4 (2.6)	1.08
	Silent	SP	9	564	7.3 (3.5)	0.48	114	4.5 (3.6)	0.80
		USP	9	502	3.8 (2.3)	0.60	118	2.8 (3.1)	1.11
CE	Dutch	SP	6	331	6.1 (3.7)	0.61	84	3.5 (2.3)	0.66
		USP	6	333	4.9 (2.0)	0.41	74	3.2 (1.9)	0.60
	English	SP	6	346	5.3 (4.4)	0.83	64	3.0 (1.6)	0.53
		USP	6	338	3.9 (2.6)	0.67	52	3.0 (1.8)	0.60
ZP	Polish	SP	6	275	7.1 (4.2)	0.59	90	2.8 (2.6)	0.93
		USP	5	281	4.9 (2.4)	0.49	92	3.4 (3.5)	1.03
	English	SP	5	283	6.7 (3.0)	0.45	85	2.7 (2.4)	0.89
		USP	6	292	3.5 (1.5)	0.43	83	2.1 (1.3)	0.62

possibility that any of the subjects used this strategy for any type of reading. The distributions were slightly narrower for unspaced reading, as would be expected given that saccades were shorter with unspaced texts. When mean saccade size is scaled down, the standard deviation should change proportionally. The ratios of the standard deviation to the mean for progressive saccade size is shown in Table 1. These ratios range from 30 to 80% showing that the variability in saccade size was too large for a constant-step strategy to be useful in describing the data. Furthermore, standard deviations remained about the same relative to the mean in both spaced and unspaced reading. This suggests that the subjects did not switch to the constant-step strategy when spaces were removed. Thus, a global scaling operation is sufficient to describe the observed change in mean progressive saccade size and it is neither necessary nor reasonable to assume that different oculomotor strategies were used when spaced and unspaced texts were read. A change in strategy is not precluded by this analysis, but if different strategies were used, both had the same variability relative to the mean.

For subjects, who read unspaced texts relatively easily, the size of regressions was the same in spaced and unspaced texts. Consider the distributions of regressions, the left hump of the distributions in Fig. 5 (the mean size of regressions is summarized in Table 1). There was considerable variability in the sizes of individual regressions within subjects, but only JE showed a statistically significant difference in the mean size of her regressions in spaced and unspaced texts [$P < 0.001$; $t(655) = 5.9$ for aloud; $t(230) = 7.0$ for silent]. Her regressions with unspaced texts were about 36% shorter both when she read aloud and silently. The only other difference approaching statistical significance [$t(166) = 1.9$, $P < 0.06$] was that of ZP, whose regressions were about 21% shorter when he read unspaced English text than when he read spaced English text. His regressions in spaced and unspaced Polish texts were not significantly different [$t(180) = 1.4$, $P > 0.08$]. Recall that both JE and ZP had considerably more difficulty reading unspaced text than the other three subjects.

It is interesting to note that while progressive saccade size was scaled down for all subjects, regression size remained the same for RS, ME and CE. Even JE and ZP, who did show a significant difference for regression size between spaced and unspaced texts, did not change the size of their regressions as much as they changed the size of their progressive saccades. This suggests that progressive saccades and regressions may be programmed independently, at least with respect to their size.

The percentage of regressions was the same for spaced and unspaced texts. The percentage of regressions provides a popular measure of the quality of reading performance from which comprehension is inferred (Kennedy, 1986). An increase in the percentage of regressions may reflect either an increase in the difficulty of the text or a decrease in the competence of the reader. Large regressions (longer than a single word) are believed to result from cognitive factors, such as the line of sight getting too far ahead of the word being processed mentally. For example, large regressions are common when the reader encounters ambiguous or garden path sentences (Frazier & Rayner, 1982). Many reading researchers also think that saccades within a word (both rightward and leftward) may occur when the eye fails to fall on the "optimal viewing position" (e.g. Vitu *et al.*, 1990; O'Regan, 1990). Thus, percentage of regressions can serve as an indicator of both cognitive and oculomotor competence.

Figure 7 summarizes the percentage of regressions. Percents regressions were lower, when texts were read silently as compared to reading aloud, as expected from prior work (Buswell in Kolers, 1976). However, none of the subjects showed statistically significant differences in the percentage of regressions between spaced and unspaced texts when they read either silently or aloud. So, the percentage of regressions, perhaps the most important and valid measure of reading competence, revealed no real advantages to providing spaces between words in texts.

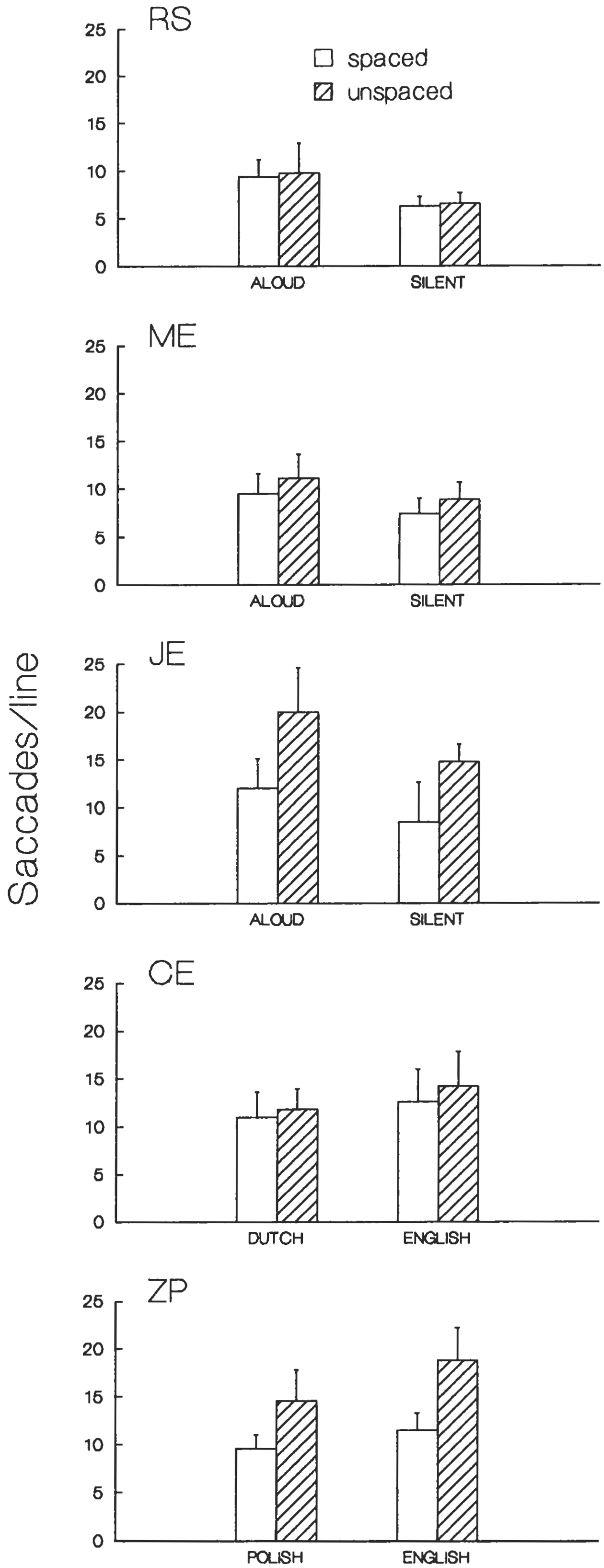

FIGURE 6. Mean saccades/line for spaced (open bars) and unspaced (filled bars) texts. Each bar represents a mean of 12–128 lines. Error bars indicate 1 standard deviation.

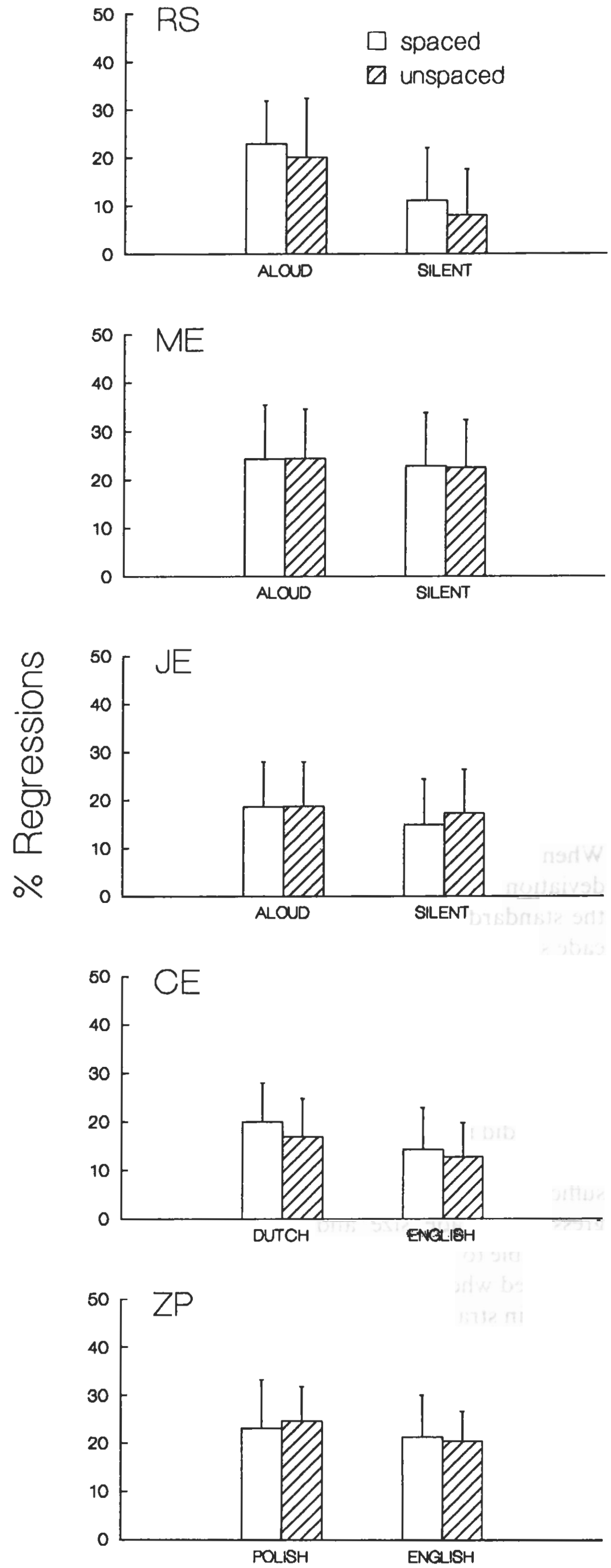

FIGURE 7. Mean % regressions/line for spaced (open bars) and unspaced (filled bars) texts. Each bar represents a mean of 12–128 lines. Error bars indicate 1 standard deviation.

So far only global characteristics of reading have been considered. Here, at least in those subjects who had very little difficulty reading unspaced texts, differences could be, to a large degree, accounted for by a single global difference between the two types of text; namely, the unspaced texts were denser, i.e. they contained more information bearing characters/degree of visual angle than the spaced texts. Local characteristics, such as where within texts the subjects looked, have to be examined to determine whether only this global scale change mattered, or, alternatively, whether qualitatively different oculomotor strategies were responsible for the differences observed between spaced and unspaced reading. Such local characteristics will be considered next. The next sections are ordered with respect to the degree of what could be called, "localness" of the information examined. Suppes' probabilistic analysis is described first because it acts as a transition between the global and the local measures. Namely, this analysis looks at the probabilities of performing relatively high-level operations as the line of sight moves from word to word within a text. A more local analysis is undertaken next. Specifically, the average number of fixations within a word as a function of the length of the word is examined. Finally, the preferred fixation letter within individual words and the probability of staying within the word as a function of the initial landing letter are examined.

Local reading characteristics

Suppes' probabilistic approach can be used to model both spaced and unspaced reading with only a change of scale. Suppes' (1990) text-dependent probabilistic control model for reading (described in the Introduction) is a modification of his model of eye movements during arithmetic developed earlier and more fully (Suppes *et al.*, 1983). The reading model assumes that there are several different operations, including "stay within the word", "go to the next word", "skip the next word", "backtrack to a previous word" and "other", which serves as a catch all for saccades not described by the other categories. These operations are performed with different probabilities, depending on local properties of the text.

Table 2 summarizes the probabilities of performing each of these operations for the different types of texts and reading tasks in our experiment. Suppes' operations ("stay", "next", "skip", "backtrack") were used for our analysis with "backtrack" divided into two levels, for going back one or two words. Backtracking more than two words was not included in our analysis because it happened very rarely, < 0.1% of the time. We also had a catchall operation, "other", which included all other operations, such as looking at a word not on the current line, backtracking more than two words, skipping more than one word, etc. The probabilities of the various operations were calculated for individual trials. Those shown in Table 2 are averages based on 5–25 trials, depending on the subject. t-Tests were performed on each spaced/unspaced pair of probabilities. "Stay" and "next" operations were by far the most prevalent in both spaced and unspaced texts. The "skip" and "stay" operations showed the greatest numbers of significant differences between spaced and unspaced texts, with lower probabilities of "skip" and higher probabilities of "stay" in unspaced texts. This pattern is consistent with the observation of smaller progressive saccades when unspaced texts were read.

An interesting observation can be made about the "other" operation. In Suppes' study of arithmetic, the

TABLE 2. Mean probabilities of staying within a word (Stay), going to the next word (Next), skipping the next work (Skip), backtracking to a previous word (Back 1), backtracking two words (Back 2) and performing some other eye movement operation (Other) for spaced (SP) and unspaced texts (USP)

Subject	Condition	SP/USP	Trials	Probabilities of operations: Stay	Next	Skip	Back 1	Back 2	Other
RS	Aloud	SP	16	0.239	0.422	0.186	0.100	0.004	0.049
		USP	15	0.261	0.367	0.188	0.097	0.018	0.069
	Silent	SP	12	0.182	0.316	0.319†	0.042	0.004	0.138
		USP	12	0.208	0.350	0.274	0.023	0.002	0.143
ME	Aloud	SP	25	0.268†	0.381	0.189*	0.079*	0.014	0.068
		USP	23	0.309	0.377	0.158	0.095	0.014	0.047
	Silent	SP	9	0.251	0.369	0.220	0.049	0.014	0.098
		USP	9	0.252	0.379	0.211	0.064	0.023	0.070
JE	Aloud	SP	24	0.304‡	0.449†	0.150‡	0.047	0.004	0.047
		USP	22	0.490	0.395	0.045	0.048	0.003	0.020
	Silent	SP	9	0.235‡	0.418	0.235‡	0.034	0.009	0.70†
		USP	9	0.420	0.406	0.105	0.046	0.003	0.020
CE	Dutch	SP	6	0.344	0.404	0.133	0.081	0.007	0.031
		USP	6	0.377	0.374	0.171	0.059	0.005	0.014
	English	SP	6	0.412	0.300*	0.152†	0.043	0.007	0.087
		USP	6	0.420	0.405	0.086	0.038	0.002	0.048
ZP	Polish	SP	5	0.434‡	0.380	0.092	0.052	0.007	0.035*
		USP	6	0.512	0.384	0.062	0.061	0.009	0.019
	English	SP	6	0.365‡	0.403†	0.153*	0.065	0.000	0.015*
		USP	5	0.525	0.331	0.077	0.055	0.010	0.002

The types of reading shown are Aloud vs Silent reading for the main subjects (RS, ME and JE) and reading texts in native language vs English for the bilingual subjects (CE and ZP). The probabilities that were significantly different statistically are marked (*$P < 0.05$, †$P < 0.01$, ‡$P < 0.001$).

probability of performing the "other" operation was much greater than the probability of the "other" operation in our reading data (his probabilities ranged from 0.08 to 0.36, whereas ours ranged from 0.002 to 0.14). Suppes suspected that reading requires a more stereotyped eye movement pattern than arithmetic and predicted that the incidence of the "other" operation would be smaller for reading. However, on the basis of his finding for arithmetic that the probability of the "other" operation was greater for less competent subjects (children vs adults) and for more difficult problems (subtraction vs addition), Suppes concluded that most of the eye movements falling into the "other" category represent "aimless wanderings" and are, therefore, detrimental to the performance of arithmetic. The situation may be different for reading. All subjects, except RS, showed a tendency to have higher probabilities of the "other" operation in spaced than in unspaced texts. This difference was most pronounced (and statistically significant) in the least competent unspaced reader, JE, who hardly ever "wandered aimlessly" when she read unspaced texts. It also reached statistical significance for ZP, the other relatively poor unspaced reader. The probability of the "other" operation was also greater when subjects read silently than when they read aloud. Taken together, these results suggest that when the reading task is more difficult, the reader is more, not less, likely to maintain an orderly progression through the text. So, the application of Suppes' model to our results shows quantitatively that reading and doing arithmetic are quite different visuo-motor-cognitive tasks.

Overall, only 18 (30%) of the 60 pairs of probabilities for spaced and unspaced texts listed in Table 2 show significant differences ($P < 0.05$). If subjects RS, ME and CE, who had virtually no trouble reading unspaced texts, are considered separately, only 6 of their 36 pairs (17%) were significantly different statistically. For subjects JE and ZP, however, 12 out of 24 pairs (50%) were significantly different and these 12 pairs were more highly significant than the 6 pairs of the better readers.

This analysis shows that although subjects were somewhat more likely to stay within a word and less likely to depart from an orderly sequence of reading eye movements when reading unspaced texts than when they read spaced texts, these differences can be described simply by changing a single global parameter, namely the size of the progressive saccades. This difference between spaced and unspaced texts is smaller than the differences observed between reading silently and aloud, where two parameters, the size of the progressive saccades and the percentage of regressions, must be adjusted. And, of course, the difference between spaced and unspaced reading is much smaller than the difference between doing arithmetic and either kind of reading with either kind of text. Based on the Suppes model of reading and arithmetic, these are different oculomotor tasks because the purpose of "other" operation was different in each of these tasks (see above). However, based on the same type of analysis, reading spaced and unspaced texts are not different oculomotor tasks. This is another indication that spaces are not essential for reading normally.

The question of under what circumstances a word is fixated more than once or skipped altogether is considered next.

Word length affects the probability of fixating a letter, but this effect is the same in spaced and unspaced texts. The probability of fixating a letter in words of different lengths has been used to support the hypothesis that reading eye movements are under moment-to-moment control, i.e. the size of each saccade depends heavily on the lengths of the words currently fixated and the lengths of the words to the right of fixation (Rayner & McConkie, 1976). The probability of fixating a letter is calculated by first dividing the total number of fixations on n-letter words by the number of n-letter words to get the probability of fixating an n-letter word. Then this result, obtained for each word length, is divided by n, to get the probability of fixating any one letter in an n-letter word. If eye movements were independent of word length, the expectation is that the probability of fixating a letter would be the same regardless of whether this letter occurred in a 2-letter word or in a 9-letter word. Furthermore, the line of sight would be expected to fall on spaces between words as often as on any other characters in the text. If reading saccades are assumed *not* to depend on local properties of the text (i.e. word length), the expected probability of fixating a letter can be calculated by dividing the total number of fixations by the total number of characters (letters, spaces and punctuation) in the text, ignoring word boundaries entirely. In our data for reading spaced text aloud, we found around 0.2 fixations/character for each subject. For unspaced text it ranged from 0.2 to 0.4 fixations/character, depending on the subject.

Figure 8 shows the probability of fixating a letter plotted against word length. Data for 1-letter words and words longer than 10 letters are not shown because there were not enough such fixations to allow for a meaningful analysis.

Two features stand out in these graphs. First, the functions are not horizontal lines as would be expected if the subjects were equally likely to fixate any character in the text, regardless of word length. Second, the curves for spaced and unspaced texts were very similar except that the curves for unspaced reading all lie above the curves for spaced reading. This means that, on average, subjects fixated each letter of unspaced text more often than they fixated each letter of spaced text. This is consistent with the observation that the decrease in saccade size from spaced to unspaced text was slightly greater than the increase in the density of the text, resulting in an increase in the number of saccades/line (see Fig. 6).

Quadratic functions were fitted to the probability of fixating a letter curves (Fig. 8) to permit a more quantitative analysis of each subject's reading strategy. An F-test was used to determine whether adding a quadratic component significantly improved the goodness-of-fit (Bevington, 1969). Table 3 summarizes this analysis. In most cases, the quadratic coefficients were negative for both spaced and unspaced texts (the curves were concave

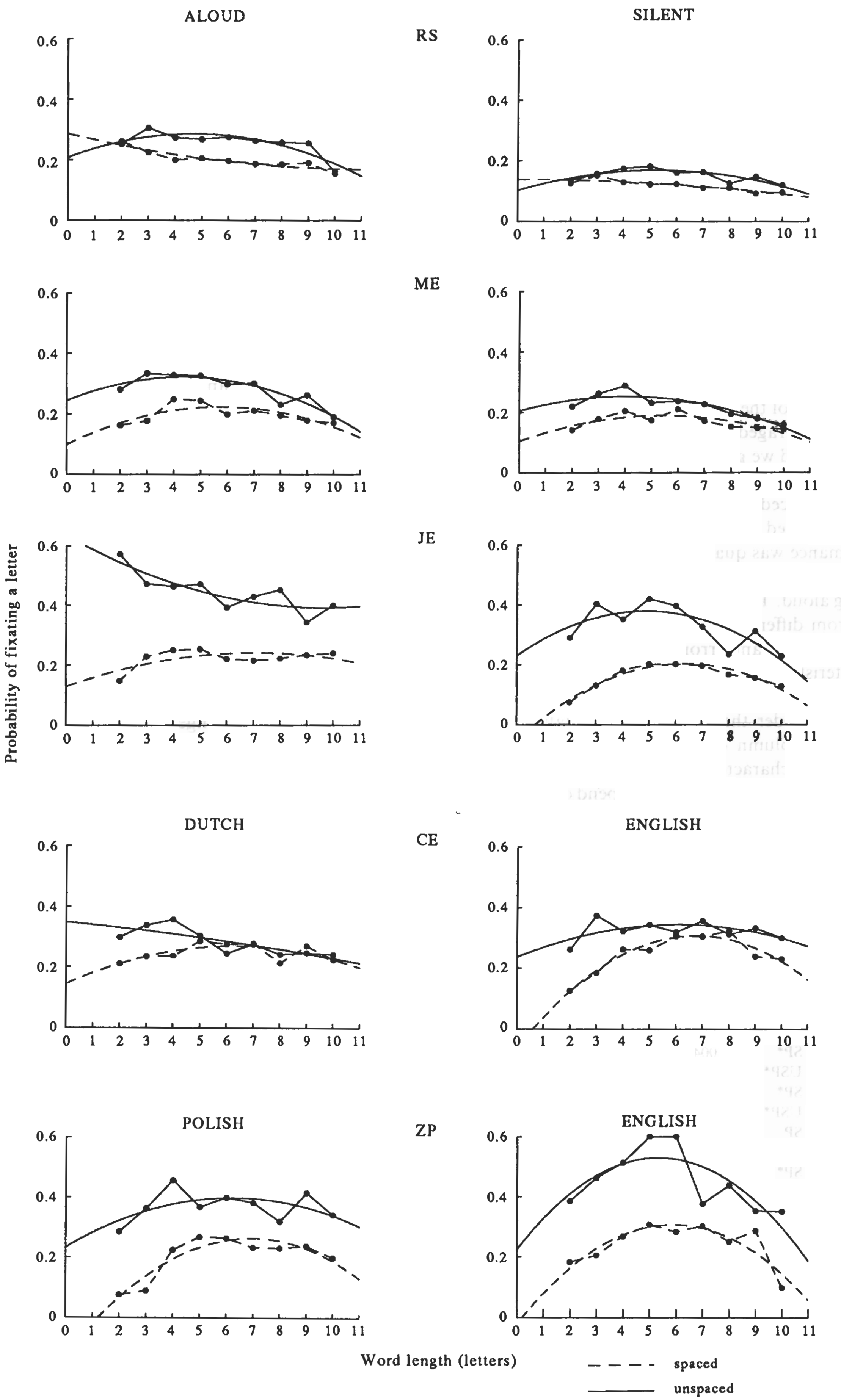

FIGURE 8. Probably of fixating a letter plotted as a function of word-length for spaced (solid lines) and unspaced (dashed lines) texts. Each point was computed on the basis of 29–240 words for subjects RS, ME and JE, and 8–76 words for bilingual subjects CE and ZP. Quadratic curves, fitted to the data points, are also shown.

downwards). There were some differences among the subjects. The linear fits to RS's data were as good as quadratic for both spaced and unspaced reading when he read both aloud and silently. CE, who was just as fast reading spaced and unspaced texts in Dutch, shows a quadratic curve for spaced and a linear curve for unspaced reading. JE's data was linear for both spaced and unspaced texts when she read aloud and quadratic, when she read silently. ZP, who, like JE, did not read unspaced texts as fast as the others, had quadratic fits to both spaced and unspaced texts in English and in Polish. These individual differences are important, because Rayner and McConkie (1976) used data averaged over 10 subjects to show that the probability of fixating a letter is a quadratic function of word length and used this average function to reject the hypothesis that reading eye movements are independent of the local properties of the text being read. When we averaged our data for subjects RS, ME and JE reading aloud we got a quadratic fit for both spaced and unspaced texts. The coefficients were −0.002, 0.027, 0.145 for spaced and −0.002, 0.015, 0.333 for unspaced. These averaged curves make it appear as if the subjects' performance was quadratic, while in reality, only one of the subjects, ME had significant quadratic fits when reading aloud. This example shows clearly that averaging data from different subjects can be misleading and can produce important errors of interpretation when local characteristics of the reading eye movement pattern are under study.

Next consider the probability of fixating spaces (the right-most column of Table 3). In spaced texts, about 15% of all characters were spaces between words. If reading eye movements did not depend on local properties of the text, 15% of all fixations would be expected to fall on these spaces. This is almost what we found, i.e. 12.6–18.9% of our subjects' fixations fell on spaces.

TABLE 3. Mean fixations/letter as function of word length and probability of fixating spaces for spaced (SP) and unspaced (USP) text

		Coefficients (a, b, c)			Probability of fixating spaces
RS aloud	SP	0.001	−0.021	0.287	0.184
	USP	−0.001	0.033	0.209	
RS silent	SP	0.000	0.000	0.140	0.189
	USP	−0.020	0.025	0.104	
ME aloud	SP*	−0.004	0.012	0.104	0.157
	USP*	−0.004	0.032	0.254	
ME silent	SP*	−0.003	0.031	0.106	0.142
	USP*	−0.003	0.023	0.206	
JE aloud	SP	−0.002	0.033	0.130	0.134
	USP	0.003	−0.050	0.636	
JE silent	SP*	−0.006	0.081	−0.053	0.140
	USP*	−0.006	0.061	0.230	
CE Dutch	SP*	−0.003	0.041	0.142	0.137
	USP	0.000	−0.008	0.348	
CE English	SP*	−0.008	0.110	−0.065	0.144
	USP*	−0.003	0.03	0.237	
ZP Polish	SP*	−0.008	0.120	−0.124	0.129
	USP*	−0.004	0.056	0.225	
ZP English	SP*	−0.010	0.112	−0.025	0.126
	USP*	−0.012	0.125	0.202	

The coefficients are least-square estimates fitted to the equation: $y = ax^2 + bx + c$, where y is mean fixations/letter and x is word length. *Conditions where adding a quadratic component significantly improved the fit.

The probability of fixating a letter was computed on the basis of information about *which* word was fixated, but this measure does not consider *where* within individual words most fixations occurred. If spaces play the role of highly visible landmarks that guide the line of sight from one word to the next as has been suggested, examining the landing positions within words in our data should surely show differences between spaced and unspaced reading. This issue is considered next.

Subjects' initial saccades into words longer than 5 letters tended to land in the first half of the word in both spaced and unspaced texts. In his "strategy-tactics" theory of eye movements, O'Regan suggested that coarse visual cues, particularly spaces between words, guide the line of sight to what he called the "convenient" or "optimal" landing position in each word (O'Regan *et al.*, 1984). The optimal landing position (OVP) is the location in a word which when fixated produces the fastest word recognition. The OVP is believed to be near the middle of the word for most words (O'Regan, 1990).

Figure 9 shows the probabilities of landing on each letter for 3–8 letter words for reading aloud (a) and silently (b). These curves plot the probability of the *initial* progressive saccade into the word as a function of the letter in the word on which the line of sight landed at the end of this saccade. Except for a tendency to land in the first half of words longer than 5 letters, there were no well-defined "preferred" (Rayner, 1978) landing positions in either spaced or unspaced texts. In most cases shown in Figs 9 and 10, the curves for spaced and unspaced texts look similar. In those cases where the curves are different, the differences appear to be random, rather than systematic. JE was an exception. She tended to land closer to the beginnings of words in unspaced text than in spaced texts. These results show that spaces, as such, do **not determine** where the line of sight will land within a word. O'Regan (1990) suggested that instead of landing each saccade exactly on what he called the OVP, the reader may make use of a less taxing strategy by landing near the OVP and then using a "rescue tactic", which takes the line of sight to the opposite side of the OVP (see also Jacobs, 1987). According to this theory, when the line of sight falls close to the OVP, which is near center for most words, the probability of making a saccade within this word, i.e. performing a "stay" operation, should be smaller than when the line of sight falls either on the beginning or on the end of the word. The probabilities of the "stay" operation for different locations within words is considered next.

The probability of performing a "stay" operation in both spaced and unspaced texts was higher when the initial saccade into a word landed at the beginning or end of the word than when it landed near the middle of the word. The probability of staying within a word was calculated as a function of the initial landing letter. The results for 4- and 7-letter words are shown in Fig. 10. According to O'Regan, as the difference between the initial landing

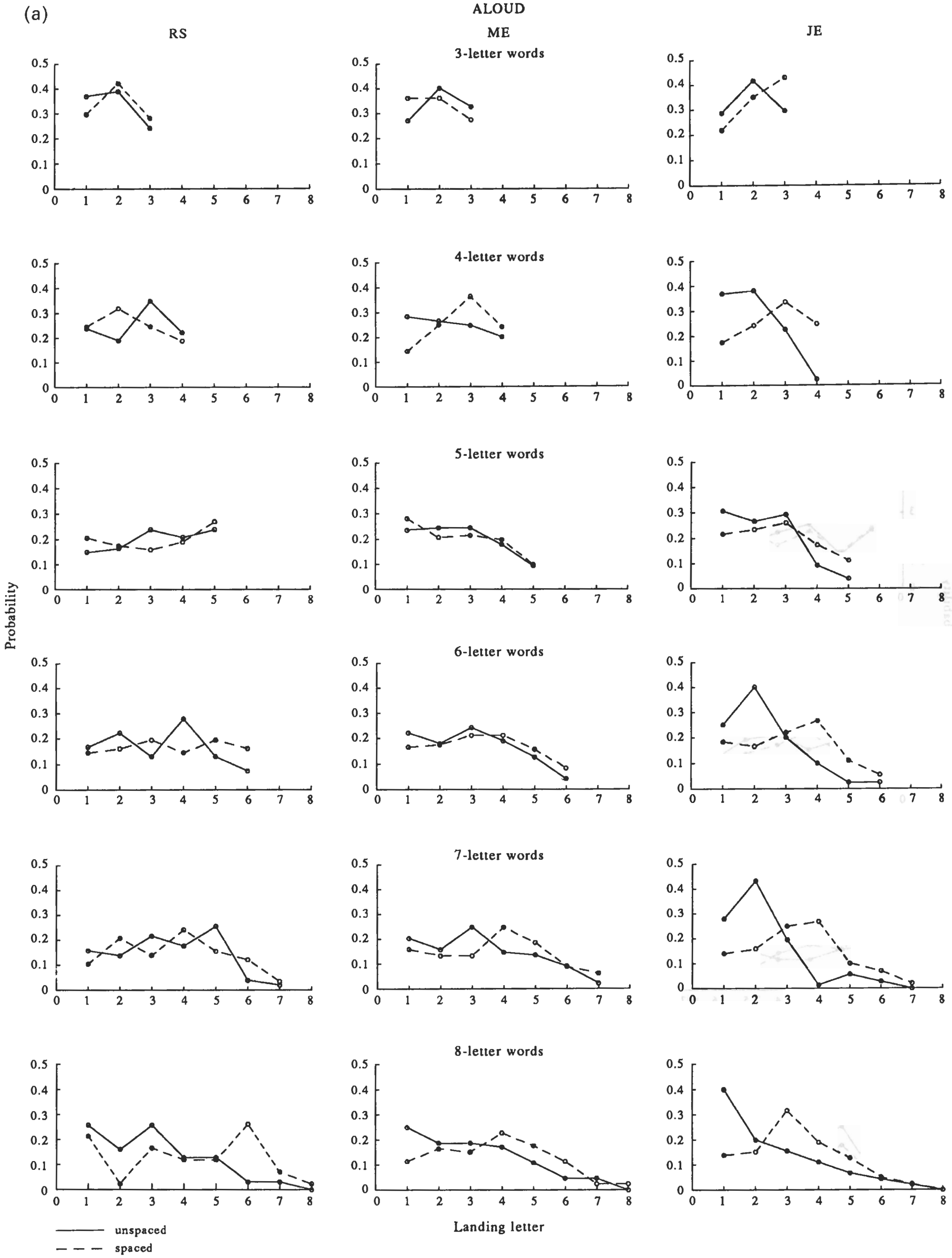

FIGURE 9(a). *Caption overleaf.*

letter and the OVP increases, the probability that the next saccade will keep the line of sight within a word should also increase. The results shown in Fig. 10 support this view for both spaced and unspaced texts. Namely, when the initial saccade landed near the middle of the word, the probability of remaining within this word after the second saccade was smaller than when the initial saccade took the line of sight near the beginning

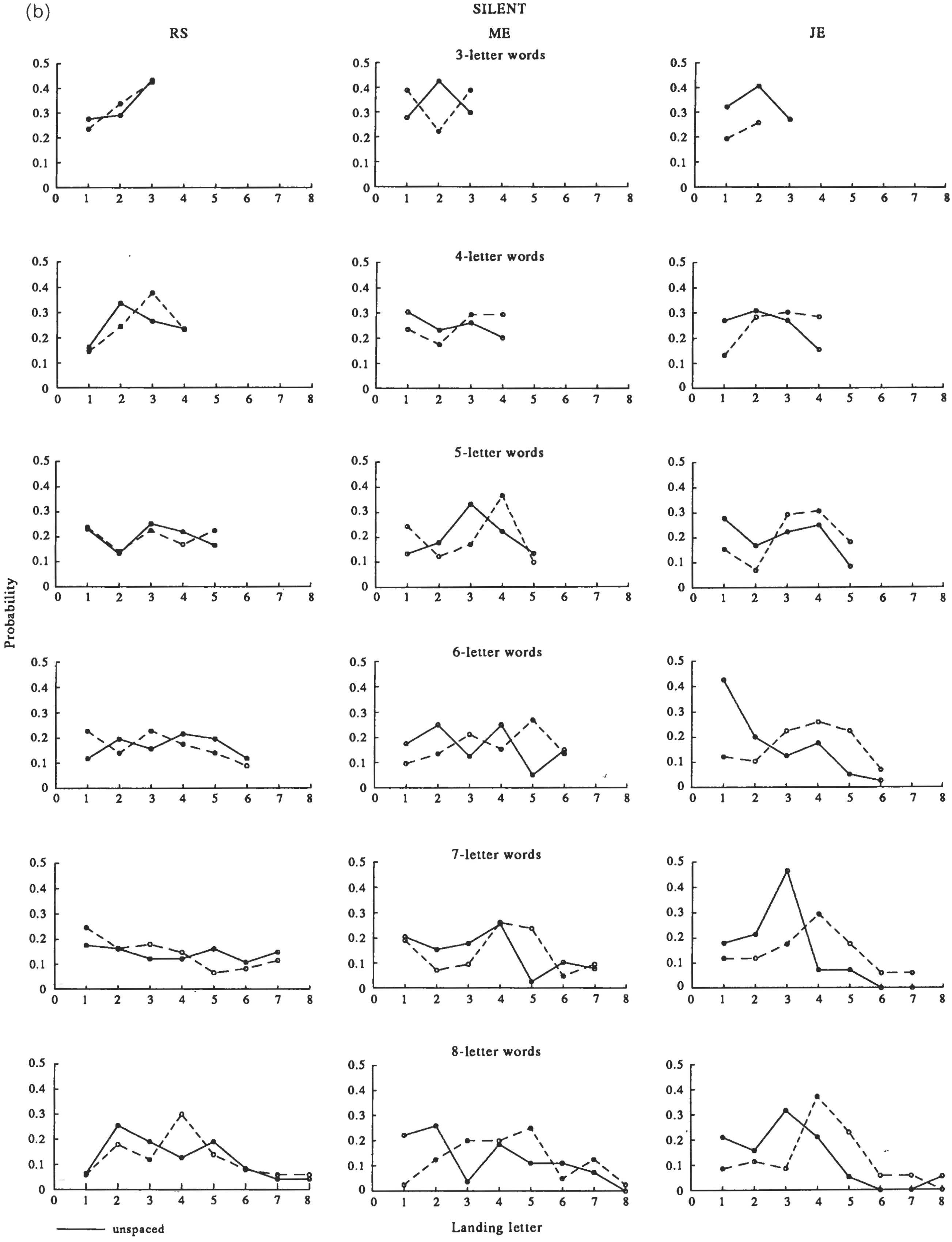

FIGURE 9. Probability of the initial saccade into a word landing on a particular letter of 3–8 letter words for subjects RS (left), ME (middle) and JE (right) reading aloud (a) and silently (b). Dashed lines show data for spaced texts. Solid lines show data for unspaced texts.

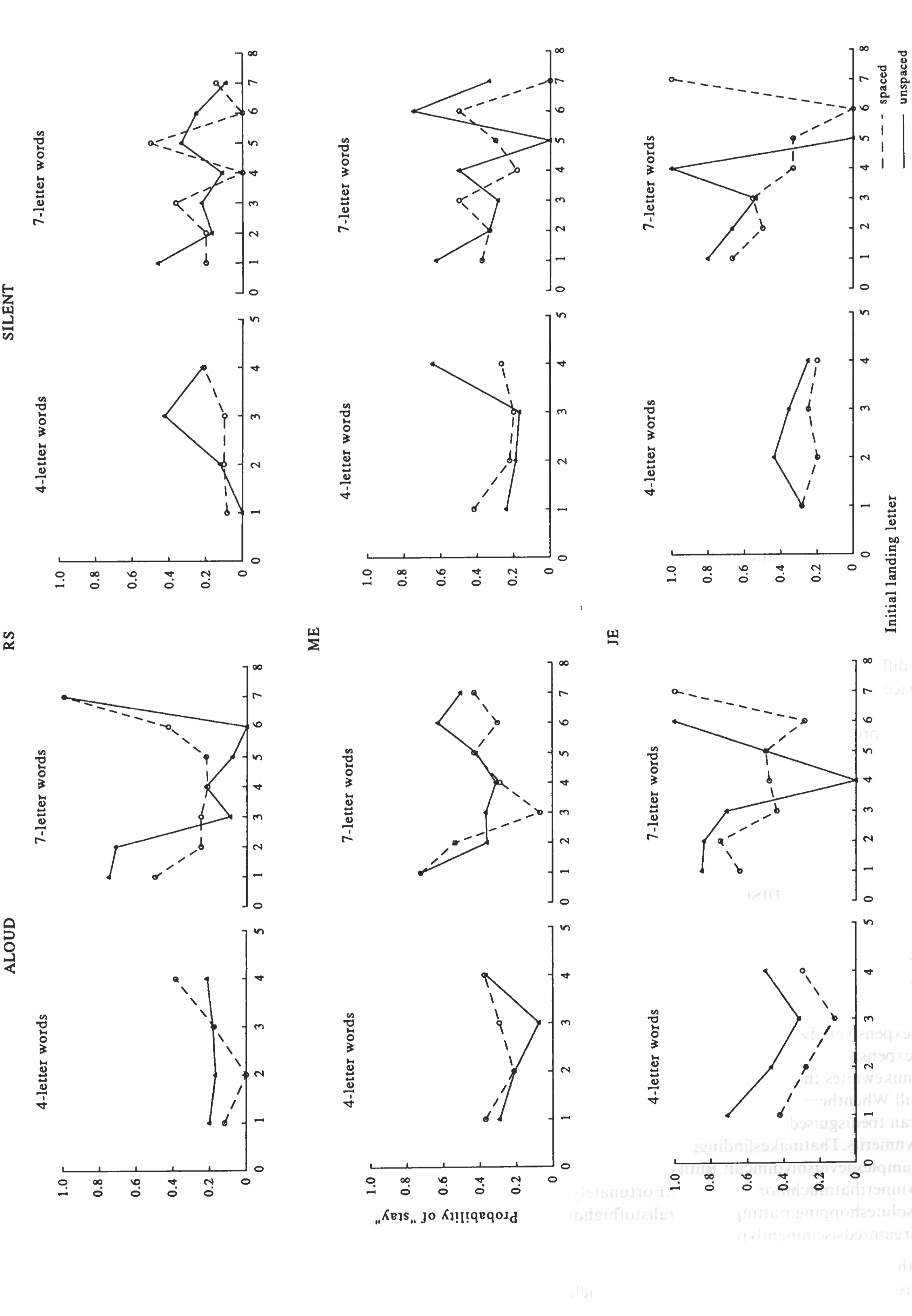

FIGURE 10. Probability of performing a "stay" operation as a function of the initial landing letter for 4- and 7-letter words for subjects RS (top), ME (middle) and JE (bottom) reading aloud (left) and silently (right). Dashed lines show data for spaced texts. Solid lines show data for unspaced texts.

or near the end of the word. Note, however, that this result can be explained without making any assumptions about the dependence of saccadic programming on local properties of the text. Specifically, if the line of sight is in the middle of a word, either a progressive saccade, or a regression is likely to move the line of sight outside of this word. If, however, the line of sight falls near the beginning of the word, a progressive saccade is likely to land in the same word. And, if the line of sight falls near the end of the word, a regression is likely to take it back into the same word. Thus, a text-independent, random eye movement model, as well as O'Regan's theory, predicts the U-shaped curves shown in Fig. 10. The possibility that the U-shape of what they called "refixation curves" is a statistical artifact was suggested and rejected by McConkie, Kerr, Reddix, Zola and Jacobs (1989). Their reasoning, however, had problems and the U-shapes of the refixation curves could still be statistical artifacts, despite McConkie *et al.*'s analyses. These problems and the results of a more straightforward simulation based on our data, which suggest that the U-shapes, may, in fact, be artifacts, will be considered in the Discussion.

The results summarized in Figs 9 and 10 provide only ambiguous support for the importance of the OVP or for O'Regan's strategy-tactics theory. They also show that spaces between words do not play a big role in determining either the initial landing letter or the probability of staying within a word once the line of sight falls within that word.

In summary, neither global nor local properties of the reading eye movement pattern support the hypothesis that different strategies are employed when spaced and unspaced texts were read. The differences in global parameters that were observed were only differences in scale (smaller progressive saccades and slightly longer reading fixations when unspaced texts were read). Furthermore, these differences appear to be primarily designed to compensate for the difference in the density of the two kinds of text produced by the presence or absence of spaces between words.

DISCUSSION

Unspaced text is relatively easy to read

The skeptical reader should read the following unspaced text aloud. Do it no matter how hard it seems to start.

> Inexpensiveredwineslackamajoradvantageof inexpensivewhitewines,theyshouldn'tbeservedcold. Unlikewhites,theycan'thidebehindapalatenumbing chill.Whentheyareflawed,itshows.Iftheyaresimple, itcan'tbedisguised.Inshort,redsriseandfallontheir ownmerits.Thatmakesfindinggoodinexpensive examplesdevilishlydifficult.Butitalsomakestasting awinnerthatmuchmorerewarding.Fortunately,with resoluteshopping,puttingtogetheralistofhighquality bargainredsiseminentlypossible.

If this was difficult, try turning up the lights, varying your reading distance and cleaning your spectacles. Clear vision is essential for reading unspaced texts. Fuzzy spaced texts can be read, but fuzzy unspaced texts cannot (see Legge *et al.*, 1985). All of our subjects and every other person asked to read unspaced text aloud since we started working on this problem 3 yr ago, agreed that when visibility is good, reading unspaced text is surprisingly easy, once the initial hesitation to read such seemingly meaningless strings of letters was put aside.

Our data confirm these informal observations. Most of our subjects slowed down only modestly when they read unspaced texts. All our subjects, including JE and ZP, who were not nearly as fast as the others when they read unspaced texts had the same percentage of regressions in spaced and unspaced texts. The fact that removing spaces had no effect on this widely-accepted measure of reading competence supports our conclusion that reading unspaced texts is not much more difficult than reading spaced texts. The outcome of our experiment is surprising only in light of the voluminous research literature which stresses the importance of spaces. This outcome could have been expected, however, once the history of western writing, rather than recent trends in research on reading eye movements, is considered.

The finding that it is possible to read unspaced texts competently is not, in itself, remarkable. Kolers (1968) and Kowler and Anton (1987) had already shown that it was possible to read and understand geometrically transformed and "twisted" texts, i.e. texts rotated 180 deg about horizontal and vertical axes, with word-order and/or letter-order reversed. Unlike unspaced texts, however, some of Kowler and Anton's twisted texts, were quite difficult to read and required the subject to fixate every letter or every other letter of each word to construct the meaning of the text. Reading our unspaced texts was much faster and easier, i.e. reading speeds were quite high and the reading eye movement pattern was the same as the pattern used with normal, spaced texts. Even a detailed examination of local properties of our subjects' reading eye movements showed no major differences between spaced and unspaced reading. Furthermore, in three of our five subjects, the observed differences in the global characteristics of eye movements could be accounted for largely by a change in a single global parameter, namely, the average size of progressive saccades, which the subjects adjusted to compensate for the increase in text density introduced when spaces were removed.

Our analyses of both the global and the local properties of the eye movement pattern suggest that the same oculomotor strategy was used for reading spaced and unspaced texts, implying that spaces are relatively unimportant for guiding reading eye movements. Since prior research on the role of visual factors in programming eye movements assumed that spaces were important, it is clear that the role of such visual factors in reading has been greatly overestimated. So what does determine where the line of sight will go next in a text?

Two obvious alternatives are as follows: first, the reading eye movement pattern is largely text-independent. If it is, the average saccade size and the average duration of reading fixations are adjusted on the basis of a global parameter, namely, the density of the information in the text. If, on the other hand, the reading eye movement pattern is largely text independent, the small effects of word length on the probability of fixating a letter (see Fig. 8), the tendency to land in the first half of longer words (see Fig. 9) and the effect of the initial landing-letter on the probability of performing a "stay" operation (see Fig. 10) resulted from the fact that words of different lengths were not distributed randomly in the texts. The second alternative is that the reading eye movement pattern was, at least to some extent, text dependent, but cognitive and perceptual factors played a much greater role than spaces in the programming of reading saccades. For example, the word-length information, which seems to have an effect, albeit small, on saccadic programming, could have been be obtained by recognizing the fixated word, rather than by detecting spaces to the right of fixation.

To distinguish between these two alternatives, it is necessary to determine the extent to which the programming of reading saccades was dependent upon local properties of the text. Our attempt to make this distinction is described next.

Local properties of the reading eye movement pattern are only weakly dependent on local properties of the text. The analyses performed to decide whether moment-to-moment saccadic programming was text dependent produced ambiguous results. Specifically, we found that for four of our five subjects, the probability of fixating a letter was slightly lower for short and long words than for words of medium length (see Fig. 8). The quadratic coefficients, for the cases where quadratic fits were more appropriate than linear fits, were quite small (see Table 3). We also noted that this result could be explained simply by assuming that words of different lengths were not distributed randomly in the texts. As far as where, within words, the readers fixated, there were two findings. First, we found that for words longer than five letters, the initial saccade into a word was more likely to land in the first half than in the second half of the word for both spaced and unspaced texts (see Fig. 9). Second, we found that for both types of texts, if the initial reading fixation was near the center of the word, the probability of performing a "stay" operation was lower than if the initial reading fixation was near the beginning or near the end of the word (see Fig. 10). The shapes of the curves in Fig. 9 could have been expected simply on the basis of the distribution of the sizes of reading saccades. Namely, progressive saccades were, on average, six letters long when subjects read aloud. This means that no matter where within the previous word the line of sight was, the progressive saccade that took the line of sight into the next word was more likely to land in the first half of the word if it was longer than 5 letters. However, spaces made distances between words larger. Therefore, if the mean progressive saccade size were to remain the same during spaced and unspaced reading, the peaks of the curves in Fig. 9(a) would be expected to shift to the right for unspaced reading. But, except for JE's data, the peaks of the curves coincided, or were at most 1 letter apart in most cases shown in Fig. 9. This is another piece of evidence that mean progressive saccade size was adjusted by most subjects, so as to match the increase in density of the unspaced text. JE, however, overcompensated for the increase in text density and for her, the unspaced reading curves in Fig. 9 were shifted to the left, showing that her line of sight tended to fall closer to the beginning of the word for unspaced texts than for spaced texts.

A similar line of reasoning can be used to explain the U-shaped curves in Fig. 10. If the initial reading fixation occurs near the center of the word, either a progressive saccade or a regression is likely to take the line of sight out of the word, thus reducing the probability of a "stay" operation. Whereas, if the initial reading fixation is near the beginning of the word, a progressive saccade is more likely to keep the line of sight within this word. And, if the initial reading fixation is near the end of the word, almost any regression will land within the same word. The possibility that the U-shapes of the refixation curves is caused by this type of statistical artifact was considered by McConkie *et al.* (1989). They rejected this idea by showing that if progressive saccades and regressions are picked randomly from an observed frequency distribution of saccade sizes, the shapes of the resulting refixation curves were still U-shaped, but that their shapes were somewhat different from the shapes of the observed refixation curves. However, these authors used a combined frequency distribution of saccade sizes for 66 subjects and compared the refixation curves simulated using this "average" distribution to the refixation curves produced by averaging data over the same 66 subjects. Given the individual differences observed in both saccade size distributions and the shapes of refixation curves (see Figs 5 and 10), the McConkie *et al.* analysis is questionable. It is possible that the U-shapes of refixation curves for each subject were, in fact, statistical artifacts, but when combined distributions of saccade sizes were used, differently shaped curves were produced. We performed a different type of simulation on our individual subjects' data to try to resolve this issue.

To explore the question of text dependence, each subject's reading eye movements were superimposed on texts other than those actually read when the eye movements were recorded. For example, ME's eye movements recorded when he read the text in trial 1 were superimposed on the text he read in trial 2. The three types of analyses of local properties of reading eye movements (described in the Results) were then performed on these new, simulated data. If reading eye movements depended only on the global properties of text, then switching the text in this manner should not make a difference in the results because the texts were taken from the same population (newspaper articles) and should, therefore, have very similar global parameters. If, however, the eye movements were contingent on local properties of text, switching texts should produce very different results, because local features of the substituted texts occurred in different places than in the text that was actually read. For example suppose the subject read the text "The fox jumped". His first fixation was on 'h', then he aimed for 'o' in 'fox' and made an accurate 4-letter saccade. Then he wanted to fixate left of center of the next word, but went too far and landed on 'p' (a 6-letter saccade). Then he used a "rescue tactic" to go to 'j' (a 3-letter regression). In the switched text simulation, the saccades sizes 4, 6 and -3 are superimposed on a new text, for example "He jumped high". If the first fixation is on 'e', the next saccade will land on 'm', the next on 'i' and then a regression will go to 'd' in 'jumped'. In this example, the "strategy-tactics" theory fits the original data very well, but the eye movement pattern produced after a new text is substituted implies a very different oculomotor strategy.

The results of the analyses performed on the switched text simulation for ME are shown in Fig. 11. ME was chosen to illustrate this point because he, among our main subjects, was the least variable and had the largest number of reading trials. The results of the analyses of switched texts for the other subjects showed similar trends. The only striking difference between the real (top) and the simulated data (bottom) can be seen in the left column, where the graph plots the probability of fixating a letter as a function of word length. The real data were clearly quadratic, while the simulated data were clearly linear with a slope close to zero. Thus, the small effect of word-length on the probability of fixating a letter went away when a different text was substituted for the text actually read. This suggests that this effect, albeit small, cannot be explained by a global property of the text, such as the non-random distribution of words of different lengths and must, therefore, be attributed to local properties of the text. The differences in the other graphs shown in Fig. 11 are less striking. The data for the switched text departed further from the best fit curves than the data for real text (the best-fit curves were quadratic in the case of the probabilities of fixating a letter and performing a "stay" operation curves and normal in the case of the preferred landing-letter curves). The effects of local properties of text on the initial landing letter or on the shapes of the probability of "stay" curves, however, were small. This implies that the landing letter and probability of "stay" (or refixation) curves are not good diagnostics for whether eye movements are dependent on local properties of text because the shapes of these curves were similar for real and switched texts. These kinds of curves are used extensively in research on reading eye movements and serve as the basis for many theories of reading eye movements. If they are nothing more than statistical artifacts, as our switched text simulation suggests, the conclusions derived from these observations, including those on the importance of spaces, must be reconsidered.

To summarize, Fig. 11, especially the probability of fixating a letter graphs (left column), shows that local properties of the text did have *some* effect on the reading eye movement pattern. Since the effects were the same for spaced and unspaced texts, spaces could *not* have been responsible for these effects. Now that spaces are known to be relatively unimportant, local and global factors, which may be important in the programming of reading eye movements, will be discussed.

The role of visual, perceptual and cognitive factors in the programming of reading eye movements

Given that word-length affects the probability of fixating a letter in unspaced texts, we must ask why spaces were introduced into modern languages. Reading speed was probably not their primary purpose because we found that it is not much more time consuming to program saccades in unspaced texts. Recall that the distributions of reading fixation durations were virtually identical when spaced and unspaced texts were read (see Fig. 4). However, we found that reading unspaced texts required much better visual acuity than reading spaced texts. Legge *et al.* (1985), had already reported that a considerable amount of blur can be tolerated when regular spaced texts are read. Our subjects could not read blurred unspaced texts. This suggests that spaces may have been introduced into texts to make it possible to read under poor lighting conditions or in the presence of refractive errors, including presbyopia.

Once unspaced texts could be seen clearly, however, most of our subjects could read them fairly easily. They must have been using perceptual information (letter groupings) or context (meaning) for programming their saccades because the most salient visual cue in conventional texts, spaces, had been removed. It is hardly news that meaning can speed up programming a sequence of saccades. Huey (1900) observed that pauses between saccades, made to a series of meaningless targets, were longer than reading fixations. This observation was confirmed recently by Kowler *et al.* (1992), who had subjects read a "text", where all letters except the initial letter of each word were whited-out. Their fixation durations were 20–30% longer than the durations of their reading fixations when the real text was read. This kind of simulated reading task provided ample visual information (large blank spaces between single letters), but scattered letters, unlike words, conveyed no meaning whatsoever. This saccadic scanning task might be viewed as less demanding than reading actual texts because it requires no cognitive or perceptual processing beyond detecting the next letter and making a saccade to it. But Kowler *et al.*'s removal of meaning from a text slowed

FIGURE 11 (*facing page*). Comparison of 3 local analyses for real (top panel) and switched (bottom panel) data for subject ME reading aloud and silently. Analyses are: (1) probability of fixating a letter as a function of word-length (left), (2) probability of performing a "stay" operation as a function of the initial landing letter (middle) and (3) the probability of the initial saccade into a word falling on a particular letter (right). Dashed lines show data for spaced texts. Solid lines show data for unspaced texts. See the text for an explanation of the difference between the real and switched texts.

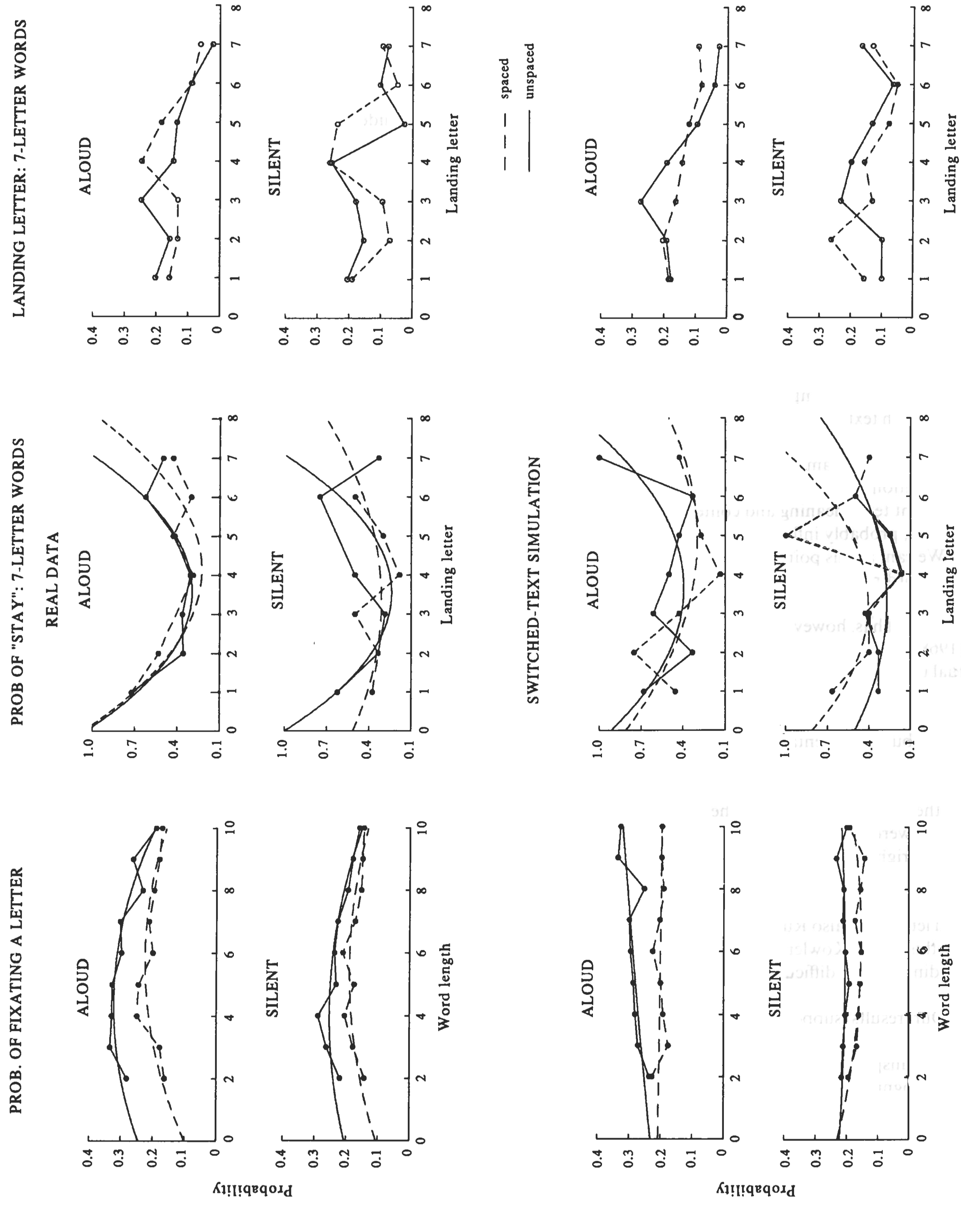

FIGURE 11. *Caption opposite.*

down saccades more then our removal of spaces from meaningful texts (our durations of reading fixations were at most 11% longer with unspaced then with spaced texts while reading aloud and only 13–16% longer while reading silently). Our result, as well as, those of Huey (1900) and Kowler *et al.* (1992), suggests that context facilitates saccadic programming.

Note, however, that the "text" (initial letters of words) used in the saccadic scanning task of Kowler *et al.* (1992) contained much less visual information than a real text. This raises the question of whether adding more visual information might be sufficient to eliminate the differences between saccadic scanning of initial letters and actual reading. To test this possibility, we tried to read texts that contained the same amount of visual information as regular texts, but where letter groupings were perturbed, so as to modify learned perceptual groups. Specifically, we removed spaces from one text and replaced them with spaces from another text. This resulted in groupings of letters that rarely corresponded to real words. Such, inappropriately-spaced, texts were very difficult, virtually impossible, to read. Our subjects had to work each text out on a letter by letter basis. This suggests that word recognition may be necessary, as well as sufficient, for programming reading saccades. Since word recognition is faster when words occur in the context of a coherent text, meaning and context, as well as perceptual factors, probably influence reading eye movements.

We can, at this point, only speculate as to how context and word recognition might be used to program reading eye movements, because we have not yet studied these factors. It has, however, already been suggested by Kolers (1968) that words or familiar letter patterns act as perceptual units during reading. He observed that when subjects were asked to read a text where the order of letters was reversed (right-to-left instead of left-to-right for English texts) but the orientation of letters was preserved, they tended to make a particular class of errors. Namely, they sometimes read individual words in the direction opposite to their reading direction. The words that evoked such errors were those that were meaningful when read either left-to-right or right-to-left (e.g. "was" and "saw"). He suggested that word recognition is an automatic process developed over years of experience with familiar words and letters (see also Rudnicky & Kolers, 1984). In support of this idea, Kowler and Anton (1987) showed that reading is most difficult when familiar letter patterns are perturbed.

Our results support the idea that word recognition speeds saccadic programming. Consider the following: blurry unspaced texts, where individual letters are difficult to recognize, cannot be read. Inappropriately-spaced texts, where familiar letter combinations are broken by spaces, are nearly impossible to read. Reading unspaced texts in a second language, where fewer words are familiar, is somewhat more difficult than reading unspaced texts in a native language. All of these findings suggest that word recognition speeds the line of sight's progression through the text. In unspaced reading, extra letters surrounding the actual words may give rise to familiar letter combinations that can be mistakenly recognized as words, but these words are inappropriate in the context of the text being read and can, therefore, interfere with reading (Jusczyk, 1986, p. 27). On the other hand, once a word is recognized, its length becomes known to the reader, so it is not necessary to rely on spaces to access word-length information and use it to program the next saccade in the reading sequence. The idea that word-length information, which may be used to guide the line of sight, is accessed through word recognition, rather than through spaces, is plausible because word recognition is relatively fast, especially when the word is relatively familiar and occurs in the context of a coherent text. Thus, on the basis of our findings, combined with the prior research by Kolers (1968), Rudnicky and Kolers (1984) and Kowler and Anton (1987), we conclude that words (or familiar letter combinations contained within them), not spaces, serve as the features that guide the line of sight along in the text. Spaces may serve a perceptual role by facilitating word recognition, but they do not, in themselves, play an important role in the programming of reading eye movements.

REFERENCES

Andriessen, J. J. & De Voogd, A. H. (1973). Analysis of eye movement pattern in silent reading. *IPO Annual Program Report*, *8*, 30–35.

Bader, L. A., Pearce, D. L. & Thompson, D. R. (1980). Effect of discourse on processing of left- and right-embedded syntactic structures. *Perceptual and Motor Skills*, *50*, 883–889.

Balota, D. A., Pollatsek, A. & Rayner, K. (1985). The interaction of contextual constraints and parafoveal information during reading. *Cognitive Psychology*, *17*, 364–390.

Bevington, P. R. (1969). *Data reduction and error analysis for the physical sciences*. New York: McGraw Hill.

Boorstin, D. J. (1983). *The discoverers*. New York: Random House.

Bouma, H. & De Voogd, A. H. (1974). On the control of eye saccades during reading. *Vision Research*, *14*, 273–284.

Collewijn, H. (1977). Eye and head movements of freely moving rabbits. *Journal of Physiology*, *266*, 471–498.

Collewijn, H., Erkelens, C. J. & Steinman, R. M. (1988a). Binocular coordination of human horizontal saccadic eye movements. *Journal of Physiology*, *404*, 157–182.

Collewijn, H., Erkelens, C. J. & Steinman, R. M. (1988b). Binocular coordination of human vertical saccadic eye movements. *Journal of Physiology*, *404*, 183–197.

Collewijn, H., van der Mark, F. & Jansen, T. C. (1975). Precise recording of human eye movements. *Vision Research*, *15*, 447–450.

Collewijn, H., Van der Steen, J. & Steinman, R. M. (1985). Human eye movements associated with blinks and prolonged eyelid closure. *Journal of Physiology*, *54*, 11–27.

Cunitz, R. J. & Steinman, R. M. (1969). Comparison of saccadic eye movements during fixation and reading. *Vision Research*, *9*, 683–693.

Ehrlich, S. F. & Rayner, K. (1981). Contextual effects on word perception and eye movements during reading. *Journal of Verbal Learning and Behavior*, *20*, 641–655.

Ehrlich, S. F. & Rayner, K. (1983). Pronoun assignment and semantic integration during reading: Eye movements and immediacy of processing. *Journal of Verbal Learning and Behavior*, *22*, 75–87.

Epelboim, J. Booth, J., Airey, D. & Steinman, R. M. (1992) Eye movements while reading unspaced text. *Investigative Ophthalmology and Visual Science (Suppl.)*, *33*, 1358.

Erkelens, C. J., Steinman, R. M. & Collewijn, H. (1989a). Ocular vergence under natural conditions—I. Continuous changes of target distance along the median plane. *Proceedings of the Royal Society of London B*, *236*, 417–440.

Erkelens, C. J., Steinman, R. M. & Collewijn, H. (1989b). Ocular vergence under natural conditions—II. Gaze shifts between real targets differing in distance and direction. *Proceedings of the Royal Society of London B*, *236*, 441–465.

Fisher, D. (1976). Spatial factors in reading and search. The case for space. In Monty, A. & Senders, W. (Eds), *Eye movements and psychological processes* (pp. 417–427). Hillsdale, N.J.: Erlbaum.

Frazier, L. (1983). Processing sentence structure. In Rayner, K. (Ed.), *Eye movements in reading: Perceptual and language processes* (pp. 215–236). New York: Academic Press.

Frazier, L. & Rayner, K. (1982). Making and correcting errors during sentence comprehension: Eye movements in the analysis of structurally ambiguous sentences. *Cognitive Psychology*, *14*, 178–210.

Grainger, J., O'Regan, J. K., Jacobs, A. M. & Segui, J. (1992). Neighborhood frequency effects and letter visibility in visual word recognition. *Perception & Psychophysics*, *51*, 49–56.

Haber, R. N. (1976). Control of eye movements during reading. In Monty, R. A. & Senders, J. W. (Eds), *Eye movements and psychological processes*. Hillside, N.J.: Erlbaum.

Heller, D. & Müller, H. (1978). On the relationship between saccade size and fixation during reading. In Senders, J. W., Fisher, D. F. & Monty, R. A. (Eds), *Eye movements and higher psychological functions*. New York: Erlbaum.

Henderson, J. M. & Ferreira, F. (1990). Effects of foveal processing difficulty on the perceptual span in reading: Implications for attention and eye movement control. *Journal of Experimental Psychology: Learning, Memory and Cognition*, *16*, 417–429.

Huey, E. B. (1900). On the psychology and physiology of reading. *The American Journal of Psychology*, *11*, 283–302.

Huey, E. B. (1908). *The psychology and pedagogy of reading* (1968 edn). Cambridge, Mass.: MIT Press.

Hyona, J., Niemi, P. & Underwood, G. (1989). Reading long words embedded in sentences: Informativeness of word halves affects eye movements. *Journal of Experimental Psychology: Human Perception and Performance*, *15*, 142–152.

Inhoff, A. W. & Rayner, K. (1986). Parafoveal word processing during eye fixations in reading: Effects of word frequency. *Perception & Psychophysics*, *40*, 431–439.

Jacobs, A. M. (1987). On the role of blank spaces for eye-movement control in visual search. *Perception & Psychophysics*, *41*, 473–479.

James, W. (1890). *Principles of psychology* (1950 edn). New York: Dover.

Judd, C. H. & Buswell G. T. (1922). Silent reading: A study of the various types. *Supplementary Educational Monographs*, *23*.

Jusczyk, P. (1986). Speach perception. In Boff, K., Kaufman, L. & Thomas, J. (Eds), *Handbook of perception and performance* (Vol. 2, Chap. 27). New York: Wiley.

Just, M. A. & Carpenter, P. A. (1980). A theory of reading: From eye fixations to comprehension. *Psychological Review*, *87*, 329–354.

Kennedy, A. (1986). The case for place: Text arrangement and reading skill. *Current Psychological Research and Reviews*, *5*, 94–104.

Kennedy, A. & Murray, W. S. (1984). Inspection times for words in syntactically ambiguous sentences under three presentation conditions. *Journal of Experimental Psychology: Human Perception and Performance*, *10*, 833–849.

Khurana, B. & Kowler, E. (1987). Shared attentional control of smooth eye movement and perception. *Vision Research*, *27*, 1603–1618.

Kiegel, R., Olson, R. K. & Davidson, B. J. (1982). Regression analysis as a tool for studying reading processes: Comment on Just and Carpenter's eye fixation theory. *Memory and Cognition*, *10*, 287–295.

Kiegel, R., Olson, R. K. & Davidson, B. J. (1983). On problems of unconfounding perceptual and language processes. In Rayner, K. (Ed.), *Eye movements in reading: Perceptual and language processes* (pp. 333–343). New York: Academic Press.

Kolers, P. A. (1968). The recognition of geometrically transformed text. *Perception & Psychophysics*, *3*, 57–64.

Kolers, P. A. (1976). Buswell's discoveries. In Monty, R. A. & Senders, J. W. (Eds), *Eye movements and psychological processes*. Hillside, N.J.: Erlbaum.

Kowler, E. (1990). The role of visual and cognitive processes in the control of eye movement. In *Eye movements and their role in visual and cognitive processes* (pp. 353–393). Amsterdam: Elsevier.

Kowler, E. (1991). The stability of gaze and its implications for vision. In Carpenter, R. H. S. (Ed.), *Eye movements* (pp. 71–94). London: Macmillan.

Kowler, E. & Anton, S. (1987). Reading twisted text: Implications for the role of saccades. *Vision Research*, *27*, 45–60.

Kowler, E., Pizlo, Z., Zhu, G., Erkelens, C. J., Steinman, R. M. & Collewijn, H. (1992). Coordination of head and eyes during the performance of natural (and unnatural) visual tasks. In Berthoz, A., Vidal, P. P. & Graf, W. (Eds), *The head-neck sensory motor system* (pp. 419–426). Oxford: Oxford University Press.

Legge G. E., Rubin, G.S. & Luebker, A. (1987). Psychophysics of reading— V. The role of contrast in normal vision. *Vision Research*, *27*, 1165–1177.

Legge, G. E., Pelli, D. G., Rubin, G. S. & Schleske, M. M. (1985). Psychophysics of reading—I. Normal vision. *Vision Research*, *25*, 239–252.

Levy-Schoen, A. & O'Regan, J. K. (1979). The control of eye movements in reading. In Kolers, P. A., Wrolstad, M. E. & Bouma, H. (Eds), *Processing of visible language I* (pp. 7–36). New York: Plenum Press.

Malt, B. C. & Seamon, J. G. (1978). Peripheral and cognitive components of eye guidance in filled-spaced reading. *Perception & Psychophysics*, *23*, 399–402.

McClelland, J. L. & O'Regan, J. K. (1981). Expectations increase the benefit derived from parafoveal information in reading words aloud. *Journal of Experimental Psychology: Human Perception and Performance*, *7*, 634–644.

McConkie, G. W. (1983). Eye movements and perception during reading. In Rayner, K. (Ed.), *Eye movements in reading. Perceptual and language processes* (pp. 65–96). New York: Academic Press.

McConkie, G. W. & Rayner, K. (1975). The span of the effective stimulus during a fixation in reading. *Perception & Psychophysics*, *16*, 578–586.

McConkie, G. W., Underwood, N. R., Zola, D. & Wolverton, G. S. (1985). Some temporal characteristics of processing during reading. *Journal of Experimental Psychology: Human Perception and Performance*, *11*, 168–186.

McConkie, G. W., Kerr, P. W., Reddix, M. D., Zola, D. & Jacobs, A. M. (1989). Eye movement control during reading: II. Frequency of refixating a word. *Perception & Psychophysics*, *46*, 245–253.

Morris, R. K., Rayner, K. & Pollatsek, A. (1990). Eye guidance in reading: The role of parafoveal letter and space information. *Journal of Experimental Psychology: Human Perception and Performance*, *16*, 268–281.

Morrison, R. E. (1984). Manipulation of stimulus onset delay in reading: Evidence for parallel programming of saccades. *Journal of Experimental Psychology: Human Perception and Performance*, *10*, 667–682.

O'Regan, J. K. (1979). Saccade size control in reading: Evidence for the linguistic control hypothesis. *Perception & Psychophysics*, *25*, 501–509.

O'Regan, J. K. (1990). Eye movements and reading. In Kowler, E. (Ed.) *Eye movements and their role in visual and cognitive processes* (pp. 395–453). Amsterdam: Elsevier.

O'Regan, J. K. & Jacobs, A. M. (1992). Optimal viewing position effect in word recognition: A challenge to current theory. *Journal of Experimental Psychology: Human Perception and Performance*, *18*, 185–197.

O'Regan, J. K. & Levy-Shoen, A. (1987). Eye movement strategy and tactics in word recognition and reading. In Coltheart, M. (Ed.), *Attention and performance XII: The psychology of reading* (pp. 363–383). Hillsdale, N.J.: Erlbaum.

O'Regan, J. K., Levy-Shoen, A. & Jacobs, A. M. (1983). The effect of visibility on eye movement parameters in reading. *Perception & Psychophysics*, *34*, 457–464.

O'Regan, J. K., Levy-Shoen, A., Pynte, J. & Brugaillere, B. (1984). Convenient fixation location within isolated words of different length and structure. *Journal of Experimental Psychology: Human Perception and Performance*, *10*, 250–257.

Pollatsek, A. & Rayner, K. (1982). Eye movement control in reading: The role of word boundaries. *Journal of Experimental Psychology: Human Perception and Performance*, *8*, 817–833.

Pollatsek, A. & Rayner, K. (1990). Eye movements and lexical access in reading. In Balota, D. A., Flores D'Arcais, G. B. & Rayner, K. (Eds), *Comprehension processes in reading* (pp. 143–163). Hillsdale, N.J.: Erlbaum.

Pollatsek, A., Rayner, K. & Balota, D. A. (1986). Inferences about eye movement control from perceptual span in reading. *Perception & Psychophysics*, *40*, 123–130.

Rayner, K. (1978). Eye movements in reading and information processing. *Psychological Bulletin*, *85*, 618–660.

Rayner, K. (1979). Eye guidance in reading: Fixation locations within words. *Perception*, *8*, 21–30.

Rayner, K. (1993). Eye movements in reading: Recent developments. *Current Directions in Psychological Science*, *2*, 81–85.

Rayner, K. & Balota, D. A. (1989). Parafoveal preview and lexical access during eye fixations in reading. In *Lexical representation and processes* (pp.261–290). Cambridge, Mass.: MIT Press.

Rayner, K. & McConkie, G. W. (1976). What guides a readers eye movements? *Vision Research*, *16*, 829–837.

Rayner, K. & Morris, R. K. (1992). Eye movement control in reading: Evidence against semantic processing. *Journal of Experimental Psychology: Human Perception and Performance*, *18*, 163–172.

Reeves, A. & Sperling, G. (1986). Attentional gating in short-term visual memory. *Psychology Review*, *93*, 180–206.

Robinson, D. A. (1963). A method of measuring eye movements using a scleral search coil in a magnetic field. *IEEE Trânsaction of Biomedical Engineering*, *10*, 137–145.

Rubens, S. R. (1945). Cube-surface coil for producing a uniform magnetic field. *Review of Scientific Instruments*, *16*, 243–245.

Rudnicky, A. I. & Kolers, P. A. (1984). Size and case of type as stimuli in reading. *Journal of Experimental Psychology: Human Perception and Performance*, *10*, 231–249.

Sereno, S. C. & Rayner, K. (1992). Fast priming during eye fixations in reading. *Journal of Experimental Psychology: Human Perception and Performance*, *18*, 173–184.

Sperling, G. & Dosher, B. A. (1986). Strategy and optimization in human information processing. In Boff, K., Kaufman, L. & Thomas, J. (Eds), *Handbook of perception and performance* (Vol. 1, Chap. 2, pp. 1–65). New York: Wiley.

Suppes, P. (1990). Eye-movement models for arithmetic and reading performance. In Kowler, E. (Ed.), *Eye movements and their role in visual and cognitive processes* (pp. 455–477). Amsterdam: Elsevier.

Suppes, P., Cohen, M., Laddaga, R., Anliker, J. & Floyd, H. (1983). A procedural theory of eye movements in doing arithmetic. *Journal of Mathematical Psychology*, *27*, 341–369.

Underwood, G., Bloomfield, R. & Clews, S. (1988). Information influences the pattern of eye fixations during sentence comprehension. *Perception*, *17*, 267–278.

Underwood, G., Hyona, J. & Niemi, P. (1987). Scanning patterns on individual words during the comprehension of sentences. In O'Regan, J. K. & Levy-Schoen (Eds), *Eye movements: From physiology to cognition* (pp. 467–477). Amsterdam: North-Holland.

Vitu, F. (1991a). The existence of a center of gravity effect during reading. *Vision Research*, *31*, 1289–1313.

Vitu, F. (1991b). The influence of parafoveal processing and linguistic context on the optimal landing position effect. *Perception & Psychophysics*, *50*, 58–75.

Vitu, F. O'Regan, J. K. & Mittau, M. (1990). Optimal landing position in reading isolated words and continuous text. *Perception & Psychophysics*, *47*, 583–600.

Viviani, P. (1990). Eye movements in visual search: Cognitive, perceptual and motor control aspects. In Kowler, E. (Ed.) *Eye movements and their role in visual and cognitive processes* (pp. 353–393). Amsterdam: Elsevier.

Wishner, R. A. (1976). The effects of syntactic expectations during reading. *Journal of Educational Psychology*, *68*, 597–602.

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