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Fixation location effects on fixation durations during reading: an inverted optimal viewing position effect

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Abstract

Previous research has found that words are identified most quickly when the eyes are near their center (the Optimal Viewing Position effect). A study was conducted to determine whether this same phenomenon is observed during reading, as revealed by a relationship between fixation position in a word and the duration of the fixation. An analysis of three large existing corpora of eye movement data, two from adults and one from children, showed a surprising inverted Optimal Viewing Position curve: mean fixation duration is greatest, rather than lowest, when the eyes were at the centers of words. From this phenomenon, we suggest an alternative explanation to the fixation duration trade-off effect in word refixations [O'Regan & Lévy-Schoen, Attention and performance XII: the psychology of reading (1987)]; the phenomenon also contradicts expectations of both oculomotor and cognitive theories of eye movement control. Attempts to test alternative explanations led to the discovery of another phenomenon, the Saccade Distance effect: mean fixation durations vary with the distance of the prior fixation from the currently-fixated word, being longer with greater distances. The durations of fixations in reading are complexly determined, with influences both from language and perceptual/oculomotor levels. © 2001 Elsevier Science Ltd. All rights reserved.

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1. Introduction

In reading, our eyes progress along the line of text by making saccades of variable lengths. About two-thirds of the words are generally fixated, and the most frequent initial landing position is the center of the word or slightly left of it, a position called the *Preferred Viewing Location* (Dunn-Rankin, 1978; McConkie, Kerr, Reddix, & Zola, 1988; Rayner, 1979; Vitu, O'Regan & Mittau, 1990). In many instances, the eyes land at other locations ranging from the very-beginning of the word to its end. This variability of initial landing sites in words has been attributed mostly to visual and oculomotor factors related to saccadic programming, though cognitive influences can also be observed (for reviews, see Brysbaert & Vitu, 1998; O'Regan, 1990; Rayner, 1998). As will be shown, where the eyes initially land in a word has repercussions for both word identification and within-word eye behavior.

Several studies have shown that the identification of isolated words varies greatly with the initial eye fixation location in the word. First, the likelihood of correctly identifying a word is highest when the eyes initially fixate near its middle, and decreases as the initial fixation deviates from the word's center (Brysbaert, Vitu, & Schroyens, 1996; O'Regan, 1990). Second, the time required to identify a word is shortest when the eyes initially fixate near the middle of the word (O'Regan & Jacobs, 1992; O'Regan, Lévy-Schoen, Pynte, & Brugaillère, 1984). These phenomena, which have been called *Optimal Viewing Position effects* (or *OVP effects*), are assumed to result mainly from the rapid drop-off of visual acuity with retinal eccentricity that makes the center of the word the position from which

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most letters from the word can be seen in a single glance (McConkie, Kerr, Reddix, Zola, & Jacobs, 1989; Nazir, O'Regan, & Jacobs, 1991; Nazir, Jacobs, & O'Regan, 1998; see also Clark & O'Regan, 1999 for an alternative account).

Other studies where subjects' eye movements were recorded while they were reading either isolated words or words in sentences and texts indicate that the within-word eye behavior is also influenced by the initial eye fixation location in the word. First, the frequency of refixating a word (that is, of making an additional fixation after the initial fixation on the word) is lowest when the eyes initially fixate the middle of the word (McConkie et al., 1989; O'Regan & Lévy-Schoen, 1987; Rayner & Fischer, 1996; Rayner, Sereno, & Raney, 1996; Vitu, 1991; Vitu et al., 1990). Second, the gaze duration, or total time the eyes spend fixating a word, is shortest for initial fixations located toward the center of the word. Both of these phenomena have also been called OVP effects, and will be referred to as the *Refixation OVP effect*, and the *Gaze Duration OVP effect*, respectively (Holmes & O'Regan, 1987; O'Regan et al., 1984; Vitu et al., 1990). While the Refixation OVP effect is fairly robust for both words in isolation and in reading, the Gaze Duration OVP effect is attenuated during reading (Vitu et al., 1990).

In addition, for words presented in isolation, fixation durations vary with the initial eye fixation location in the word, but only when a series of two consecutive fixations occur on the same word (O'Regan & Lévy-Schoen, 1987). In these particular two-fixation cases, there is a tendency for the duration of the initial fixation to be longer, and for the duration of the second fixation to be shorter, the closer the initial fixation lies toward the center of the word. Thus, in two-fixation cases, there is a trade-off in the allocation of time to the two fixations, which we will refer to as the *fixation duration trade-off effect*. In contrast, for single-fixation durations, there appears to be no effect at all of the initial fixation position. Data collected during the reading of passages confirm this last finding, but fail to replicate the fixation duration trade-off effect in two-fixation cases (Rayner et al., 1996).

All phenomena related to the initial eye fixation location in a word were originally accounted for by the 'Strategy-Tactics' theory of eye movement control in reading (O'Regan, 1990, 1992; O'Regan & Lévy-Schoen, 1987). In this theory, it is assumed that the within-word eye behavior results from pre-determined scanning routines (or 'tactics'), which are based on readers' prior experience that visual processing becomes less efficient as the eyes deviate from the center of the word. When the eyes land on a word, a mechanism is initiated that first locates the current eye position, and then decides on the basis of prior experience whether or not a second fixation must be initiated. If the initial fixation lies toward the center of the word where processing is known to be the most efficient, a within-word refixating saccade is less likely to be programmed than if it lies towards one of the word's ends, producing a Refixation OVP effect. In addition, the localizing mechanism or the decision to program a within-word refixation saccade may be slower when the eyes lie closer to the center of the word, resulting in longer first fixations. However, since the processing of a given word is assumed to require a constant amount of time, the longer the eyes remain at the initial location, the less processing will be required from the second eye location, and the shorter is the second fixation duration. In cases where no refixation occurs, the eyes simply remain at the same location until the word is identified, and for a duration that is constant and independent of the fixation location.

The Strategy-Tactics theory's assumption that fixation location related phenomena are not the result of language processing influences is supported by the finding of a Refixation OVP effect for pseudo-reading of meaningless letter strings where no language processing is involved (Vitu, O'Regan, Inhoff, & Topolski, 1995; see also Rayner & Fischer, 1996). This suggests that any variation in the duration of initial fixations in two fixation cases that occur in isolated words as a result of initial fixation locations must result from an oculomotor strategy rather than from direct cognitive control of eye behavior based on language processing. At the same time, the existence of cognitive influences, including the frequency of the words in the language or their predictability from a prior linguistic context on both refixation likelihood and first fixation durations in two-fixation cases has been demonstrated in numerous studies (McConkie et al., 1989; Pynte, 1996; Pynte, Kennedy, & Murray, 1991; Rayner, Sereno, Morris, Schmauder, & Clifton, 1989; Rayner et al., 1996; Vitu, 1991; Vitu & O'Regan, 1995).

An alternative account of within-word eye behavior comes from cognitive control theories that posit that oculomotor decisions are under the direct control of cognitive processes (Henderson & Ferreira, 1990; Just & Carpenter, 1980, 1987; McConkie, 1979; Morrison, 1984; Pollatsek & Rayner, 1990; Rayner & Pollatsek, 1989; Rayner, Reichle, & Pollatsek, 1998; Reichle, Pollatsek, Fisher, & Rayner, 1998). These assume that the within-word eye movement pattern is a direct response to the ongoing processing needs of the reader as interpreted in real time. In that framework, any difficulty in word processing would result in higher refixation likelihood and/or longer fixation times, thus accounting for variations in fixation and gaze duration with word-related factors on eye behavior. Cognitive control theories can also account for the Refixation-OVP effect. If the eyes land very far from the center of the word, word identification is made more difficult, which often leads to a second fixation in order to provide adequate visual information. Similarly, processing may be more efficient when the eyes are at the center of the word where a clearer view is provided, resulting in a greater likelihood of rapid identification and a smaller refixation probability.

However, cognitive control theories would predict an OVP effect also for fixation durations. Since a word is more likely to be rapidly identified with the eyes near the center of the word, first fixations should be shorter with the eyes at this location. In the same way, the duration of single fixations should also be shorter at the center of words. As noted above, these relations have never been clearly established. The durations of first fixations in two-fixation cases are longest and not shortest when the eyes are near the centers of words as in isolated word identification data (O'Regan & Lévy-Schoen, 1987), and they do not vary with fixation location as suggested by data from continuous reading (Rayner et al., 1996). Furthermore, there is no clear evidence that the initial fixation location in a word affects the duration of single fixations during reading. Both O'Regan and Lévy-Schoen (1987), and Rayner et al. (1996) report that single-fixation durations do not vary with the eyes' location in the word. However, both studies were limited in the number of data points available for single fixations towards the ends of words, which may have resulted in a weak test of the expected effects.

The present study was an attempt to further test for effects of the initial eye fixation location in a word on fixation durations. This study was conducted by carrying out a-posteriori analyses of three large existing corpus of eye movement data collected during the reading of continuous texts: one from 69 adults, one from four adults, and one from 30 fifth-grade children. Data from adults and children were not analyzed from a developmental perspective, but rather to determine whether regular effects of initial fixation location on fixation durations are found with different populations.

2. Methods

In all three data sets, subjects' eyes were monitored using a SRI Dual Purkinje Image Eye-tracker (Cornsweet & Crane, 1973), sampling eye position every millisecond. Text was presented on a computer screen. Four letters subtended 1° of visual angle.

2.1. Adults—Set 1

The first corpus of adult data, referred to as 'Adults—Set 1', came from a study by McConkie, Reddix, and Zola (1985) and has been used for other analyses of eye behavior during reading (McConkie et al., 1988, 1989). In the original experiment, the eye movements of 69 native English adult subjects were recorded as they read the first two chapters of a contemporary novel, presented on the computer screen one line at a time. Subjects were in control of the presentation, with the next line of the text appearing each time the reader pressed a button. For purposes unrelated to those of the current study, on about 25% of the lines of text, a single word was replaced by either a non-word letter string or an erroneous word. The subjects were instructed to read the passage for meaning, without regard to the errors. They were stopped and tested for comprehension 15 times during their reading, but were never asked about the errors. The data used in the present analysis came from 50 or 100 of the lines in which there were no errors. These lines served as the control condition in the study. This yielded a set of 43,662 eye fixations.

In the present analyses, the only cases used were those in which the first fixation on the word was preceded by a forward (rightward) saccade, and the word was 4, 5, 6, 7, or 8 letters in length and not preceded or followed by punctuation. In addition, data were excluded if there was a blink or other signal irregularity present. After selection, 13,654 cases remained for analysis, with 3833, 3396, 3079, 2244, and 1102 cases for 4- to 8-letter words respectively.

2.2. Adults—Set 2

The second corpus of adult data, referred to as 'Adults—Set 2' came from a study by Kerr (1992) and has been used for other analyses of eye behavior during reading (Vitu & McConkie, 2000). It was based on the eye movement data of four native English adult readers (three males and one female) who were between 21 and 34 years old, had normal uncorrected vision, and were above average in terms of reading speed and reading comprehension abilities.

All subjects read the entire book 'Gulliver's travels' written by Swift. The text was presented in its original version, except that (1) it was reformatted for presentation on the computer screen (8385 lines, each line being no more than 73 characters), (2) British spelling was changed to American English (e.g. 'honour' to 'honor'), and (3) outdated spellings were modernized ('hath' to 'have'). It was divided into sections that required no longer than 5 min to read. Reading of the entire book took place over several sessions of 1–2 h each.

The text was presented one line at a time. Subjects were in control of the presentation, with the next line of text appearing each time the reader pressed a button. They were instructed to read the text for comprehension, and after each section, they summarized the section's content. Before each text section, a calibration phase took place where subjects were asked to fixate a dot appearing successively at five different locations along the display line.

The data include a total of 369,186 eye fixations, with 82,966, 73,376, 88,411 and 124,433 fixations, respectively, for Subjects 1–4. For the particular data analyses presented below, the selected cases were those in which the initial and final fixations on a word were respectively preceded and followed by a minimum of two fixations on the same line of text, the first fixation on the word was preceded by a forward (rightward) saccade, and the word was fixated with 1–4 consecutive fixations and had not previously been fixated. The word was 4, 5, 6, 7, or 8 letters in length and not preceded or followed by punctuation. It was never the first or the last word on the line. In addition, data were excluded if there was a blink or other signal irregularity present on the line of text. After selection, 64,357 cases remained, with 18,425, 15,875, 11,323, 11,648, and 7086 cases for 4-to 8-letter words, respectively.

2.3. Children

The corpus of children data has been used for other analyses of eye behavior during reading (Vitu, McConkie, & Zola, 1998). It consists of eye-movement data from 30 native English-speaking fifth-grade students who were all about 12 years.

Each subject read six chapters of a children's novel appropriate to their age ('Old Yeller' by Frederick B. Gipson). The text was presented in its original version except that it was reformatted for presentation on the computer screen (seven lines at a time in triple-spaced format). Eye movements were recorded in the same manner as in the adult study described above. The reader advanced the page by pressing a button. Subjects were asked to read the story for meaning and were tested for comprehension after each chapter. A set of 395,415 eye fixations was obtained.

In the present analyses, the only cases used were those in which the first fixation on the word was preceded by a forward (rightward) saccade, and the word had not been previously fixated. The first and last fixations on the word were never (respectively) the leftmost or rightmost fixation on the line or the beginning or end fixation on the page of text. In addition, data were kept if there had been no blink or other signal irregularity present during the first run on the word or on the fixation preceding the first run. The word was 4, 5, 6, 7, or 8 letters in length and not preceded or followed by punctuation. After selection, 75,844 cases remained with 30,375, 17,438, 14,861, 8643, 4527 cases for 4- to 8-letter words, respectively.

3. Results

For each analysis presented in this section, means or proportions were calculated for each subject, and these were then averaged across subjects. In this way, the weights of individual subjects' contributions to the final values were not influenced by the number of fixations that qualified for a particular condition. Analyses of variance were run on the means obtained for each subject in each condition. In cases where no data were available for one or more subjects in a given condition, missing data points were replaced by the mean for the condition from the remaining subjects. This occurred in 5114 cells over a total of 17,181 cells (29.7%) in the Adult—Set 1 data, in 8 cells over a total of 996 (.8%) in the Adult—Set 2 data, and in 348 cells over a total of 11,340 (3%) in children data. In all three data sets, missing data points corresponded mostly to initial fixations located towards the end of long words (7 and 8 letters long), and cases where two consecutive fixations were made on the words. Also, the likelihood of observing missing data points was increased in all analyses that involved partitioning the data by word frequency or the prior saccade launch site.

Data from individual subjects were taken into account when they complemented averaged data.

3.1. Initial landing sites

Fig. 1a–c present the frequency of initially landing at different letter positions in words of different lengths (4–8 letters), for the three data sets. The curves for the different word lengths are very similar for all three data sets, all showing a variability of initial landing positions in words, and favoring the fourth letter position in the word for adults, and the third or fourth position for children. This preferred position was near the center of 6- to 8-letter words, but near the end of shorter words. For the longer words, this replicates the Preferred Viewing Location phenomenon (see Rayner, 1979).

3.2. Refixation probability

Fig. 2a–c present for the three data sets the mean refixation probability (that is, the likelihood of making at least one additional fixation on the word before leaving it), as a function of the initial fixation position on the word, for words of different lengths. All show the Refixation OVP curve, with minima at, or slightly to the left of, the word center. This replicates previous findings from both text reading (McConkie et al., 1989; Rayner et al., 1996; Vitu et al., 1990), and isolated word identification (O'Regan & Lévy-Schoen, 1987; Vitu, 1991; Vitu et al., 1990).

Quadratic analyses show a significant effect of the initial fixation location at the 0.0005 level for all word lengths, in the Adult—Set 1 data [$F(1,68) = 28.85$, $F(1,68) = 70.84$, $F(1,68) = 118.39$, $F(1,68) = 101.96$, $F(1,68) = 202.10$], and in children's data, [$F(1,29) = 95.80$, $F(1,29) = 142.64$, $F(1,29) = 186.59$, $F(1,29) = 114.08$, $F(1,29) = 47.83$]. In the Adult—Set 2 data, the quadratic trend is significant only for words longer than 5 letters [$F(1,3) = 3.70$, $F(1,3) = 5.25$, $P < 0.10$, $F(1,3) = 11.64$, $P < 0.05$, $F(1,3) = 25.95$, $P < 0.05$, $F(1,3) = 54.05$, $P < 0.005$, respectively, for 4- to 8-letter words].

While the Refixation OVP effect is present in all three corpora, the curves appear to rise more steeply in the case of children. Both sets of adult data have a zone around the middle of the word, in which refixation likelihood does not vary much. This is probably due to floor effects, since the refixation likelihood is near zero in that region for adults, whose overall refixation rate is low (0.13 and 0.09, as compared to 0.26 for children). One subject in the Adult—Set 2 data (Subject 4) had a refixation rate (0.21) that was close to that of the children; his Refixation OVP curves (not presented here) are quite similar to those of the children. Thus, the shape difference appears to result from the overall refixation likelihood, resulting in floor effects, rather than being a developmental difference.

The minimum point in the Refixation OVP curves varies somewhat for the different data sets, a fact for which we have no explanation.

3.3. Durations of eye fixations

3.3.1. Fixation-duration trade-off in two-fixation cases

Fig. 3a–c show, for all three data sets, the fixation-duration trade-off effect that occurs in cases where exactly two fixations occurred on the word: the duration of the first fixation is longest when the initial fixation is at the center of the word, and the duration of the second shows a mirror reversal, with shortest fixations when the first fixation was at the center of the word. Notice that these data do not indicate the location of the second fixation; data are all conditional on the location of the first fixation only. The data are more stable for children because they made two fixations on a much larger proportion of words (21.6% for children, as opposed to 12.3% and 8.7% for adults in Sets 1 and 2).

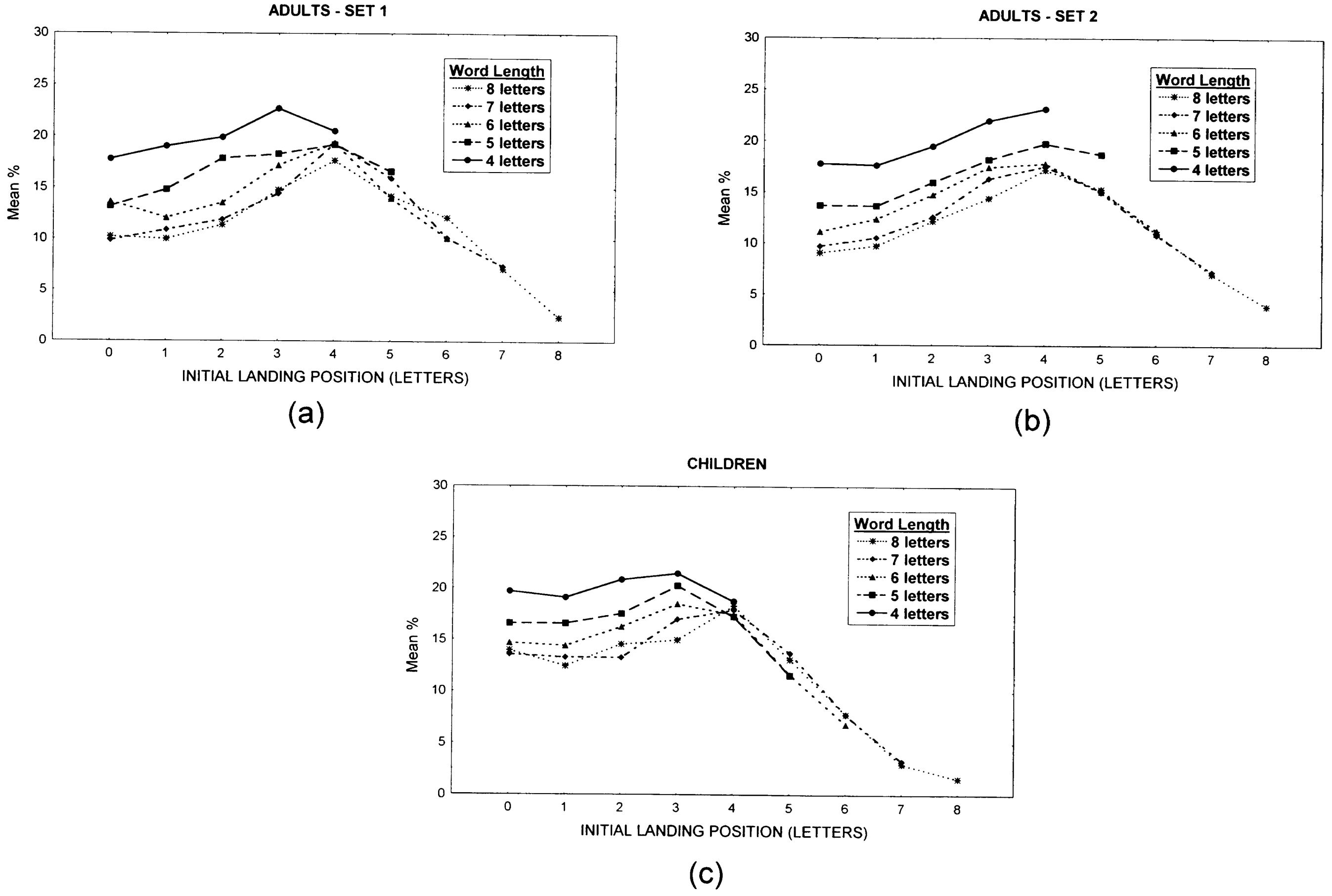

Fig. 1. Distribution of initial landing positions (expressed in letters) in 4- to 8-letter words, for Adult—Set 1 and Adult—Set 2 data (a and b, respectively) and for fifth-grade children (c). Letter 0 corresponds to the space in front of the word.

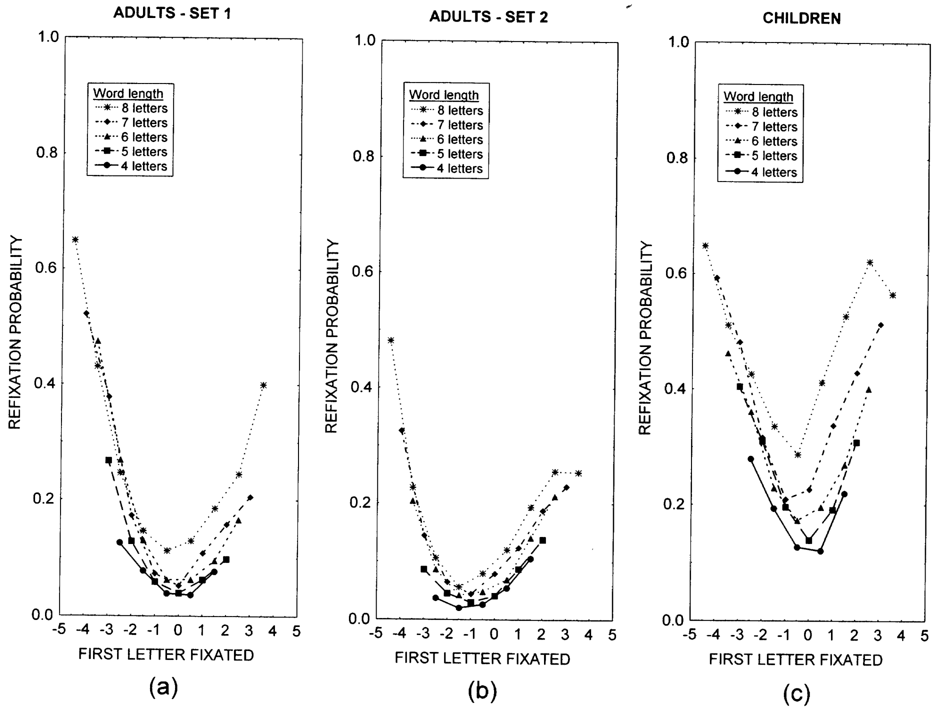

Fig. 2. Mean refixation probability in Adult—Set 1 and Adult—Set 2 data (a and b) and children's data (c), as a function of the initial eye fixation position in the word, for 4- to 8-letter words. The first fixation position in the word is expressed in letter position relative to the center of the word.

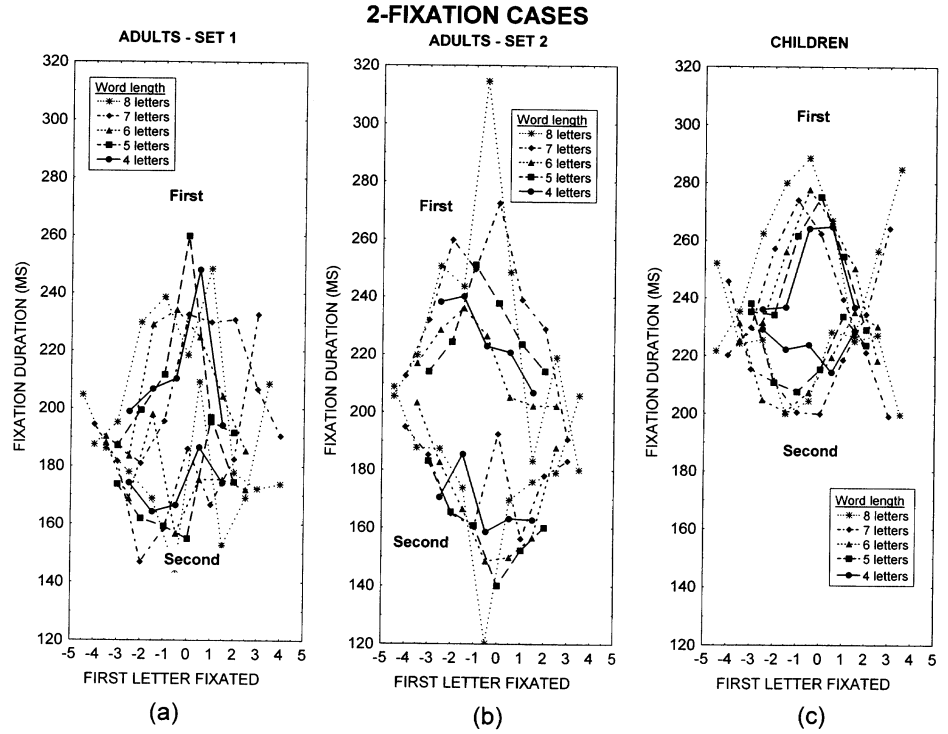

Fig. 3. Mean duration of first and second fixations in the cases where the eyes made exactly two fixations on the word, for Adult—Set 1 and Adult—Set 2 data (a and b) and children (c), as a function of the initial eye fixation position in the word, for 4- to 8-letter words.

Quadratic analyses of children's data revealed significant effects at the 0.0005 level for all word lengths for first fixation durations [$F(1,29) = 14.33$, $F(1,29) = 27.66$, $F(1,29) = 53.12$, $F(1,29) = 109.60$, $F(1,29) = 53.58$], and significant effects at the 0.0005 level for second fixation durations except for the case of 4-letter words [$F(1,29) = 2.12$, $F(1,29) = 18.73$, $F(1,29) = 10.87$, $F(1,29) = 29.87$, $F(1,29) = 34.58$]. For the Adult—Set 1 data, there were significant quadratic trends at the 0.0005 level for all word lengths in first fixation durations [$F(1,68) = 31.24$, $F(1,68) = 58.73$, $F(1,68) = 79.74$, $F(1,68) = 113.13$, $F(1,68) = 237.77$], and for 5-, 7-, and 8-letter words in second fixation durations [$F(1,68) = 0.54$, $F(1,68) = 9.74$, $P < 0.005$, $F(1,68) = 1.00$, $F(1,68) = 47.48$, $P < 0.0005$, $F(1,68) = 34.29$, $P < 0.0005$]. The Adult—Set 2 data show the same pattern but are statistically significant only for the second fixation duration on 6-letter words [$F(5,15) = 2.96$, $P \leq 0.05$]. In general, first fixation duration curves show a larger effect of initial fixation location across word lengths than second fixation duration curves do. This point is further developed in Section 4.

In order to combine data across word lengths, fixation location in the word was converted to a relative measure that indicates relative position in the word regardless of its length (Vitu et al., 1995). This was done by using the formula $fp = (f - 0.5)/wl$, where fp is the proportional location, f is the letter position fixated, and wl (word length) is the number of letters in the word. The fp absolute value was then divided into five zones by taking $z = \text{int}(fp*5) + 1$, where int converts the value to an integer through truncation.

Fig. 4a–c present a view of the fixation duration trade-off effect, with zone data averaged across word length. A clear fixation duration trade-off effect is seen in all three data sets. Analyses of variance show, for all three sets of data, that the fixation number (first vs. second) produced a significant effect on fixation durations [$F(1,68) = 108.37$, $P < 0.0005$, $F(1,3) = 13.87$, $P < 0.05$, $F(1,29) = 36.37$, $P < 0.0005$] and that it interacted significantly with the zone initially fixated [$F(4,272) = 12$, $P < 0.0005$, $F(4,12) = 3.92$, $P < 0.05$, $F(1,3) = 33.97$, $P < 0.0005$, respectively, in Adult—Set 1, Adult—Set 2 and children's data]. Quadratic analyses conducted on

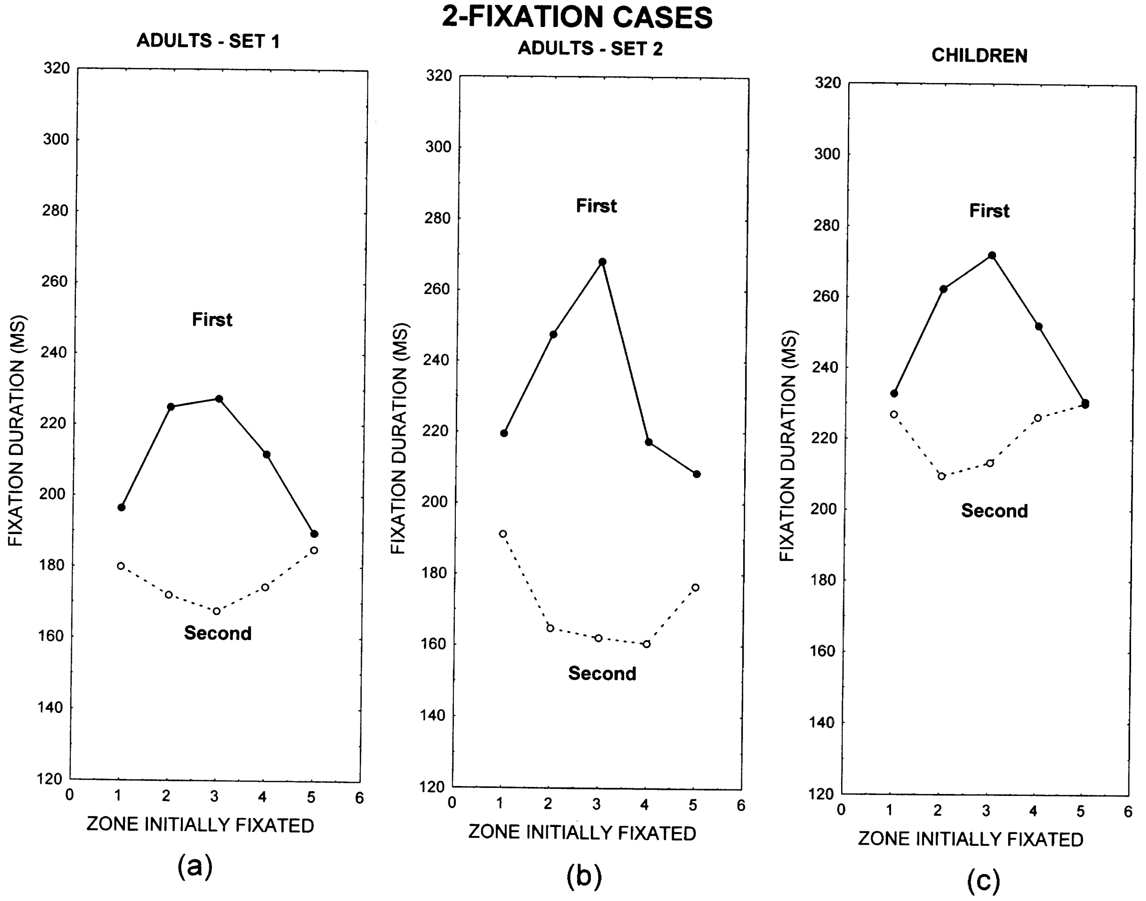

Fig. 4. Mean duration of first and second fixations in two-fixation cases, for Adult—Set 1 and Adult—Set 2 data (a and b) and children (c), as a function of the zone initially fixated in 4- to 8-letter words. Words of all lengths were divided into five zones, and data for each zone were averaged across word lengths and subjects.

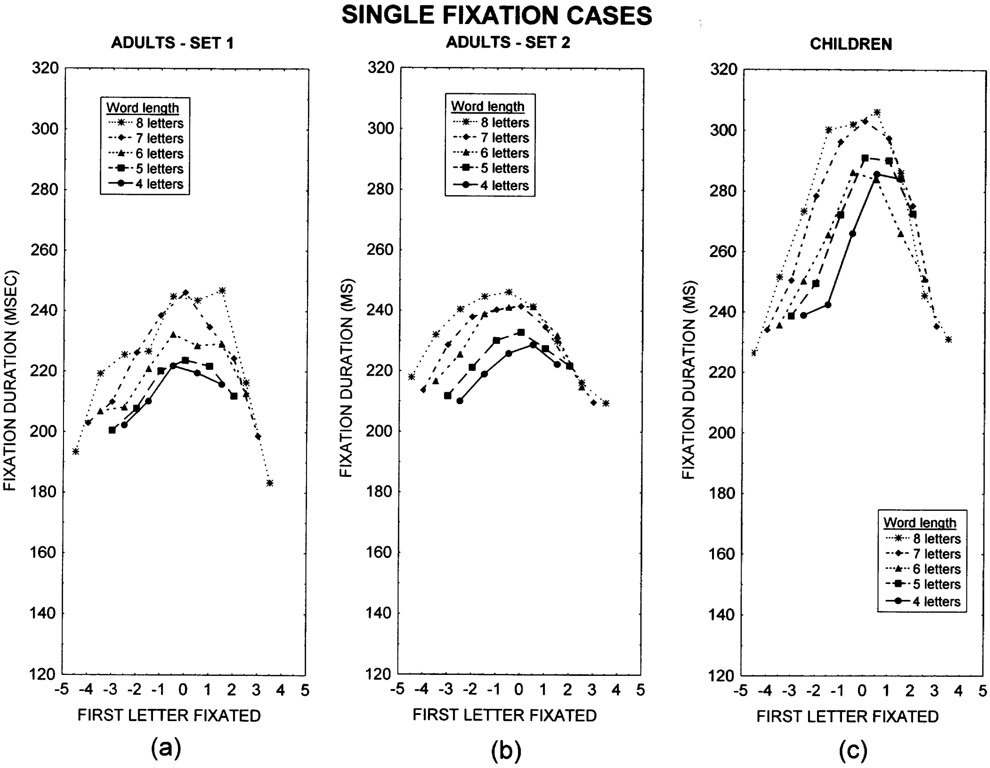

Fig. 5. Mean duration of single fixations in Adult—Set 1 and Adult—Set 2 data (a and b) and children (c), as a function of the initial eye fixation position in the word, for 4- to 8-letter words.

first and second fixation durations separately reveal that the zone initially fixated produced a significant effect on second fixation durations for all sets of data [$F(1,68) = 6.24$, $P < 0.05$, $F(1,3) = 16.17$, $P < 0.05$, $F(1,29) = 21.44$, $P < 0.0005$] and a significant effect on first fixation durations for the Adult—Set 1 and children's data [$F(1,68) = 51.01$, $P < 0.0005$, $F(1,29) = 69.97$, $P < 0.0005$]. The effect for the Adult—Set 2 data was only marginally significant [$F(1,3) = 7.31$, $P < 0.10$].

Thus, the fixation-duration trade-off effect, previously observed in the identification of isolated words (O'Regan & Lévy-Schoen, 1987), is clearly present in continuous reading for both adults and children. We will call these two functions F12 (first fixation of two) and F22 (second fixation of two). The fact that the two functions are opposite in shape can result in an overall lack of effect of initial fixation location on gaze durations (see Vitu et al., 1990).

3.3.2. *Single-fixation cases*

We have shown that the initial eye fixation location in a word has consistent effects on the duration of both the first and the second fixation in cases where the word receives two consecutive fixations. The next question concerns whether the position of a single fixation on a word also influences the duration of that fixation. Fig. 5a–c present mean single-fixation durations for words of lengths 4–8 letters as a function of their locations for each of the three data sets. All three groups of subjects show fixation durations that are longer when the eyes are near the center of the word than when they are toward the end, similar to the F12 curve. We will call this relationship F11.

Quadratic analyses found the effect of fixation position to be significant at the 0.0005 level for all word lengths in the Adult—Set 1 data [$F(1,68) = 11.54$, $F(1,68) = 16.85$, $F(1,68) = 17.32$, $F(1,68) = 64.01$, $F(1,68) = 120.22$] and for all word lengths except 4-letter words, in the children's data [$F(1,29) = 1.74$, $F(1,29) = 44.56$, $F(1,29) = 80.13$, $F(1,29) = 37.81$, $F(1,29) = 128.60$]. In the Adult—Set 2 data, the effect was significant at the 0.05 level for 6- to 8-letter words [$F(1,3) = 17.24$, $F(1,3) = 16.78$, $F(1,3) = 26.89$] and marginally significant ($P < 0.10$) for shorter words [$F(1,3) = 6.25$, $F(1,3) = 7.82$].

The same analysis was carried out with fixation location grouped by zones in word (see above), and with no distinction of word length. As can be seen in Fig. 6, the curve for children differs somewhat from those for adults, but the maximum point is still located toward the center of the word. While the F11 curves are similar in shape to the F12 curves, the slopes appear to be less steep. This difference might be attributed to the fact that single fixations are more likely to occur on shorter words that have more shallow curves.

Quadratic analyses show a significant effect for the Adult—Set 1 and children's data [$F(1,68) = 135.42$, $P < 0.0005$, $F(1,29) = 109.35$, $P < 0.0005$] and a marginally significant effect for the Adult—Set 2 data [$F(1,3) = 7.52$, $P < 0.10$].

Thus, there is a consistent relationship between fixation location and fixation duration in both single- and two-fixation cases, with initial fixations being longest for initial fixations in the central region of the word. We will refer to this as the Fixation Duration Inverted-OVP effect. Indeed, the curve is inverted, as compared to the Gaze Duration OVP effect, where gaze duration is shortest when the initial fixation is at the center of the word.

3.3.3. Second-fixation cases

In the above analyses, the general shape of the relationship between eye position and fixation duration was similar for single fixations on a word (F11) and for the first of two fixations (F12). This raises the question of whether the same relationship might hold between the location and mean duration of the second fixation, as well: that is, are second fixations on a word longer when their location is at the center of the word? This relation will be referred to as F22′, to distinguish it from F22, the mean duration of the second of two fixations as a function of the location of the first fixation on the word. Fig. 7 presents the F22′ relationship separately for the three sets of data. In this analysis, all word lengths have been grouped together, and fixation locations have been grouped in 5 word zones as described above. As Fig. 7 indicates, F22′ shows the same general relationship as F11 and F12 curves show, with fixations at the center of the word being longer than those toward the ends, with only one data point deviating from this pattern (Adult—Set 2, rightmost point). The quadratic trend appears weaker than those in F11 and F12 data, though they are still significant for Adult—Set 1 and children's data [$F(1,68) = 30.92$, $F(1,29) = 23.56$] but not for the Adult—Set 2 data.

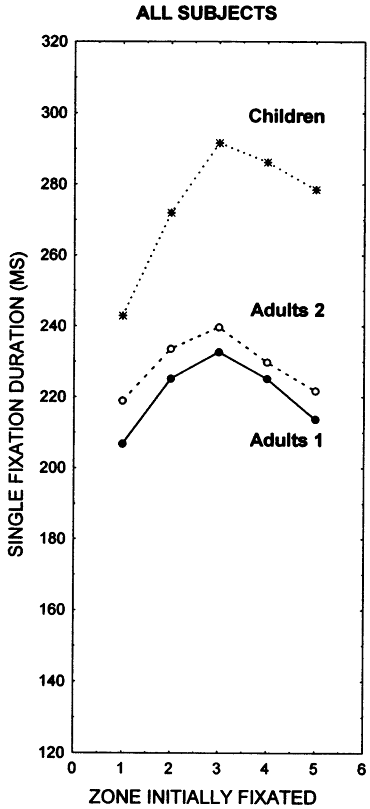

Fig. 6. Mean duration of single fixations, in Adult—Set 1 and Adult—Set 2 data, and in children, as a function of the zone initially fixated in 4- to 8-letter words.

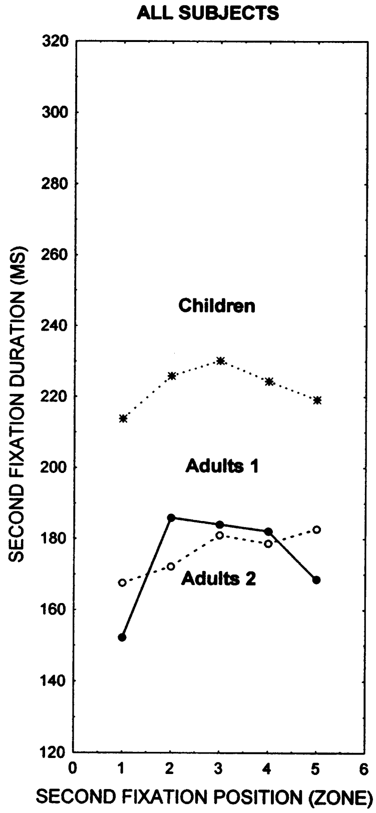

Fig. 7. Mean duration of second fixations in two-fixation cases, in Adult—Set 1 and Adult—Set 2 data, and in children, as a function of the zone fixated with the second fixation in 4- to 8-letter words.

3.4. Explanations of the fixation-duration inverted-OVP effect

The above analyses show that the initial eye position on a word affects the subsequent within-word eye behavior for both adults and children during the reading of continuous text. First, as was previously reported (McConkie et al., 1989; Rayner et al., 1996; Vitu et al., 1990), there exists a refixation OVP effect such that the likelihood of refixating a word is smaller when the eyes initially fixate near the middle of words. Second, as suggested by previous studies (O'Regan & Lévy-Schoen, 1987), there exists a fixation duration trade-off effect for cases where two fixations occur on a word: the duration of the first fixation is longer, and the duration of the second fixation is shorter when the initial fixation lies towards the center of the word. Third, the durations of fixations are longer when the eyes are located near the word's center. This latter effect not only applies to the first of two fixations (F12) as previously observed in isolated word recognition (O'Regan & Lévy-Schoen, 1987), or to all initial fixations including single fixations as previously found in isolated object identification (Henderson, 1993), but it also applies to single fixations on words (F11), and to the second of two fixations (F22′). We have called this the Fixation Duration Inverted-OVP effect. This is an unexpected finding that is not readily explained by either the Strategy-Tactics theory (O'Regan, 1990, 1992; O'Regan & Lévy-Schoen, 1987), in which it is assumed that eye-movement decisions are primarily determined on the basis of strategies developed through past experience together with low-level visual information, or by Cognitive Control theories (Henderson & Ferreira, 1990; Pollatsek & Rayner, 1990; Rayner et al., 1998; Reichle et al., 1998), which assume that eye-movement decisions are made on the basis of current language processing events. Furthermore, these are relatively large effects, producing differences in the durations of fixations of 20 ms to 60 ms or more.

3.4.1. Strategy–Tactics theory

O'Regan and Lévy-Schoen (1987) previously reported a Refixation OVP effect, and a fixation duration trade-off effect when two fixations were made on isolated words, with the durations of initial fixations showing an Inverted-OVP effect, but the second fixations showing the opposite, as seen in Fig. 3a–c. These authors (see also O'Regan, 1990, 1992) attributed this phenomenon to an oculomotor strategy that determines the within-word eye behavior during reading. As soon as the eyes land on a word, the system detects when the eyes are in a non-optimal location and, in these cases, initiates a second fixation on the word. Such a decision is made more quickly, and the resulting saccade initiated more quickly, when the eyes lie further from the center of the word, resulting in shorter initial eye fixations in those cases. Additionally, O'Regan and Lévy-Schoen (1987) assumed that a constant amount of time is required for processing a word, regardless of the eyes' position on it, and therefore, the duration of the second fixation will reflect that duration of the first: if the first is longer, the second can be shorter, and vice versa, resulting in shorter fixations following initial fixations at the center of the word than following fixations at either end. This constant time assumption predicts that the durations of single fixations should remain unaffected by the eyes' location in the word.

The results of the current study give a rather different perspective on word-related eye movement control. It appears that there is a general tendency for fixations at the center of a word to be longer than fixations at either end, and this holds for initial fixations, second fixations and single fixations on the word. Thus, the apparent trade-off that O'Regan and Lévy-Schoen observed probably results from a simple statistical fact that initial fixations near the center of a word (which tend to be longer) are more likely to be followed by a fixation toward one end (which tend to be shorter), and vice versa. The fact that the Inverted-OVP effect is found with single fixations on words (F11) and also with second fixations (F22) contradicts the constant-time assumption that underlies the trade-off interpretation of O'Regan and Lévy-Schoen (1987).

Alternative visuo-motor explanations of the inverted-OVP effect for fixation durations are possible, providing reasons for why it may take longer to initiate saccades from the centers of words. First, the sizes of saccades leaving the center of a word may be smaller on average than the size of saccades leaving one of the word's ends. Since short saccades tend to take longer to program than longer saccades (Hallett & Kalesnikas, 1993; Kowler & Anton, 1987; Wyman & Steinman, 1973), fixations located near the words' middle would be longer. Second, it is possible that it takes longer to disengage a fixation when the eyes are in the center of a word than when they are nearer one end. Third, programming a saccade may require estimating the eyes' position in the current word, which may be faster when the eyes are nearer one end of the word.

Only the first of these alternatives can be tested with the current data. For both adults and children, saccades following the first fixation of two were indeed shorter when coming from the center of a word, as predicted. However, for saccades following single fixations, the results were exactly opposite: saccades from the centers of words were longer than saccades from either end. Thus, an explanation based on saccade length does not account for the Fixation Duration inverted-OVP effect.

3.4.2. Cognitive Control theories

The basic assumption of Cognitive Control theories is that the within-word eye movement pattern is a direct response to the needs of ongoing processing. Upon encountering a word that is difficult to process at either a perceptual or lexical level, a longer fixation or within-word refixation is likely, either because more time is required for processing or because added visual information is needed from a different part of the word (i.e. no-parafoveal preview vs. preview conditions, low- vs. high-frequency words, and less- vs. more-predictable words; Balota, Pollatsek, & Rayner, 1985; Ehrlich & Rayner, 1981; Inhoff & Rayner, 1986; Rayner & Duffy, 1986; Rayner & Fischer, 1996; Rayner et al., 1996; Vitu, 1991). Since words have been shown to be more efficiently processed when the eyes are near their centers than near one of their ends (Brysbaert et al., 1996; O'Regan, 1990; O'Regan & Jacobs, 1992; O'Regan et al., 1984), the refixation probability should therefore be lowest, and fixation durations shortest, with the eyes near that location. Our data confirm only the first of these two predictions, showing a Refixation-OVP effect. However, fixation durations are consistently longest in F11, F12 and F22 data, when the eyes are located at the centers of words, rather than being shortest as predicted. Thus, longer fixations are found under conditions where the processing efficiency is believed to be greatest. Also, while other variables that reduce word-processing time tend as shown in previous studies, to reduce both fixation duration and refixation likelihood, which is the normal pattern, fixating at the centers of words during reading reduces refixations but increases fixation duration.

In a-posteriori analyses of eye behavior in continuous reading, such as those conducted above, many variables are uncontrolled, and the possibility exists that the observed phenomena are the result of correlated effects, particularly factors that would lead to more difficult (i.e. lower frequency) words being more likely to be fixated at the center rather than at the beginning or end, with fixation duration varying with word frequency. As words are less likely to be identified when the eyes are far from their center, words receiving only one fixation located at their beginning or end are probably easier on average and, therefore, require less processing time, than words fixated only once at their center. Similarly, words that require more than one fixation to be identified when the initial fixation is near the words' center are probably more difficult than words fixated twice with the initial fixation located at their beginning or end. Thus the Fixation Duration Inverted-OVP curve could be due to such selectional factors, rather than directly reflecting fixation location differences. Consider three possible predictions from such an explanation. First, there should be a U-shape function between the positions of initial fixations and word difficulty (i.e. word frequency) for both single- and two-fixation cases; that is, the average frequency of words receiving a single fixation (or the first of two fixations) at the center should be lower than the average frequency of words having a single fixation (or first of two fixations) at the beginning or ending of the word. Second, if we assume that the Fixation Duration Inverted-OVP curves result from such word frequency differences for words initially fixated at different locations, then partitioning the data by word frequency should reduce, or possibly even eliminate, the inverted-OVP effect for first and single-fixation durations. Third, if initial fixation location effects are confounded with effects of word-processing difficulty, then both effects should emerge at the same time in the time course of fixations. Each of these predictions was tested.

The first prediction was tested by calculating the median word frequency for words fixated at different locations for single-fixation cases, and for the first of two fixations, separately for both sets of adult data and for children. The frequency counts were taken from the Brown Corpus (Kucera & Francis, 1970) in both sets of adult data, and the American Heritage corpus, which is best adapted to children (Carroll, Davies, & Richman, 1971), for children's data. The median frequency for words initially fixated at their center letter (or average of the medians for the two center letters) was identified for each word length in each data set, as well as the median frequencies for words initially fixated at their extreme (beginning or ending) letters, and again for words initially fixated at their next-to-extreme letters. A sign test was then performed by counting, in single-fixation data and across data sets, the number of cases in which words fixated at the beginning and at the end showed a median word frequency that was greater than the words that were fixated at their center. A second sign test was performed using words fixated at the next-to-extreme letters in comparison to words fixated at their centers. Both of these were highly significant (critical ratios of 8.39 and 6.47, $P < 0.001$), indicating a tendency for words receiving a single fixation on extreme letters to have higher frequencies than words receiving a single fixation at the center. This difference was present in all three sets of data. Thus, it appears that there is a selectional factor contributing to the Fixation Duration Inverted-OVP curve for single fixation cases: landing on an extreme location on a lower-frequency word is likely to lead to a second fixation on it, thus taking it out of the pool of single-fixation cases.

Similar sign tests were performed on the first fixation data for cases with exactly two fixations on the word. Here, there were no median word frequency differences between words initially fixated at the center or the extreme or next-to-extreme locations (critical ratios less than 1.0). Thus, this selectional hypothesis cannot account for the Fixation Duration Inverted-OVP curve in two-fixation cases.

The second prediction was that if the data were partitioned on the basis of the frequencies of words, then the Fixation Duration Inverted-OVP Curves for first fixation durations in both one- and two-fixation cases should be flattened. To test this prediction, words were grouped into two classes, referred to as low-frequency (the bottom 40%) and high-frequency (top 40%) words of each word length. Table 1 indicates the resulting cut-off frequencies for adults. Since children read text with a more restricted frequency range, the same criteria could be used for all word lengths: low frequency was less than 118 per million, and higher frequency, more than 196 per million. Median frequencies (expressed in occurrences per million) for 4-, 5-, 6-, and 7-letter words were, respectively, 70, 31, 15, and 13, for low-frequency words,

Table 1
Criteria used to distinguish between high- and low-frequency 4- to 7-letter words, and median word frequency for both categories (in occurrences per million), in the first and second set of adult data

	Low-frequency words		High-frequency words	
	Criterion	Median	Criterion	Median
First set of data				
4-letter words	Less than 140	45	More than 430	1789
5-letter words	Less than 72	23	More than 169	272
6-letter words	Less than 32	6	More than 60	163
7-letter words	Less than 18	5	More than 40	108
Second set of data				
4-letter words	Less than 600	183	More than 1350	3567
5-letter words	Less than 160	65	More than 270	392
6-letter words	Less than 50	14	More than 110	251
7-letter words	Less than 50	12	More than 110	282

and 1420, 673, 421, and 558 for high frequency. Thus, splitting the data in this fashion greatly restricted the word frequency range in each resulting subset of the data.

Fig. 8a–c present mean single-fixation durations for high- and low-frequency 6-letter words in all three sets of data as a function of fixation location. Other word lengths show similar patterns. The curves for all words are presented in Fig. 9a–c, for comparison sake. While the inverted-OVP effect is weaker for high- than for low-frequency words, splitting the data does not flatten the curves, as would be the case if the curves were the result of selection based on word frequency.

In the Adult—Set 1 data, the quadratic analyses found a significant effect of fixation location for each of the word length and frequency combinations, except for 4-letter words of high frequency [$F(1,68) = 5.34$, $P < 0.05$, $F(1,68) = 14.51$, $P < 0.0005$, $F(1,68) = 15.64$, $P < 0.0005$, $F(1,68) = 93.93$, $P < 0.0005$, for low-frequency words, and $F(1,68) = 1.43$, $F(1,68) = 6.12$, $P < 0.05$, $F(1,68) = 5.14$, $P < 0.05$, $F(1,68) = 31.59$, $P < 0.0005$, for high-frequency words]. In the Adult—Set 2 data, the effect was significant at the 0.05 level for low-frequency 4- to 7-letter words [$F(1,3) = 14.61$, $F(1,3) = 18.94$, $F(1,3) = 19.67$, $F(1,3) = 15.25$], and for high-frequency 6- and 7-letter words, [$F(1,3) = 12.13$, $F(1,3) = 15.86$]. In the children's data, the effect was also significant at the 0.0005 level for all word lengths and frequencies, except for 4-letter words [$F(1,29) = 3.42$, $F(1,29) = 30.35$, $F(1,29) = 73.74$, $F(1,29) = 54.47$, for low-frequency words, and $F(1,29) = 0.17$, $F(1,29) = 25.70$, $F(1,29) = 24.26$, $F(1,29) = 23.92$, for high-frequency words].

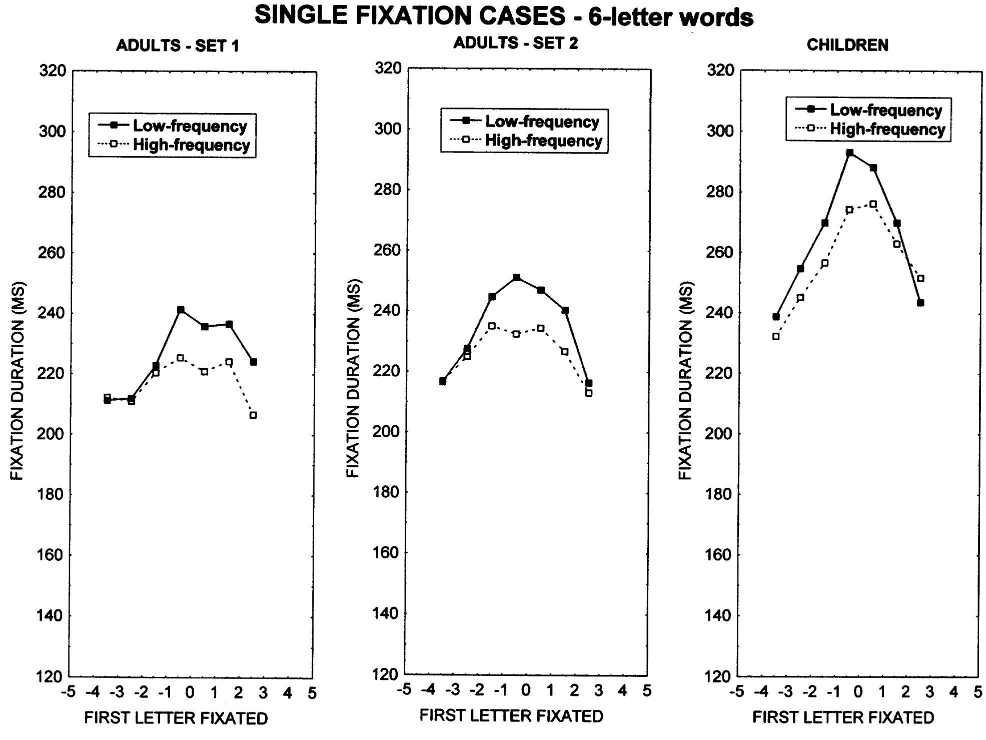

Fig. 8. Mean duration of single fixations in Adult—Set 1 and Adult—Set 2 data (a and b), and children (c) as a function of the initial eye fixation position in the word, and for high vs. low-frequency words of 6 letters.

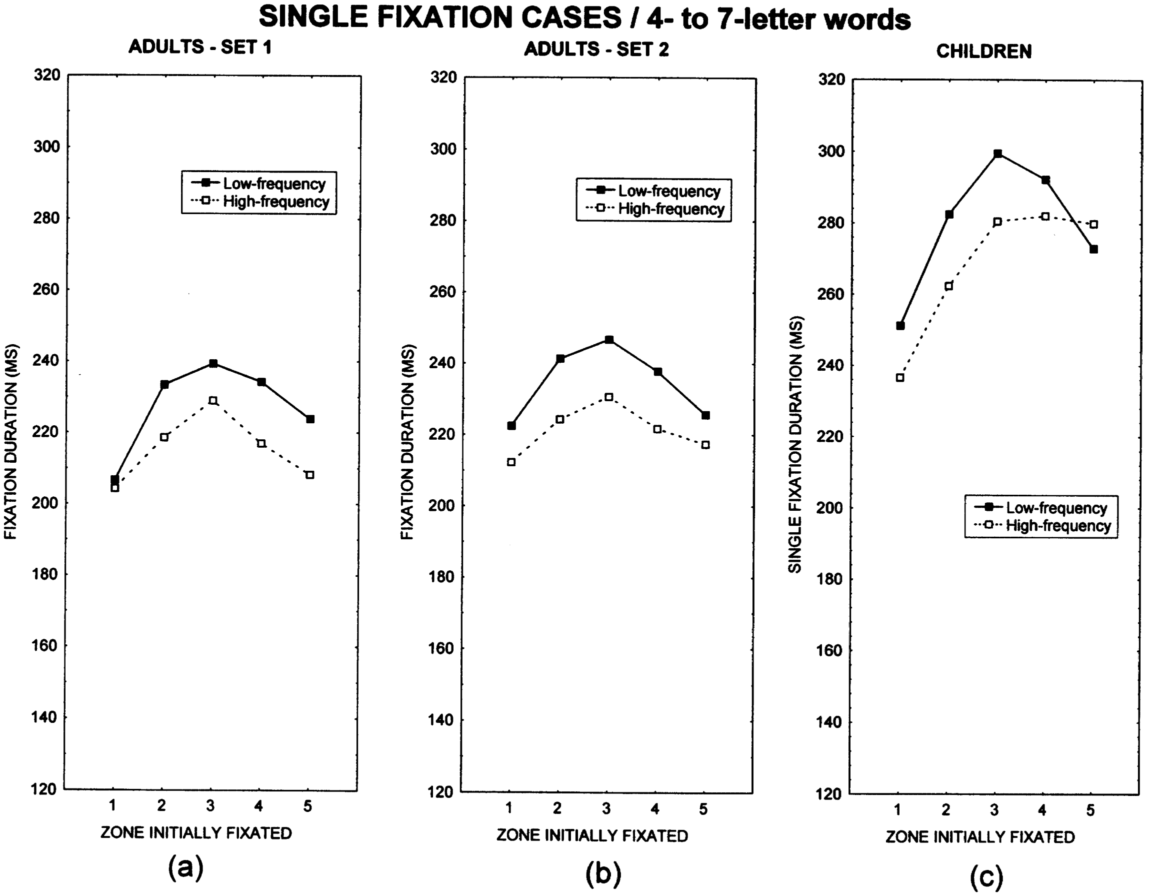

Fig. 9. Mean duration of single fixations in Adult—Set 1 and Adult—Set 2 data (a and b), and children (c) as a function of the initial eye fixation position in the word (expressed in word zones), and for high vs. low-frequency words. Data from words of length 4–7 letters were averaged.

In each of the data sets, the effect of word frequency was significant for all word lengths [$F(1,68) = 35.26$, $P < 0.0005$, $F(1,68) = 4.42$, $P < 0.05$, $F(1,68) = 9.55$, $P < 0.005$, $F(1,68) = 8.05$, $P < 0.01$, in the Adult—Set 1 data, $F(1,3) = 50.61$, $P < 0.005$, $F(1,3) = 74.04$, $P < 0.005$, $F(1,3) = 39.75$, $P < 0.01$, $F(1,3) = 62.62$, $P < 0.005$, in the Adult—Set 2 data, and $F(1,29) = 28.64$, $P < 0.0005$, $F(1,29) = 24.80$, $P < 0.0005$, $F(1,29) = 8.68$, $P < 0.01$, $F(1,29) = 4.53$, $P < 0.05$, in children's data]. The interaction between fixation location and word frequency was significant only for 5- and 7-letter words in the Adult—Set 1 data [$F(5,340) = 3.07$, $P < 0.01$, $F(7,476) = 3.97$, $P < 0.0005$], and 4- and 7-letter words in children's data [$F(4,116) = 3.07$, $P < 0.05$, $F(7,203) = 4.01$, $P < 0.0005$].

The same analysis was performed on the durations of first fixations in two-fixation cases, but only for children, since the number of two-fixation cases in both sets of adult data was too small for this analysis. The results are very similar to those obtained in single-fixation cases. The quadratic trends were significant for all word lengths, in high-frequency words [$F(1,29) = 7.15$, $P < 0.05$, $F(1,29) = 9.03$, $P < 0.005$, $F(1,29) = 23.71$, $P < 0.0005$, $F(1,29) = 43.65$, $P < 0.0005$], and low-frequency words [$F(1,29) = 22.14$, $P < 0.0005$, $F(1,29) = 36.42$, $P < 0.0005$, $F(1,29) = 56.39$, $P < 0.0005$, $F(1,29) = 85.64$, $P < 0.0005$]. In addition, the effect of word frequency was significant at the 0.05 level for all word lengths, except 6-letter words [$F(1,29) = 6.04$, $F(1,29) = 5.40$, $F(1,29) = 0.00$, $F(1,29) = 4.32$]; the interaction was significant only for 4-letter words [$F(4,116) = 3.64$, $P < 0.01$, other F's ≤ 0.85].

Thus, there is no evidence that restricting the word frequency range reduces or eliminates the Fixation Duration Inverted-OVP effect.

A final prediction made by the hypothesis that word frequency and initial fixation location might be confounded variables is that the effects of both variables should emerge together (or at the same time) in the time course of a fixation. To test this prediction, the frequency distributions of the durations of single fixations were plotted for the three sets of data as a function of initial fixation location and word frequency. These distributions were prepared by combining data from 4- to 7-letter words using only initial fixations on letter positions 0–4, inclusive. Fig. 10a–f indicate that fixation location effects emerge much earlier (at about 100–125 ms) than word frequency effects do (about

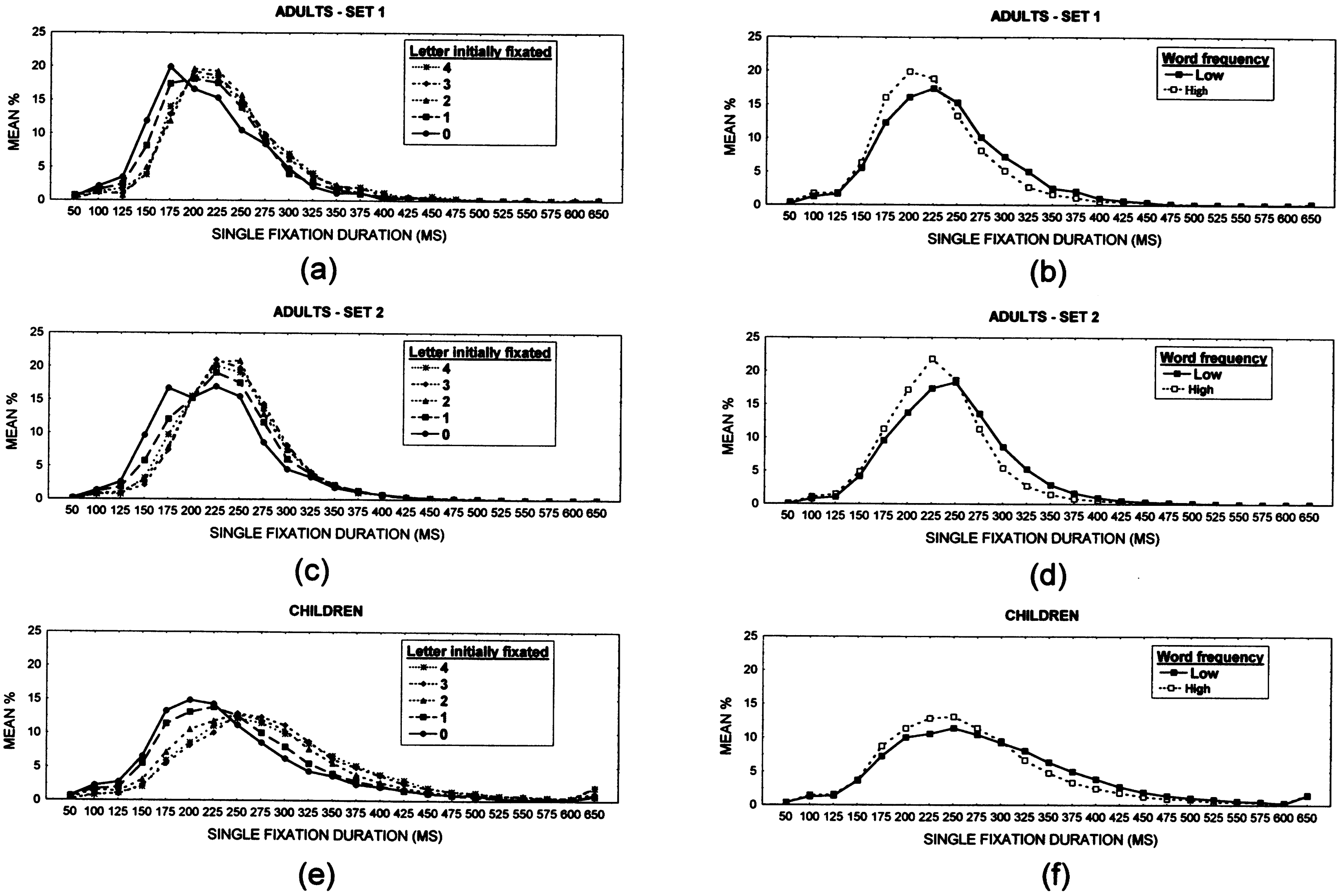

Fig. 10. Distribution of single fixation durations in Adult—Set 1 and Adult—Set 2 data (a–d), and children (c), for different initial fixation locations (0–4) across words of length 4–7 letters (a, c, and e), and for high- against low-frequency words (b, d, and f).

150–175 ms), indicating that the fixation location effect is not due to a confounding with word frequency effects.

In summary, the hypothesis that the Fixation Duration Inverted-OVP effect is due to tendencies for words of different frequencies, producing different mean fixation durations, to be fixated at systematically different locations is not supported. It will be necessary for cognitive control theories to account for this phenomenon on some other basis.

3.4.3. *A peripheral preview explanation*

A third possible explanation that is compatible with either oculomotor strategy or cognitive theories is based on the common assumption that fixation durations reflect the amount of processing that is required, and that information acquired from words during the fixations prior to fixating them, referred to as peripheral preview, reduces the processing requirement. Furthermore, the amount of information obtained from a peripheral word during a fixation is assumed to vary with its retinal eccentricity: the further it lies into the periphery, the less visual information is obtained from it (Brysbaert et al., 1996; Reichle et al., 1998). Thus, we would expect that the fixation duration would be longer when the previous fixation had been a greater distance from the currently fixated word, thus yielding less prior information from it, than if the previous fixation had been closer to the word. If this phenomenon exists, then the Fixation Duration Inverted-OVP effect could result from differences in the launch-site distances for fixations at different locations in the word; in particular, the inverted-OVP effect could be the result of longer distances preceding fixations at the center of the word than fixations toward the ends of the words.

Testing this hypothesis requires two steps: first, determining whether the predicted relation between launch site distance and fixation duration exists, and, if so, then determining whether fixations at different locations on a word tend to be preceded by different launch site distances. A final step is to determine whether the Fixation Duration Inverted-OVP effect is reduced or eliminated when launch site of the prior saccade is controlled.

For each single fixation on words of length 4–7, separately, the launch site distance, or distance of the prior fixation from the beginning of the word, was calculated. These distances were then divided into close (less than 8 letter positions away for Adults—Set 2; 6 letter positions for Adults—Set 1, and children) and far (8 or greater for Adults—Set 2, 6 or greater for Adults—Set 1, and children) launch sites. This corresponded roughly to having or not having at least part of the fixated word within the perceptual span for letter distinctions during the previous fixation (McConkie & Rayner, 1975; McConkie & Underwood, 1985). Mean fixation duration curves over letter positions in 6-letter words, for near and far launch sites separately, are presented in Fig. 11a–c. Other word lengths showed the same pattern. In all three data sets, single-fixation durations were shorter when the previous fixation had been close rather than far from the currently fixated word, as predicted [Adult—Set 1 data, $F(1,68) = 42.88$, $P < 0.0005$, $F(1,68) = 18.11$, $P < 0.0005$, $F(1,68) = 11.50$, $P < 0.005$, $F(1,68) = 17.61$, $P < 0.0005$ for 4- to 7-letter words; in the Adult—Set 2 data, $F(1,3) = 10.55$, $P < 0.05$, $F(1,3) = 24.69$, $P < 0.05$, $F(1,3) = 74.83$, $P < 0.005$, $F(1,3) = 9.51$, $P < 0.05$, and in children, $F(1,29) = 52.41$, $P < 0.0005$, $F(1,29) = 12.39$, $P < 0.005$, $F(1,29) = 66.66$, $P < 0.0005$, $F(1,29) = 14.99$, $P < 0.001$]. All curves show an inverted-OVP effect following both close and far launch sites. For most word lengths, in all three data sets, quadratic analyses showed significant effects at the 0.05 level or better for both close and far data, with no significant distance by fixation location interaction (F's < 1.0).

Only the children's data set had enough refixations to allow a similar analysis to be conducted for the first fixation in two-fixation cases. Results are presented in Fig. 12a–d, which again show longer fixations following more distant launch sites. However, unlike single fixations, there is a shift in the curves: fixations at the beginnings of the word tend to have longer fixations following far launch sites, and fixations at the ends of the words tend to have longer fixations following close launch sites. Quadratic analyses indicated significant effects for initial fixation location for all word length by launch site distance combinations [close launch sites, $F(1,29) = 12.51$, $P < 0.001$, $F(1,29) = 17.35$, $P < 0.0005$, $F(1,29) = 87.02$, $P < 0.0005$, $F(1,29) = 92.60$, $P < 0.0005$, and far launch sites, $F(1,29) = 4.72$, $P < 0.05$, $F(1,29) = 8.86$, $P < 0.01$, $F(1,29) = 22.61$, $P < 0.0005$, $F(1,29) = 31.79$, $P < 0.0005$]. The effect of launch site was significant only for 5- and 6-letter words [$F(1,29) = 1.18$, $F(1,29) = 5.27$, $P < 0.05$, $F(1,29) = 5.30$, $P < 0.05$, $F(1,29) = 0.23$], but the interaction between initial fixation location and launch site was significant for all word lengths [$F(4,116) = 10.39$, $P < 0.0005$, $F(5,145) = 4.36$, $P < 0.001$, $F(6,174) = 5.02$, $P < 0.0005$, $F(7,203) = 5.73$, $P < 0.0005$].

This result was replicated with adult data, using the larger data set, Adult—Set 2, and combining across words of length 4–7 by grouping data into five zones, as described above. The results (not shown here) again showed the inverted-OVP pattern with the curve shifted to the right for the close-distance data, compared to the far-distance data.

Finally, an analysis was conducted to see whether this same phenomenon appears in data for the second fixation on a word; that is, does fixation duration increase with distance between the first and second fixation? To test this, cases in which 4- to 7-letter words received two fixations were identified in the children's data set. Fixation locations were grouped into one of five zones, and the data were collapsed across word length. The cases were then classified by the locations of the first and second fixations, and mean fixation durations for each of the resulting 25 cells were computed. Fig. 13 presents these data, showing separate mean fixation duration curves for refixation location, plotted according to the location of the initial fixation. Four of the five smallest mean fixation durations result from data in which the same zone was refixated. There is a tendency for the means to increase with distance of the refixated zone from the zone of the initial fixation. This was quantified by grouping data points in Fig. 13 according to the distance between the initial fixation and refixation (refixation in the same zone = 0; refixation in an adjacent zone = 1, etc.), and computing the mean fixation duration for each refixation distance. The results for each distance are: 0 = 197; 1 = 213; 2 = 217; 3 = 228; 4 = 226. Thus, in these data, as well, there is a tendency for the distance between the last and current fixation to affect fixation duration. Data from Adult—Set 2, while less stable due to lower *N*s, tend to show a similar pattern.

These analyses have demonstrated a consistent tendency for fixations following prior fixations at greater distances to have longer durations.

The second task was to determine whether there is a tendency for fixations at the centers of words to follow more distant fixations than fixations toward the ends of words, thus providing an explanation for the Fixation Duration Inverted-OVP effect. Fig. 14a–c show curves indicating the mean launch site of saccades preceding single fixations at different letter positions in words of different lengths for the three sets of data. It appears that fixations at the centers of words are not preceded by further launch sites than fixations towards the ends of words. Rather, there is a linear relationship between launch site and initial fixation location such that fixations located towards the end of the words are preceded by closer launch sites than fixations towards the beginning of words. These data, which replicate previous

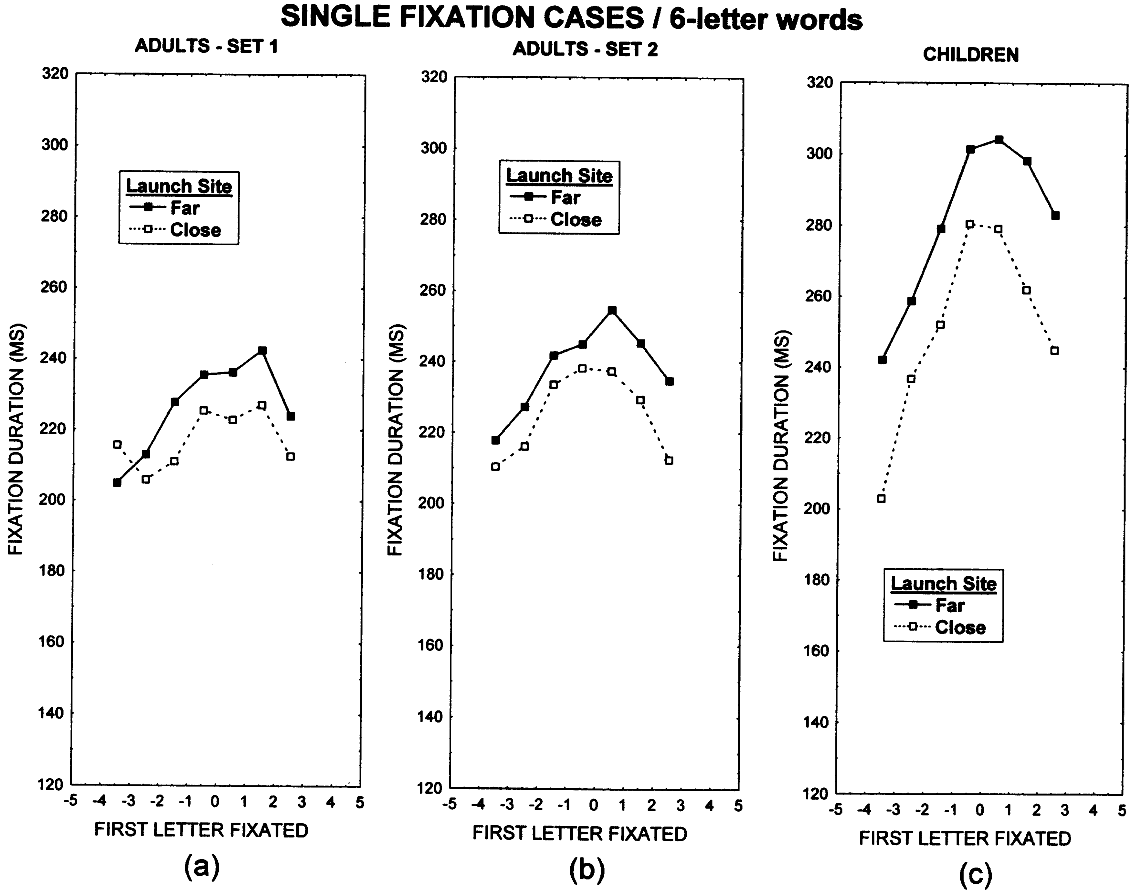

Fig. 11. Mean duration of single fixations in Adult—Set 1 and Adult—Set 2 data (a and b), and children (c) as a function of the initial eye fixation position in 6-letter words and for close vs. far launch sites. Close launch sites corresponded to cases where the fixation that preceded the initial fixation on the word was located within less than 6 (in Adults—Set 1, and in children) or 8 (in Adults—Set 2) characters away from the first letter of the word. Far launch sites corresponded to cases where the prior fixation was located that distance or further away from the first letter of the word.

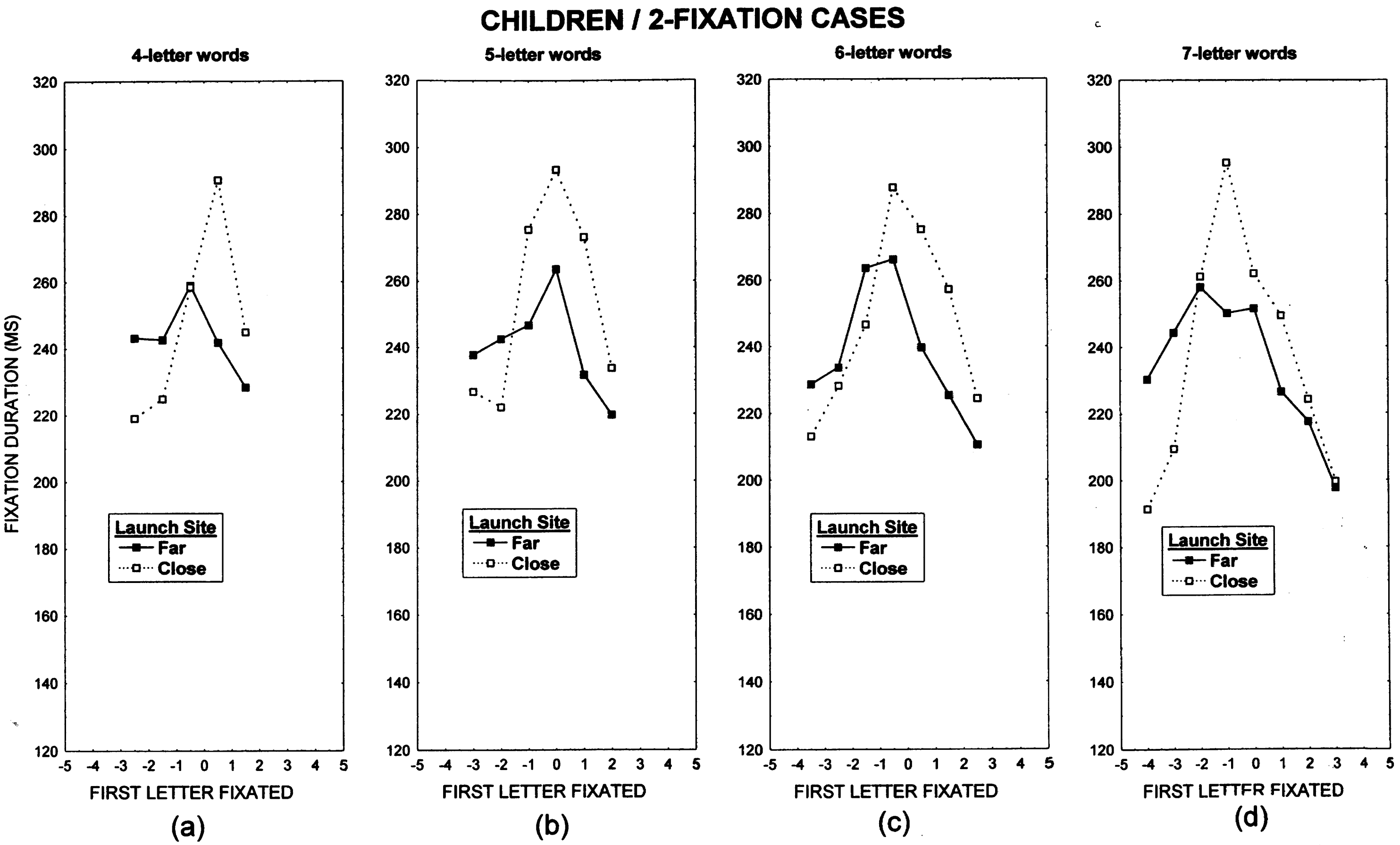

Fig. 12. Mean duration of first fixations in two-fixation cases in children, as a function of the initial eye fixation position in the word, and for close vs. far launch sites, for 4- to 7-letter words (a–d).

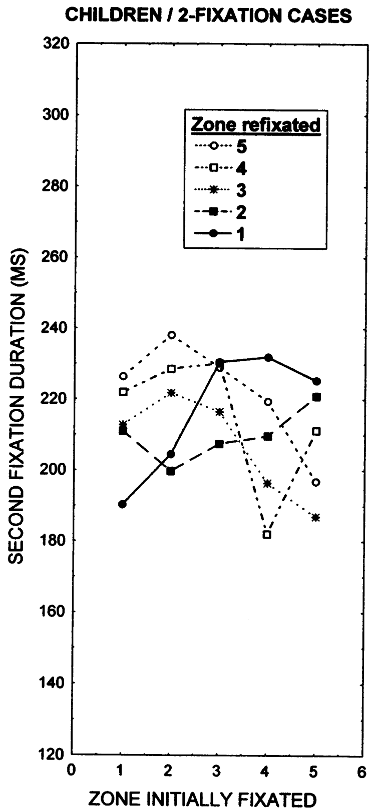

Fig. 13. Mean duration of second fixations in two-fixation cases for children, as a function of the zone initially fixated in 4- to 7-letter words, and the word zone fixated with the second fixation.

observations by McConkie et al. (1988), provide no support for the peripheral preview hypothesis.

Finally, a visual comparison of the Fixation Duration Inverted-OVP curves for close and far data, in comparison with those of the entire data sets provided no indication of a flattening when distance is restricted. This can be seen by comparing F11 data in Fig. 11a–c with corresponding data for 6-letter words in Fig. 5a–c. In the children's F12 and F22 data, launch site distance affects the location of the maximum fixation duration, but again does not cause a flattening of the curves (see Fig. 12a–d and 13). Thus, there is little evidence that the Fixation Duration Inverted-OVP effect is due to confounding of fixation location with distance from the prior fixation location, contrary to the prediction from the peripheral preview explanation.

4. Discussion

The research presented here has demonstrated that where the eyes land in a word during reading influences the duration of the fixation and has tested several explanations for this phenomenon. There is a general tendency for the mean durations of fixations in the centers of words to be longer than of fixations toward the beginnings or ends of words. This is a surprising result, since it is generally accepted (1) that words can be most easily identified when the eyes are near the center of the word (the Optimal Viewing Position effect, Brysbaert et al., 1996; O'Regan, 1990; O'Regan & Jacobs, 1992; O'Regan et al., 1984) and (2) that ease of processing produces shorter fixations (Balota et al., 1985; Ehrlich & Rayner, 1981; Inhoff & Rayner, 1986; Rayner & Duffy, 1986; Rayner & Fischer, 1996; Rayner et al., 1996; Vitu, 1991). Fixating the centers of words, which implies reduced processing requirements, should therefore reduce and not lengthen fixation durations.

This unexpected finding, which was previously noted in isolated word identification for the duration of first fixations in two-fixation cases (O'Regan & Lévy-Schoen, 1987), and in isolated object identification for all first fixation durations (Henderson, 1993), was not observed by Rayner et al. (1996) in data from normal text reading. We suspect that the reason for this difference from the present results is that there is a difference in statistical power. The data sets in the current study were much larger, providing a great deal more power in detecting such relationships. The fact that the Fixation Duration Inverted-OVP effect was found in three different data sets of different natures (combined data from a large group of adults, large data sets from just four adults, and data from fifth-grade children) indicates that this is a robust phenomenon in normal reading.

The explanation for the Fixation Duration Inverted-OVP effect has been elusive. It calls into question the constant processing time assumption that O'Regan and Lévy-Schoen (1987) (see also O'Regan, 1990) proposed in accounting for fixation-duration trade-off effects between the first and second of two fixations on a word, based on the location of the first fixation, and offers an alternative statistical explanation for the trade-off effect. Since the Inverted-OVP effect directly contradicts an obvious prediction from cognitive control models, an explanation based on possible confounding between word frequencies, landing positions and refixation likelihoods was proposed that could overshadow the expected relationship. Several tests for this explanation failed to support it. Mean fixation durations on higher-frequency words are shorter than on lower-frequency words, independent of fixation location, as observed by McConkie et al. (1989) and Rayner et al. (1996), but these word-frequency effects emerge much later than fixation-location effects in the time course of a fixation and so cannot provide an explanation for them. Finally, an explanation based on peripheral preview influences was proposed and tested, but not confirmed. Thus, we are unable to identify the basis for the Fixation Duration Inverted-OVP effect. Several further possibilities have been suggested, related to possible oculomotor control factors, but the current data set did not provide ways to test these. Another possibility would be to invoke a 'perceptual economy strategy' principle that states that the perceptuo-oculomotor system learns to produce longer fixations at locations where greater information is anticipated, based on prior experience. Two such conditions, identified in the current study, involve eye fixations at the centers of words, where greater word information is expected to be available, and eye fixations following longer saccades, increasing the amount of information that is likely to be available that was not available during the prior fixation, or reduced 'perceptual overlap'. This hypothesis, which assumes that the system would anticipate how long the eyes should stay at a given location based on past experience, is similar to an earlier proposal of Vaughan (1978). Further research is required to clarify and test such additional possibilities.

In the process of trying to identify the cause of the Inverted-OVP effect, a phenomenon was observed, again appearing consistently in all three data sets, which we refer to as the Saccade Distance effect: fixation durations are longer, on average, when they follow fixations that were further away (further from the currently fixated word, or, in the case of refixations, further from the current fixation), than when they follow fixations that were nearer (Radach & Heller, 2000; for a similar finding with gaze durations, see also Pollatsek, Rayner, & Balota, 1986). We have explained this phenomenon in terms of peripheral preview: a closer prior fixation provides more peripheral visual information about the currently fixated word than does a more distant prior fixation, and the more prior information that was obtained about the currently fixated word, the shorter the current fixation can be and still provide the necessary visual processing time. Whether this fixation duration difference is produced by real-time processing decisions, as cognitive theories assume, or by learned oculomotor strategy contingencies, as oculomotor control theories would assume, is a matter that we were unable to address and that will require further investigation.

One unsettling implication of the Saccade Distance effect is that it predicts that there should be a positive correlation between the lengths of forward saccades and the durations of the fixations that follow them, a relationship that has been found only in visual search tasks (Kapoula, 1983; Nattkemper & Prinz, 1986) but not in normal reading (Rayner & McConkie, 1976). In

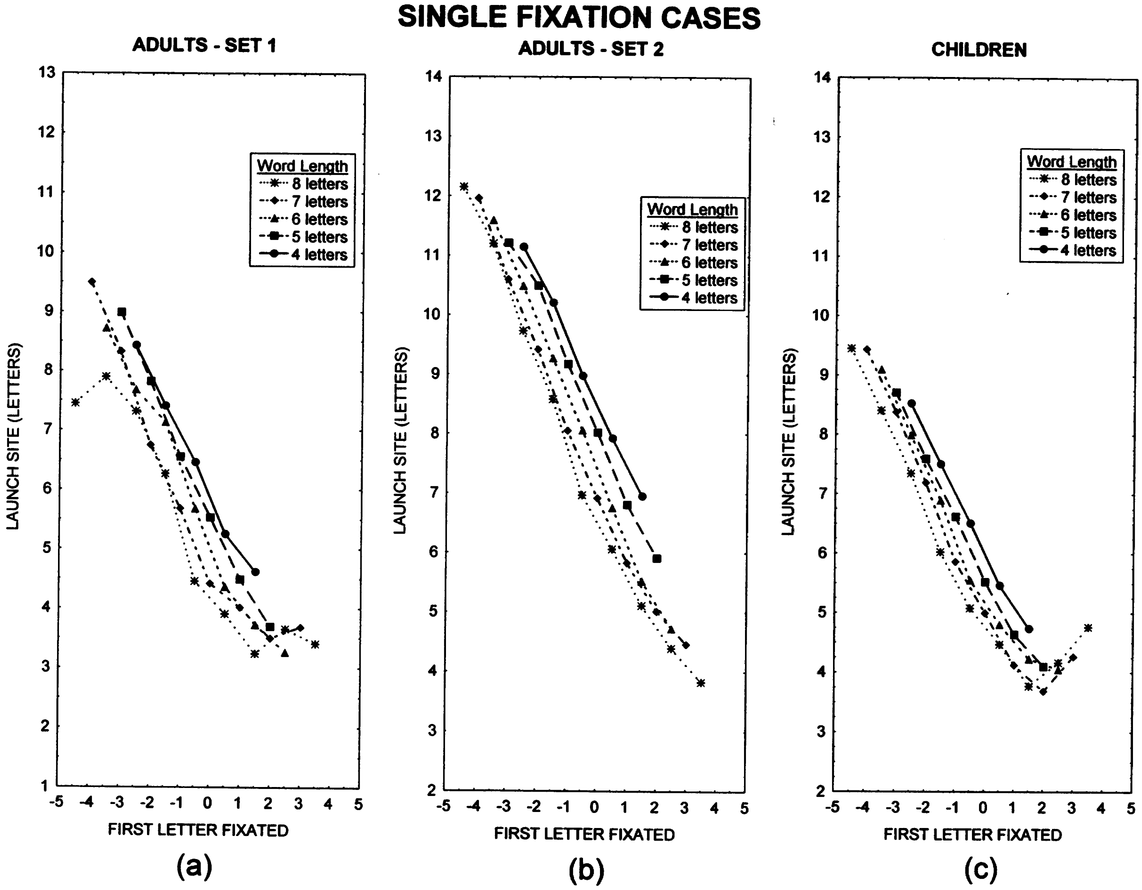

Fig. 14. Mean launch site of forward saccades prior to fixations at different locations in 4- to 8-letter words in Adult—Set 1 and Adult—Set 2 data (a and b) and children (c).

fact, in the present data sets, these correlations for fixations on words of 4–8 letters, including only saccades shorter than 20 characters, were 0.13, 0.20 and 0.07 for Adult—Set 1, Adult—Set 2 and children's data (all statistically significant with the very large *N*s involved), similar to the very low, positive correlations reported by Rayner and McConkie (1976). Since fixation duration data are extremely variable, it is not surprising that Saccade Distance accounts for only a small proportion of the total variance.

Finally, the results of the current study indicate that fixation durations on words correlate with their frequency of occurrence in the language ($r = -0.047$, -0.078 and -0.007 for Adult—Set 1, Adult—Set 2 and children's data) as previously observed (for example, see Inhoff & Rayner, 1986; Rayner & Duffy, 1986; Rayner et al., 1996) and that they are also greatly influenced by lower-level factors like where the eyes land in the word and the distance of the fixated word from the last fixation location. Further work is required in order to identify the amount of the total variance in fixation durations that is attributable to these different sources. Research is also needed to determine whether the effects of eye position in a word result from learned perceptuo-oculomotor strategies (that is, saccade latency differences based only on oculomotor and low-level vision characteristics) or from cognitive processing influences (that is, differences in the language processing of the currently perceived text that have implications for when saccades are initiated).

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