Vergence eye movements during fixations in reading

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Abstract

The purpose of this explorative study was to examine vergence eye movements during fixations in reading. Eye movements of twelve normal adults were assessed during reading of different materials, that is, words within context (prose passages) and words without context (word lists), as well as during different tasks, that is, reading while attending to the meaning and reading while attending to the sound (words had to be pronounced subvocally). Results indicated that vergence velocity was higher during the reading of prose than during the reading of word lists as well as higher during reading for meaning than during reading while subvocalizing. These findings were also true if only the initial 80 ms of each fixation were measured. Post-hoc analyses indicated that the effects of text type and reading objective were partially, but not entirely, attributable to differences in saccade sizes. Findings are taken to suggest that the increase in vergence velocity results from readers attending to larger units of the text.

PsycINFO classification: 2323; 2330; 2340; 2346

Keywords: Reading; Vergence; Eye-movement; Binocular fixation; Attention

1. Introduction

Previous research has assessed various aspects of eye movements during reading, for example, saccade size, saccadic accuracy, fixation duration, gaze duration and optimal landing position (see Rayner and Pollatsek, 1987, for a review). Typically, researchers...
have studied these parameters from a monocular perspective. Thus, while there exist some older reports regarding binocular aspects of eye movements during reading (Clark, 1935; Schmidt, 1917; Taylor, 1966), only in recent years have researchers resumed study of binocular aspects of reading (Bassou et al., 1993; Hendriks et al., 1991; Hendriks, 1992).

Binocular assessment of eye movements during reading is particularly salient for the study of disjunctive eye movements (i.e., eyes moving in different directions), behaviors that frequently occur during saccades and fixations, because the angle between the eyes changes. For example, during horizontal and vertical saccades, the eyes may not only move in the same direction (conjugately), but with respect to each other (disjunctively) as well. These disjunctive aspects of saccades not only occur when the gaze is shifted between targets positioned on different points in depth, but also when it is shifted between (nearly) equidistant targets (Bains et al., 1992; Collewijn et al., 1988a,b; Enright, 1989; Zee et al., 1992). In the first stage of a horizontal saccade, the eyes move away from or outwards with respect to each other (i.e., they diverge), while during the second part of the saccade this outward movement changes to an inward movement (i.e., the eyes converge). However, the saccade's second-stage convergence is often not sufficient to completely correct for its first-stage divergence. In essence, some divergence may remain because the movement of the abducting eye (i.e., the eye that moves away from the nose) is greater than the movement of the adducting eye (i.e., the eye that moves towards the nose). In such cases, the saccade ends with some divergence of the eyes, which means that the subsequent fixation begins with a fixation error (i.e., the fixation axes of the eyes do not cross at the target, but slightly behind it). Such fixation errors are more or less corrected by the convergence, which occurred in the latter part of the saccade, continuing into the fixation period following the saccade (Collewijn et al., 1988a; Zee et al., 1992).

The motive for the present study was as follows. Although studies using light emitting diodes (LED) have consistently found convergence during fixations, findings resulting from studies of vergence during reading have not been as consistent. Initially, and in agreement with non-reading studies using LEDs, Schmidt (1917) found that the eyes converge during fixations following a line return. When fixations followed smaller saccades, such converging adjustments were barely distinguishable on his photographic plates; however, because the eyes always seemed to diverge during saccades – as he could more easily observe – Schmidt concluded that convergence takes place during all fixations, because the divergence caused by the saccades required compensation. 1 Subsequently, Clark (1935), who was aware of Schmidt's study, stated that his readers made diverging movements at the beginning of each fixation; findings which were consistent with those of Taylor in his extensive clinical observations in the 1950's.

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1 The findings of Schmidt were described correctly by Tinker (1936, p. 247). However, Tinker (1951, 1958) stated the opposite, i.e., that the eyes “converge during saccadic inter-fixation movement and diverge during the fixation following the movement” without mentioning the source of this finding. This latter statement was quoted by Rayner (1978) in his review article.
(Taylor, 1966). In essence, there appear to be conflicts in findings regarding vergence eye movements between studies in reading versus non-reading tasks, as well as within studies of reading.

In attempts to explore possible reasons for these conflicts in findings, as well as variables that may influence eye movements during reading, the present study was designed to objectively assess vergence behavior as it occurs with adult readers in real-life reading situations. To do so, both reading material and reading tasks were varied in three separate, but related experiments. In Experiment 1 (Text Type), reading material was varied through the use of two types of text: prose passages (words within context) and word lists (words without context). Subjects were instructed to read both types of text silently. In Experiment 2 (Reading Objective), reading task was varied. One appropriate variation of reading task, that is, silent reading versus reading aloud, was not possible to use in the present study, because reading aloud involves movements of the lower jaw and may thus affect eye movement recording (e.g. Schmidt, 1917). Therefore, instead of reading-out-loud, the subject was instructed to subvocalize, that is, the subject was asked to pronounce the words of the text internally (not aloud, but to him- or herself). Silent reading was substituted by the more explicit instruction to silently read for meaning; the subject was informed that a question would be asked about the content immediately afterwards. In brief, in the second experiment, subjects read the same meaningful text twice, once while attending to the meaning and once while attending to the sound. Experiment 3 (Repetition) was a replication of the second experiment with new material and an investigation of the influence of repetition on binocular behavior: subjects had to read the prose passage twice with the same instruction.

2. Method

2.1. Subjects

Subjects were eleven adult females and one male, ranging in age from 20 to 30 years. All subjects served in all three experiments and were students of the Psychology
Department of the University of Nijmegen. Individuals volunteered to participate after an announcement was made in a public area. All subjects received credit for their participation, since participation in such experiments is part of undergraduate course requirements. Subjects were unfamiliar with the equipment, specific methods and purpose of the experiment.

Only individuals that met the following requirements participated as subjects in the experiments: (1) normal or corrected to normal vision (by contact lenses), (2) native speakers of the Dutch language without bilingual upbringing, (3) no known or reports of having suffered brain damage or other neurological deficits and (4) no known or reports of reading problems.

2.2. Eye movement recording

Horizontal movements of both eyes were recorded with the infra-red eye tracking system IRIS. When the frequency bandwidth is from 0 to 100 Hz, the IRIS has a dynamic measuring range of 30° with a noise level of 2 min of arc in the horizontal direction (Reulen et al., 1988). (During binocular measurements, the recording system does not detect changes in eye position in the vertical direction.) The recording system was firmly fixed onto the subject's head and the subject placed his or her chin on a chin rest during recording. Voltage output of the IRIS was fed on-line to a computer (Olivetti M21) with eye position being sampled at a frequency of 200 Hz. Samples were digitally stored for subsequent analysis.

2.3. Material

Stimuli (presented at a distance of 20 cm from the subjects' eyes) were three prose passages and three word lists for the first experiment; three prose passages for the second and three passages for the third experiment. Each of the twelve stimuli was typewritten on white paper that was adhered to a separate 13.3 by 6.0 cm card. (Hereafter, the expression 'stimulus cards' will be used to refer to different prose passage as well as word lists.) Capital letters on the stimulus cards subtended about 0.4 deg of visual angle horizontally and 0.6 deg vertically; lower case letters 0.4 deg horizontally and 0.5 to 0.6 deg vertically. Including spaces between letters, there was a mean of 1.7 letters per degree. The nine prose passages were taken from a Dutch scientific journal about psychology for the general public. Each of these prose passages dealt with one particular topic (e.g., violence to elderly citizens; unfaithfulness) and consisted of 42 to 55 words, occupying 6 to 8 lines of typed text. The three word lists consisted of 23 to 26 words presented in 4 or 5 horizontal lines. Lines for both prose passages and word lists were approximately 10.5 cm long. On either side of each of the lines (about 7 mm away) there was a fixation point for calibration purposes (to be explained below in the Procedure). These pairs of points preceding and following each line were alternately red and black.

For the Text Type experiment, the content words of the prose passages were matched with the unrelated words in the word lists with regard to part-of-speech, word frequency, number of letters and number of syllables. This was done with help of Celex (Burnage,
1990), a computerized lexical database which had a size of 400,000 Dutch words at the moment of the experiment. Words in the prose passages and word lists were matched on imageability (Van Loon-Vervoorn, 1985). Thus, for every content word present on the prose passage card there was a word in the corresponding word list card, similar to it in terms of part-of-speech, number of letters etc. In this way, three prose passage cards (A, B, C) were matched with three word list cards (A', B' and C'). Stimuli for the Reading Objective experiment were two cards with reading passages (D and E) differing from those used in the Text Type experiment. Stimuli for the Repetition experiment were two prose passages (F and G), with a third one serving as a filler (dummy text). Again, stimulus texts for the Repetition experiment differed from those used in the Text Type and Reading Objective experiments.

2.4. Procedure

Eye movement equipment was fastened to the head of the subject and adjusted. When this equipment could not be adequately adjusted for a particular subject within half an hour, the subject was dismissed to avoid influences of fatigue. Three such potential subjects were dismissed.

The experiment was conducted in a well-lit room, where subjects were seated in a comfortable upright position, looking straight ahead. While so seated, a chin rest was placed underneath their chin. (A bite-board was not used, in order to prevent making the reading situation too 'unnatural'.) Attached to the chin rest was a reading stand on which the stimulus cards could be placed. This stand was adjusted in such a way that the upper edge of the stimulus card was at the same height as the pupils of the subject and that the distance between the eyes of the subject and the stimulus card was 20 cm. Subjects were asked to remain very still and to try to refrain from blinking during actual recording, since blinking produces disjunctive eye movements (Collewijn et al., 1985).

The three experiments were conducted in a fixed order in one session of approximately 35 minutes. At the beginning and at the end of the session, a recording was made while the subject fixated rows of black dots presented on a separate card. This was done in order to check for possible drifts. (Virtually no drifts occurred during the experimental sessions.) The order of experiments was always the Text Type experiment, the Reading Objective experiment and the Repetition experiment. Within each of the three experiments, the order of conditions was counterbalanced, as was the order of stimulus cards within the conditions. Each time a new stimulus card was presented to the subject, the card was covered by a piece of white paper, leaving visible only the calibration points on both sides of the lines of the text. The subject was instructed to fixate the points from left to right, one line after the other. After that, the reading instruction (see below) was given, the cover was then removed and the subject commenced reading immediately.

Instruction for the first (Text Type) experiment simply was to read silently. Two instructions were given in the second (Reading Objective) experiment: (1) to read the text while attending to the meaning (subjects were informed that a question would be asked about the content) and (2) to subvocalize. To 'subvocalize', subjects had to pronounce the text internally (so not aloud, but to oneself) and they were urged to attend
to the sound of the words rather than their meaning. (After each experiment, subjects were asked whether the instruction had been clear. All answered affirmatively.) For the third (Repetition) experiment, the same two instructions (reading-for-meaning and subvocalizing) were given, but now the subjects had to read a particular text twice with the same instruction: one text was read twice with the instruction to read-for-meaning and another text was read twice with the instruction to subvocalize. Half of the subjects received text F twice with the reading for meaning and text G with the subvocal pronouncing instruction and vice versa for the other half of the subjects. The order of instructions and texts was counterbalanced. Between the first and second presentation of each text (and with the same instruction), a ‘filler’ text was presented for two reasons. First, it is not impossible that a short text is remembered almost verbatim from first time reading, when it is reread immediately; this could encourage the subject to not really read. Thus, by requiring the subjects to read another text between the two experimental reading sessions, this possibility should be less likely. Second, in the second (Reading Objective) experiment, subjects had to read two (D and E) texts twice also (although with different instructions), in the order D-E-D-E (or vice versa). In other words, each of the texts was reread only after reading of another text. Presentation of an in-between text in the Repetition experiment as well made the conditions in the second and third experiments more comparable. This was also done in attempts to provide a better estimate of the effect of repetition in the second experiment. Subjects were informed that they would have to read the texts for a second time after an intervening one and they were unaware that the intervening text was only a filler.

2.5. Data analysis

Recordings were analyzed by customized computer programs. For maximum accuracy, the eye position samples were analyzed for each stimulus line separately, using the calibration dots flanking the same line as a reference. A fixation was identified as such when the mean velocity of both eyes dropped below 20 deg/s for a period of at least 100 ms. If the end of a fixation period was detected, the program checked whether eye movement velocity was still above 20 deg/s, if velocity was calculated between the last sample pair and the third pair ahead. (This was done to rule out the chance that a single out-of-range value would cause the program to identify that as the end of the fixation period.) If so, the (first) sample pair was marked as the fixation end. If not, the fixation period was supposed to continue (see Fig. 1). The markings of the fixation periods were visually inspected and none appeared to need manual adjustment.

The chin rest support of the subject's head and the instruction to remain very still reduced but did not preclude the possibility of minimal head movements. If a small lateral movement of the head occurred, the position of the eyes would be compensated instantaneously by the subject in the opposite direction to keep fixing the same stimulus location. The eye movement equipment, which is fixed with respect to the subject's head, cannot distinguish between changes in eye position that are and those that are not accompanied by a change in fixation location. Therefore, no attempt was made to associate fixations with particular stimulus locations. Instead, the main eye movement parameters studied are those that are relatively robust with respect to minor
Fig. 1. Example of eye movements during reading of a single text. Both graphs depict the same representative sample. Upper graph: mean positions of the two eyes. Lower graph: positions of the eyes presented separately, with the top trace representing the left and the bottom trace the right eye. The small vertical bars indicate the points at which the computer program identified the beginnings and endings of fixation periods (in the lower graph, only the first fixation is marked). Note the very fast vergence movement directly following the line return: the criterion for the identification of fixations of \(< 20\) deg/s caused exclusion of such initial glissades from the analyses.

head instabilities: that is, vergence velocity (the velocity of one eye relative to the other), saccade size and fixation duration.

Saccade size was computed for each eye separately by subtracting the mean eye position on fixation \(n\) from the mean position on fixation \(n + 1\). These difference scores were then added and divided by two, to obtain the saccade size for both eyes together. Leftward saccades include line returns as well as 'true' regressions. The frequency distribution of all saccade sizes together (leftward saccades with a negative sign) showed
two peaks: a large one at the positive and small one at the negative end, with a clear dip in between at around 15 deg leftward. This indicated that line returns in the present data usually exceed a length of 15 degrees (line returns do not necessarily cover the entire line length). Indeed, the number of saccades larger than 15 degrees to the left was similar to the number of line returns that one could expect on the basis of the number of lines on the stimulus cards (315 versus 324 expected line returns for the Text Type and 264 versus 264 for the Reading Objective experiment). All saccades larger than 15 degrees were excluded from further consideration: that is, to make leftward and rightward saccades comparable, the few rightward saccades larger than 15 degrees (13 out of 2498 for the Text Type, and 9 out of 1871 for the Reading Objective experiment) were excluded as well. Following that, mean saccade size was calculated per subject/condition/stimulus card for the remaining rightward and leftward saccades (i.e., regressions) separately.

Mean velocity during a fixation period was computed for each eye separately, starting 10 ms after the beginning of the fixation and ending 10 ms before the end. A positive number for movement velocity of each eye indicates a movement of that eye to the right; a negative number, a movement to the left. Vergence velocity was calculated for each fixation by subtracting the mean velocity of the right eye from the mean velocity of the left, taking the absolute value of the result. Thus, vergence velocity is the speed of the vergence movement, regardless of whether it concerns convergence or divergence. Mean fixation duration was computed over the entire fixation period (thus including the 10 ms at beginning and ending).

Outliers among the vergence velocity and fixation duration measures were identified per subject/condition/stimulus card subset. All measures within such a subset that were either two-and-a-half times the standard deviation above or below the mean were considered outliers. (This procedure excluded virtually all fixations following blinks from the vergence computations.) The overall percentage outliers was around 3\% for each of the three experiments.

Results were analyzed by the statistical software program SPSS-X. Mean values were calculated for each subject, per stimulus card and per condition and analysed by the following analyses of variance, unless indicated otherwise. The data obtained in the Text Type experiment were analysed by a 2 X 3 analysis of variance (text type X stimulus card pair), the data of the Reading Objective experiment by a 2 X 2 analysis of variance (instruction x stimulus card) and the data of the Repetition experiment by a 2 X 2 analysis of variance (instruction x repetition).

3. Results

3.1. Vergence velocity during fixations

3.1.1. Text Type experiment

The mean velocity of the vergence movement during the fixations was significantly higher ($F(1,11) = 33.66$, $p < 0.001$), when subjects were reading prose passages than when they were reading word lists (see Table 1). There was no significant effect
Table 1
Mean vergence velocities during the complete fixation period and during the initial 80 ms of fixations, in deg/s

<table>
<thead>
<tr>
<th>Experiments</th>
<th>Vergence velocities</th>
<th></th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Vergence velocity during complete fixation period</td>
<td>Vergence velocity during initial 80 ms of fixation</td>
<td></td>
</tr>
<tr>
<td>Text Type experiment</td>
<td>Passages</td>
<td>Word lists</td>
<td>Passages</td>
</tr>
<tr>
<td>Mean</td>
<td>2.3</td>
<td>1.5</td>
<td>3.9</td>
</tr>
<tr>
<td>SD</td>
<td>0.7</td>
<td>0.4</td>
<td>1.0</td>
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<tr>
<td>Reading Objective experiment</td>
<td>Reading for meaning</td>
<td>Subvocal reading</td>
<td>Reading for meaning</td>
</tr>
<tr>
<td>Mean</td>
<td>2.2</td>
<td>1.8</td>
<td>3.6</td>
</tr>
<tr>
<td>SD</td>
<td>0.6</td>
<td>0.6</td>
<td>0.9</td>
</tr>
<tr>
<td>Repetition experiment</td>
<td>Reading for meaning</td>
<td>Subvocal reading</td>
<td>Reading for meaning</td>
</tr>
<tr>
<td>1st Presentation</td>
<td>Mean</td>
<td>2.4</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>0.7</td>
<td>1.1</td>
</tr>
<tr>
<td>2nd Presentation</td>
<td>Mean</td>
<td>2.4</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>0.9</td>
<td>1.1</td>
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</tbody>
</table>

\( (F(2,22) < 1) \) of stimulus card pair on vergence velocity: difference in vergence velocity between text and word list was similar in all three pairs. The factors text type and stimulus pair did not interact \( (F(2,22) = 1.43, \ p = 0.26) \).

The relative contribution of the two eyes to the vergence movement depended on the direction (left vs. right) of the preceding saccade: it was the adducting eye which made the largest contribution. After a rightward saccade, the right eye moved with an average velocity of 1.1 deg/s \( (SD = 0.7) \) in the opposite direction of the saccade (i.e., to the left) and the left eye with an average velocity of 0.2 deg/s \( (SD = 0.6) \) in the same direction as the saccade (i.e., to the right). After a leftward saccade, the left eye moved to the right with an average velocity of 1.5 deg/s \( (SD = 0.8) \) and the right eye to the left with 0.5 deg/s \( (SD = 1.0) \).

The vergence velocity measure computed in this study depicts the mean velocity of the vergence movement during fixations, regardless of whether it actually is convergence or divergence. Seventy-four percent (74%) of all fixations resulted in a more converged position of the eyes, 9% ended without a noticeable difference in vergence angle and 17% were fixations that resulted in a more diverged position of the eyes. Two additional analyses, one for converging and one for diverging fixations only, showed that convergence velocity was significantly \( (F(1,11) = 35.50, \ p < 0.001) \) higher during prose passages \( (M = 2.4; \ SD = 0.7) \) than during word lists \( (M = 1.5; \ SD = 0.4) \), but

\(^3\) The values given should be interpreted with caution: frequencies of the leftward and rightward saccade amplitudes in the present data base differed considerably. Fixations following line returns were included.
Table 2

Proportions of fixations with convergence and with divergence per subject

<table>
<thead>
<tr>
<th>Subject</th>
<th>Text Type experiment</th>
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<th>Reading Objective experiment</th>
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<tr>
<td></td>
<td>Percentage with convergence</td>
<td>Percentage with divergence</td>
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<td>Percentage with convergence</td>
<td>Percentage with divergence</td>
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<tr>
<td>1</td>
<td>95</td>
<td>1</td>
<td>93</td>
<td>4</td>
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<tr>
<td>2</td>
<td>86</td>
<td>5</td>
<td>89</td>
<td>5</td>
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<tr>
<td>3</td>
<td>60</td>
<td>18</td>
<td>56</td>
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<td>4</td>
<td>43</td>
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<td>62</td>
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</table>

Note: The table does not include percentages of fixations without an apparent change in vergence angle. Therefore, the percentages per subject per experiment do not add up to a hundred.

there was no difference in divergence velocity between prose passages ($M = 0.9; SD = 0.2$) and word lists ($M = 0.9; SD = 0.3$). There was no significant effect of stimulus card or an interaction with it in either of the additional analyses.

Although most of the fixations showed a converging drift, the ratios of numbers of converging and diverging fixations differed for different subjects. For instance, for subject 1 95% of the fixations showed convergence, whereas for subject 4 only 43% were converging fixations (a percentage slightly less than her percentage of diverging fixations). All other subjects made more converging than diverging fixations (see Table 2). The relative proportions of fixations with different types of vergence did not differ very much between the two conditions (results not shown).

3.1.2. Reading Objective experiment

Vergence velocity during fixations was significantly higher ($F(1,11) = 20.08, p < 0.001$) when subjects were reading texts for meaning, than when they were pronouncing the text subvocally (see Table 1). There was no significant effect ($F(1,11) < 1$) of stimulus card on vergence velocity; both texts showed the same effect of reading objective on vergence velocity. There was no interaction between the two factors ($F(1,11) < 1$).

Similar to the Text Type results, the relative contribution of both eyes to the vergence movement seemed to depend on the direction (left vs. right) of the preceding saccade. After a rightward saccade, the right eye drifted with an average velocity of 1.0 deg/s ($SD = 0.8$) to the left and the left eye with a mean velocity of 0.2 deg/s ($SD = 0.6$) to the right. Following a leftward saccade, the right eye also drifted to the left, but with a lower mean velocity than that of the rightward-drifting left eye ($M = 0.4$ deg/s, $SD = 1.0$ and $M = 1.6$ deg/s, $SD = 0.7$, respectively).
Seventy-three percent (73%) of all fixations resulted in a more converged position of the eyes, 9% ended without a noticeable difference in vergence angle and 18% were fixations that resulted in a more diverged position of the eyes. Two additional analyses, one for converging and one for diverging fixations only, showed that convergence velocity was significantly higher \((F(1,11) = 18.28, p < 0.001)\) during reading for meaning \((M = 2.3, SD = 0.7)\) than during subvocalizing \((M = 1.9, SD = 0.7)\), but there was no significant difference \((F(1,11) < 1)\) in divergence velocity between reading for meaning \((M = 1.2; SD = 0.5)\) and subvocalizing \((M = 1.1; SD = 0.3)\). There was no stimulus card effect and no interaction with it in either of the additional analyses.

Again, different subjects had different proportions of converging fixations among the total number of fixations they made, although they all appeared to make more converging than diverging fixations. For each individual, this proportion did not differ substantially from that observed in the Text Type experiment (see Table 2). There was no clear difference between the proportions of converging fixations in the two conditions (data not shown).

### 3.1.3. Repetition experiment

There was no significant effect \((F(1,11) = 1.12, p = 0.31)\) of repetition on vergence velocity (see Table 1). Again, however, vergence velocity was significantly higher \((F(1,11) = 5.36, p < .05)\) during reading for meaning than during subvocal pronouncing. There was no significant interaction \((F(1,11) < 1)\) between repetition and instruction.

Seventy-eight percent (78%) of all fixations resulted in a more converged position of the eyes, 4% ended without a noticeable difference in vergence angle and 18% were fixations that resulted in a more diverged position of the eyes. An analysis on converging fixations alone demonstrated that for these fixations, the effect of repetition on vergence velocity did not reach significance \((F(1,11) = 3.70, p = 0.08)\), the instruction effect, however, was again significant \((F(1,11) = 5.52, p < 0.05)\) (Reading for Meaning, 1st presentation: \(M = 2.6, SD = 0.8\); and 2nd presentation \(M = 2.6, SD = 0.9\); Subvocal Reading, 1st presentation \(M = 2.0, SD = 0.7\) and 2nd presentation \(M = 2.1, SD = 0.8\)). An analysis on the diverging fixations did not show significant effects of repetition \((F(1,11) < 1)\) and instruction \((F(1,11) = 1.72, p = 0.22)\) (Reading for Meaning, 1st presentation \(M = 1.1, SD = 0.4\); 2nd \(M = 1.0, SD = 0.4\). Subvocal Reading, 1st \(M = 0.8, SD = 0.5\); 2nd \(M = 1.0, SD = 0.4\)). There were no significant interactions between repetition and instruction.

### 3.2. Fixation duration and vergence velocity

A possible explanation of the differences in vergence velocity between conditions is that they are due to differences in fixation duration. If, for instance, the vergence movement takes place primarily during the first part of the fixation period, then a longer fixation duration will give a lower calculated vergence velocity. Indeed, mean fixation durations (see Table 3) were longer in those conditions in which vergence velocity was found to be lower. That is, mean fixation durations were longer in the word-list than in the prose condition of the Text Type experiment and they were longer in the subvocaliz-
Table 3
Mean fixation durations (in ms)

<table>
<thead>
<tr>
<th>Experiments</th>
<th>Conditions</th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Text type experiment</td>
<td>Passages</td>
<td>204</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>Word lists</td>
<td>244</td>
<td>35</td>
</tr>
<tr>
<td>Reading objective experiment</td>
<td>Reading for meaning</td>
<td>200</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>Subvocal reading</td>
<td>224</td>
<td>33</td>
</tr>
<tr>
<td>Repetition experiment</td>
<td>Reading for meaning</td>
<td>211</td>
<td>24</td>
</tr>
<tr>
<td>1st Presentation</td>
<td>Subvocal reading</td>
<td>226</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>212</td>
<td>29</td>
</tr>
<tr>
<td>2nd Presentation</td>
<td></td>
<td>233</td>
<td>48</td>
</tr>
</tbody>
</table>

ing than in the reading-for-meaning conditions of the Reading Objective and Repetition experiments. These means differ in the same direction as the silent and reading measures reported elsewhere (e.g., Bouma and De Voogd, 1974; Gray, 1969) contrast with previous findings (Hyöna and Niemi, 1990; Inhoff et al., 1993), fixations were similar for first and second time reading).

In order to address the concern that the vergence velocity differences were due differences in fixation duration, vergence velocity was recomputed by taking the in 80 ms of each fixation only (analogous to the prior calculations of vergence velocity, first 10 ms after the end of the saccade were excluded). Analysis of these data show that text type \( F(1,11) = 53.41, p < 0.001 \) and reading objective \( F(1,11) = 6, p < 0.05 \) already had an effect within the first 80 ms of fixations. There was a significant \( F(1,11) = 5.24, p < 0.05 \) effect of stimulus card on the reading objective but not on the text type data. No significant interactions with stimulus cards were found. The effect of reading objective on initial vergence velocity was replicated in Repetition experiment \( F(1,11) = 7.24, p < 0.05 \). However, congruent with the findings for the entire fixation period, repeated reading of the same text with the same instruction did not have an effect \( F(1,11) < 1 \) and there was, again, no interaction between reading objective and repetition \( F(1,11) < 1 \). Thus, mean vergence velocity immediately following the offset of saccades was higher during reading of passages than during reading of unrelated words and it was higher when subjects were attending to the meaning of texts than when attending to the sound. This was true for all subjects when participating in the Text Type experiment, and all but one (subject when participating in the Reading Objective experiment (see Figs. 2 and 3).

It is still conceivable that the differences in vergence velocities can be attributed to the duration of the entire fixations. That is, for movements in general there exist a relation between initial speed and total duration of a movement: initial speed of movements of long duration is higher than in movements of short duration. Thus, a h
speed in the initial 80 ms of a fixation could be the result of the fact that the total time in which the movement takes place is longer. However, in the present data, higher speeds occurred in fixations of shorter duration, which appears to contradict this interpretation.
3.3. Saccade size and vergence velocity

Another point of interest with respect to fixational vergence is the size of the preceding saccade. Previous research with LEDs has shown that vergence velocity during the initial part of a fixation period decreases as a function of the length of the preceding saccade (Collewijn et al., 1988a; Zee et al., 1992). To investigate whether this relationship exists in reading and whether vergence velocity could also be affected by the experimental manipulations directly, an additional analysis was carried out on the vergence velocity data of the Text Type and the Reading Objective experiment (to control simultaneously for the effect of differences in fixation duration, vergence velocities of the initial 80 ms of the fixations were used). For the two conditions of the two experiments separately, all fixations were categorized according to the size and direction of the preceding saccade: one group of leftward saccades (0–3°) and three groups of rightward saccades (0–3°, 3–6° and 6–9°). Fixations that did not fall within these four categories (the first fixation on each text and fixations following line returns) were excluded from the analyses (17% in total for the Text Type and 18% for the Reading Objective experiment).

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4 One might object to the procedure of sorting into groups that the size of the saccade groups was so large that the saccade sizes could still vary within each group. To check whether the mean size of the preceding saccade was kept under control as was intended, mean saccade size was calculated for each group within each condition. It turned out that the procedure had effectively reduced the difference in mean saccade amplitude between conditions from 2.2 deg to 0.1 deg for the Text Type experiment and from 1.4 deg to 0.1 deg for the Reading Objective experiment.
Similar to initial fixational vergence during viewing of LEDs, initial vergence velocity during fixations of reading material increased with increasing preceding saccade size as well. Interestingly, not all variation in vergence velocity within the initial 80 ms of the fixations seemed to be attributable to differences in saccade size. Within each of the saccade size groups, mean vergence velocities were larger for the prose passages than for the word lists (Text Type experiment) and, with exception of the largest rightward saccades, they were higher during reading-for-meaning than during subvocalizing (Reading Objective experiment) (see Figs. 4 and 5). Data of both experiments were subjected to an analysis of variance with the variables condition (2) and saccade size (4) treated as factors. For the Text Type data, the factors text type ($F(1,11) = 13.45, p < 0.005$) and saccade size ($F(3,33) = 8.02, p < 0.001$) had significant effects. The (ordinal) interaction between text type and saccade size was significant as well ($F(3,33) = 3.08, p < 0.05$). For the Reading Objective data, a significant effect of saccade size ($F(3,33) = 5.86, p < 0.005$) was found, but not of reading objective ($F(1,11) = 2.23, p = 0.16$). Their interaction did not reach significance either ($F(3,33) = 1.75, p = 0.18$).

4. Discussion

Two main findings appear to result from this study. First, a clear tendency was found for the eyes to converge during fixations in reading. For almost all of the present subjects, the majority of fixations ended in a more converged eye position, a finding more consistent with the early observations of vergence in reading by Schmidt (1917), than those by Clark (1935) and Taylor (1966) who reported observing only divergence during fixations. The present finding of convergence during fixations in reading also
corresponds with the results of more recent studies in which LEDs were used as stimuli (Collewijn et al., 1988a; Zee et al., 1992).

A second main finding is that the velocity of the vergence drift during fixations is affected by reading material and reading task. Vergence drift had a higher mean velocity during reading of prose passages than during reading of lines of unrelated words as well as when reading for meaning rather than to sound out the words internally. This held true when only the initial 80 ms of each fixation were taken into account, that is, these differences in mean vergence velocity cannot be attributed to differences in duration of the fixation periods. Vergence velocities were higher for the initial 80 ms than for the entire fixation period, showing that vergence velocity decreases over time (see Collewijn et al., 1988a, for a similar result). When texts were re-read once, vergence velocity did not alter significantly: neither when the entire fixation period was taken into account, nor when only the initial 80 ms were considered.

The present results suggest that fixational vergence during reading is faster when fixations are preceded by large saccades, as has been found previously with LEDs as stimuli by Collewijn et al. (1988a) and Zee et al. (1992). The results further suggest that higher vergence velocities cannot always be attributed entirely to differences in saccade size: reading material appeared to directly affect vergence velocity as well. Although these results were obtained in a natural reading situation (that is, without independent manipulation of saccade size), the fact that the text type effect still is highly significant when saccade size differences are taken into account calls for an explanation.

One possible explanation is that in both the prose and the reading-for-meaning condition, there is an emphasis on the processing of higher-order semantic information. Therefore, relatively more top-down information is available to help the reader identify words. In the word list and subvocal conditions on the other hand, there is much less top-down constraint. This means that in these conditions, the reader is more dependent upon the visual input itself, which may lead to an increase in number of fixations. If more fixations are made, however, the eyes have to be aimed at smaller units of the text. If in particular situations the eyes are indeed directed at smaller units, the question becomes: why would movements to small targets be slower? A well-known law that describes the relation between speed and accuracy of movement, Fitts' Law, maintains that there is a logarithmic trade-off between the duration and the spatial precision of rapid aimed movements (Fitts, 1954). As target width decreases, movement time increases (Fitts and Peterson, 1964). Accordingly, Erkelens (1987) found that a small target (a single vertical bar) elicited lower vergence velocities than a large target (a coarse random-dot stimulus). This means that the vergence velocity results might reflect the choice by the subject to attend to larger versus smaller parts of the text.

Perhaps eye movements could be slowed down when the force exerted by the agonistic muscle is countered by a simultaneous contraction of the antagonist. If an accurate eye movement has to be made, cocontraction could serve to stabilize the eye, in a similar way as has been proposed by other investigators for movements of, for instance, the hand (Van Galen and Schomaker, 1992) and the forearm (Hogan, 1984). Cocontraction presumably leads to a reduction of the spatial error of the movement result, but, at the same time, it decreases effective movement velocity. In agreement with this hypothesis, we have recently found evidence that attention to visual detail
The means for leftward saccades do not include line returns.

A second aspect of the data which agrees with the assumed relation between vergence speed and size of the attended region of text is that slow vergence co-occurred with long fixation durations. Fixation durations were longer for word lists than for prose passages and longer during subvocalizing than during reading for meaning (the latter two conditions differed, again, in the same direction as silent and oral reading (e.g. Bouma and De Voogd, 1974; Gray, 1969), and hence, in those conditions in which subjects were presumably attending to smaller text regions, which requires a higher degree of

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5 These values were obtained by dividing the number of fixations by the number of words in the text.
accuracy. There is evidence that a higher degree of accuracy requires more time. Bouma (1978) found that if the task required accurate fixation of small dots, fixation durations were about 100 ms longer than durations of fixations typically made during reading. In studies of Coëffé and O’Regan (1987) and Jacobs (1987), it was found that saccadic accuracy improved at long latencies. Thus, the fact that in the present study smaller saccades co-occurred with longer fixation durations supports the notion that the readers were actually aiming at smaller regions of the visual stimulus. 6

Apart from their possible implications for the nature of the reading process, the present results may be relevant for three additional reasons. First, the existence of vergence drifts has salience for the analysis of eye movement data. On the one hand, this finding suggests that begin- and end-points of fixations should not be selected on the basis of the mean velocities of the two eyes together, as it may lead to inappropriate inclusion of fixations with extremely high (vergence) velocities. For instance, during fixations following eye blinks the velocities of each of the two eyes separately often exceed 50 deg/s, whereas their mean velocity may be below 15 deg/s. On the other hand, the existence of vergence drifts implies that criteria for the velocity of each eye separately should not be so stringent that fixations or parts of fixations with high – but normal – vergence velocities would be excluded. During fixations following large saccades (e.g. line returns), the eyes often move with velocities much higher than velocities traditionally used as criteria for the selection of fixations.

Second, during vergence eye movements, vision seems to be suppressed in a similar way as in saccadic eye movements (Mannings and Riggs, 1984; Hung et al., 1989). Although velocities of vergence drifts are much lower than those of saccades (and thus their suppressive effect), it is conceivable that such drifts may affect the processing of visual information. This finding is consistent with the observation that visual sensitivity is reduced not only during saccades, but also during the initial part of fixations (e.g. Ishida and Ikeda, 1989; see also Volkmann, 1986).

6 An alternative view is provided by O’Regan’s strategy-tactics theory of eye movements in reading (O’Regan, 1990). This theory is based on the existence of a so-called ‘optimal landing position’ effect: the probability of refixating an (isolated) word happens to depend strongly on the position within that word that is first fixated (O’Regan, 1990; O’Regan and Levy-Schoen, 1987; Vitu et al., 1990). The exact place at which this optimal viewing position is located in each word depends on linguistic characteristics of that particular word (Holmes and O’Regan, 1987) which the reader does not know in advance. However, since the optimal landing position is usually located near the word’s middle readers choose to aim at this ‘generally optimal’ viewing position: that is, readers adopt the global strategy of moving their eyes from word to word, aiming for the middle of these words on the basis of low-level visual information (e.g. interword spaces). If the eyes do not happen to fall near the optimal viewing location, a ‘rescue tactic’ will occur: the reader will than make a rapid saccade over to the other side of the word. In other words, the decision to make a second saccade within a word is made only after the first one turned out to have landed at the wrong location. The strategy-tactics theory cannot, however, account for the present results. If the extra saccades that were induced by the manipulations of text type and reading objective result from the rescue tactic, the proportion of rightward and leftward saccades should be equal, because the probability of landing to the left of the optimal landing position should be as high as landing to the right of it. However, almost all (79%-100%) of the extra saccades made in the three experiments happened to be in the rightward direction. This indicates that readers often ‘deliberately’ land on the initial part of the word.
Third, and finally, vergence is related to accommodation and pupillary constriction: together, these three phenomena constitute the so-called ‘near triad’ (Knoll, 1949; Marg and Morgan, 1950). Of these three, both accommodation (Kruger, 1980; Malmstrom et al., 1980; Winn et al., 1991) and change in pupil size (reviewed by Beatty, 1982) have been shown to be indicators of relative cognitive difficulty across a variety of cognitive tasks. Thus, vergence velocity measures might help to further our understanding of cognitive aspects of reading.

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