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Binocular coordination of saccades in 7 years old children in single word reading and target fixation

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Abstract

The purpose of the present study was to examine in 7 years old normal children who just learnt to read, saccade and fixation characteristics during reading single words. Eight children were studied and their results were compared to those of eight normal adults doing the same task. For each group word reading data were also compared with data in a task requiring saccades and fixations to target-LEDs. Horizontal saccades from both eyes were recorded with a photoelectric device (Oculometer, Bouis). Latencies of saccades both to words and to LEDs presented at predictable location were similar, and they were also similar between children and adults. In contrast, disconjugacy of saccades was significantly increased for children and similar in the two tasks (LEDs or words). Disconjugate post-saccadic drift and its velocity were also significantly higher in children and similar in the two tasks. Substantial conjugate leftward drift was present for children only, and for the word task only. Finally, fixation duration on words was significantly longer in children than in adults. We conclude that binocular coordination and fixation stability is poor in children and that it could be partially responsible for the long fixation duration. Binocular coordination does not depend on the task (LEDs or words) neither for adults, nor for children; this contrasts prior reports.

Keywords: Children; Reading; Binocular coordination; Vergence; Post-saccadic drift

1. Introduction

Several studies showed that the latency of saccades in young children is longer and decreases with age (i.e., Fukushima, Hatta, & Fukushima, 2000; Munoz, Broughton, Goldring, & Armstrong, 1998; Yang, Bucci, & Kapoula, 2002). Long latencies are attributed to incomplete maturation of cortical areas involved in the initiation of saccades that continue to develop until 10–12 years.

In contrast, studies on binocular control of saccades in children are quite scarce. Fioravanti, Inchingolo, Pensiero, and Spanio (1995) examined horizontal saccades to target-LEDs at far viewing (1 m) in children aged between 5 and 13 years and they found that binocular coordination of saccades of 10° in young children (<9 years) is poor relative to that known in adults; the disconjugacy of saccades is 13% of the amplitude of saccades versus 5% in adults. Moreover, young children showed also increased disconjugate post-saccadic drift with respect to adults. Fioravanti and collaborators explained these findings by the immaturity of adaptative mechanisms that are necessary for the compensation of the natural and changing asymmetries of the oculomotor plants.

Most important, a recent work of Yang and Kapoula (2003) showed that, in children, the disconjugacy of saccades to target-LEDs is even worse at near distance: 17% of the saccade amplitude for children 7–8 years old versus only 7% for adults; such disconjugacy

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decreases with age via visual experience and learning, but remains higher than in adults even at 10–12 years of age. Yang and Kapoula (2003) attributed this disconjugacy to immaturity of adaptive mechanisms that could be also cortically based. Note that these observations have implications for reading given that reading is a near vision activity.

To our knowledge, studies examining the quality of binocular coordination during reading both in adults and in children are scarce. The few existing studies suggest an influence of the type of task on the binocular coordination and will be reviewed below. Hendriks (1996) investigated in adults the velocity of disconjugate drift of the eyes during the fixation following saccades (disconjugate post-saccadic drift velocity) under two conditions: reading short texts and reading a list of words. She reported higher drift velocity during text reading than during reading lines of unrelated words. Lower disconjugate drift velocity when reading a list of words was attributed to the fact that the reader is more dependent of the visual information of each word fixated; this results in smaller amplitude of the saccades to the words, and also in a more stable fixation e.g., a lower drift velocity.

Heller and Radach (1999) showed that normal adults during reading a text make saccades highly disconjugate between the two eyes: the difference can reach 15% of the saccade amplitude. During the fixation period after the saccade, disconjugate convergent drift is also present with slow mean velocity (about 1 deg/s); moreover, binocular versus monocular reading produces similar results. This led the authors to suggest that the disconjugate drift could be a pre-programmed command and not visually driven. Furthermore, Heller and Radach (1999) compared saccades during reading normal text and during reading mixed case text. Saccade disconjugacy and drift velocity after the saccades increased with increasing saccade amplitude. Importantly, drift velocity was found to be higher during reading normal text than during reading mixed case text. Heller and Radach (1999) concluded that the material of the reading task influences the binocular coordination of saccades. In sum, the authors concluded that binocular motor control while reading normal text is poor, most likely because semantic process is easier with normal text and could be achieved even in the absence of perfect binocular motor control during and after the saccade. They further suggest that monocular reading is better than binocular.

For children, only one study exists dealing with binocular recordings (using an electro-oculography) during reading (Bassou, Granié, Pugh, & Morucci, 1992). Their results are qualitative and also of low resolution because of the EOG recording. Saccades of the two eyes can be highly disconjugate in children of 10 years old. Bassou and collaborators suggested that Hering's law, according to which the two eyes are well yoked because they receive equal innervation, is not always obeyed during reading; the authors pointed out that poor binocular control in children could interfere with learning of reading. This hypothesis was also shared by other investigators (e.g., Eden, Stein, Wood, & Wood, 1994; Stein, Riddell, & Fowler, 1987, 1988) showing that in dyslexic children the quality of binocular control during fixation is poor. However, in all these studies only qualitative assessments were made of the accuracy of the saccades from the two eyes and of their difference; precise binocular recordings in children, normal or dyslexic are still missing.

In the present study, we examine the quality of binocular coordination of saccades in two tasks (reading single words and LED-targets) in normal 7 years old children who just learnt to read and in normal adults. Given that children at this age have poor binocular control particularly at close distance during saccades to LEDs (see Yang & Kapoula, 2003), we want to explore whether this occurs also during reading single words. Contrary to the thinking of Heller and Radach (1999) we thought that word identification is a perceptually demanding task that needs high quality of binocular coordination and thus a better saccade coordination than that we observed previously for the LED-task. Moreover, we could also argue that children who started to learn to read 8 months before had already improved their binocular saccade control via reading experience and learning. Consequently, we expected to found in children a better saccade coordination during reading single words than during LED fixation. The results show that the quality of binocular coordination of saccades is not influenced by the task, and that binocular control is poor in children relative to adults, as reported by Yang and Kapoula (2003) for LED-targets. Finally, our findings in adults show no influence of the task and contrast prior reports (Heller & Radach, 1999).

2. Materials and methods

2.1. Subjects

Eight children of the first class of French elementary school and eight adults participated in the study. The mean age was 7.1 ± 0.5 years; children started to learn to read 8 months earlier. The mean adults age was 24.7 ± 5 years. The investigation adhered to the principles of the Declaration of Helsinki and was approved by our institutional human experimentation committee. Informed consent was obtained from children's parents and adults after explanation of the procedure of the experiment.

All subjects had normal binocular vision (60 s of arc or better) that was evaluated with the TNO random dot test for stereoscopic depth discrimination. Visual acuity was normal (⩾9/10) for all subjects both at near and at far distance; none wore spectacles. Orthoptic evaluation of vergence (using prisms and a Maddox rod) was in the normal range (Evans, 1997; von Noorden, 2002; Ygge, Lennerstrand, Rydberg, Wijecoon, & Petterson, 1993): distant near point of convergence was on average ⩽7 cm and exophoria (i.e., latent deviation of one eye when the other eye is covered) at near viewing was less than 6 pD for all subjects, children or adults.

2.2. Eye movements recording

Data collection was directed by REX, software developed for real-time experiments and visual display run on the PC. Horizontal eye movements from both eyes were recorded simultaneously with a photoelectric device (OCULOMETER, BOUIS). This system has an optimal resolution of 2 in. of arc. Eye-position signals were low-pass filtered with a cutoff frequency of 200 Hz and digitised with a 12-bit analogue-to-digital converter; each channel was sampled at 500 Hz.

The photoelectric device (BOUIS) used here, combined with rigorous stabilization of the head, can provide reliable high quality measures of binocular coordination. The values of saccade disconjgacy in adults reported here are similar to those of previous studies in which eye movements have been recorded by the high accuracy method of magnetic-field/scleral search coil (Kapoula, Eggert, & Bucci, 1995). Importantly, the frequent calibration and the short duration of the experimental session allow to extract reliable measures of disconjugacy in children as well (see also Yang & Kapoula, 2003).

2.3. Procedure

Subject was seated in a chair which could be adjusted for height, with the head stabilized by a forehead and chin support. For children, to avoid head movements, the back of the head was also stabilized by using a special strip. Subject viewed binocularly. The viewing distance was 40 cm.

2.4. Visually guided saccades to target-LEDs

A standard saccade paradigm was used to elicit visually guided saccades to predictable locations: a target-LED jumped horizontally from 0° to 10°, 0° to 20° to the right or to the left; target remained at each location for 2 s, this time was sufficiently long to allow accurate and stable fixation. Subject was instructed to fixate as accurately as possible the target. In each block 24 rightward and leftward saccades were elicited. Subjects performed three blocks. Only rightward saccades were analysed and compared with the rightward saccades to isolated words of the reading task.

The first and last five recordings of each block were used to extract the calibration factors. Note that this procedure is similar to that of Yang and Kapoula (2003) applied to calibrate saccades at close distance in children as well as in adults using the same set-up.

2.5. Isolated words reading task

The paradigm used here has been introduced by Vitu, Kapoula, Lancelin, and Lavigne (2004). Isolated words were presented et eye level in the middle of a PC screen in front of the subject; word were in black courier font on a white background and the mean character width was 0.5°. Each trial started with the presentation of the sign '+' on the left side of the screen. After 500 ms the '+' was replaced by a cross and simultaneously a word was presented in the middle of the screen and a '+' on the right side. The beginning of the word was always at the same eccentricity to the right of fixation (at 5.4° from the '+'). Subject was invited first to fixate the cross on the left side, then to read the word silently, and finally to fixate the '+' on the right side. At this time subject had to answer whether the word read was an animal name or not by pressing a different key of the keyboard. The key press triggered the disappearance of the word and of the + sign and the next trial started. Subject had not time limit for reading. The answers from each subject were collected in a file and the scores of good responses were evaluated: they were 100% correct. Subjects were trained by performing the task a few minutes before eye movement recordings. Each block contained 21 words (of 5, 7, 9-letters at equal rate), randomly presented. The amplitude of the saccades during reading ranged between 5.4° and 9°, depending to the length of the word read. Each subject performed two blocks.

Inside each block, before and after reading words, subject made a sequence of saccades between the center and the target '+' on the left and right side of the PC. From these recordings we extracted a calibration factor applied to all saccades of that block. This frequent calibration was particularly important for children and allowed us to obtain accurate evaluation of the amplitude of the saccades and of their disconjugacy.

2.6. Data analysis

Methods are similar to those used in prior studies (Bucci, Kapoula, Yang, Roussat, & Brémond-Gignac, 2002, 2004; Yang & Kapoula, 2003). Briefly, calibration factors for each eye were extracted from the eye position during the calibration procedure; a linear function was used to fit the calibration data. From the two individual eye position signals, we calculated the conjugate saccadic signal [(left eye + right eye)/2] and the vergence disconjugate signal (left eye − right eye). Markers were placed at different points on eye position signals automatically by the computer, and were verified afterwards by an investigator. The onset of the conjugate saccadic component was defined as the time when the eye velocity reached 5% of the saccadic peak velocity; the offset of this signal was defined as the time when the eye velocity dropped below 10 deg/s. These criteria are standard and similar to those used in above cited studies. The markers of the saccadic trace were projected on the disconjugate trace.

For each saccade recorded in the two different conditions (target-LEDs and during reading isolated words) we measured the latency in ms, that is the time between the onset of the stimulus and the beginning of the first saccade. We also examined the binocular coordination by measuring the amplitude of the disconjugacy (left eye – right eye) during the saccade, and the amplitude of the post-saccadic drift over the period following the offset of the primary saccade and until the onset of the first corrective saccade. The duration of that fixation was also evaluated. Post-saccadic drift could continue after the corrective saccade. Thus, our study on post-saccadic drift is not exhaustive, but it describes the quality of binocular fixation in the first period after the primary saccade, which is important for processing the visual information immediately after the saccade. The amplitude of the conjugate drift was also measured [(amplitude of the drift of the left eye + amplitude of the drift of the right eye)/2]. The disconjugacy of the saccades and of the post-saccadic drift, and the amplitude of the conjugate drift were always expressed as percentage of the saccade amplitude. This allowed comparison with other studies using different saccade size. Finally, the mean velocity (amplitude/duration) of the disconjugate post-saccadic drift during the first 80 ms after the end of saccades was also calculated.

Statistical analysis was performed by using the analysis of variance (the two-way ANOVAs) with as between subject factor the two groups (adults and children) and as within subject factor the condition (LEDs and words). Such ANOVAs were applied for saccade disconjugacy, drift disconjugacy, conjugate drift, and disconjugate drift velocity. At the individual level, the Student's t test ($p < 0.05$) was also used in order to test for eventual difference between the two conditions (LEDs versus words).

3. Results

3.1. Qualitative observations

Fig. 1A shows binocular recordings of saccades during word reading from a child and an adult, respectively. At each panel one can see the first primary saccade directed to the word, followed by one or more corrective saccades, and finally by an other saccade to the right towards to the + displayed on the screen (see Section 2). Fig. 1B shows the conjugate signal and Fig. 1C shows the disconjugate components (i.e., the difference between the two eyes). In the child, the saccades of the two eyes are not well coordinated: at the end of the saccade the disconjugacy is about two times higher than that seen in the adult. Moreover, following the saccade, post-saccadic drift is present with both a disconjugate and a conjugate component, particularly in children. Note that drifts are present even after the corrective saccades. The duration of fixation before the first corrective saccade and also the total duration needed for reading the word is longer in the child than in the adult.

Next we will present quantitatively results on latency and on binocular coordination of saccades recorded in the two different conditions for children and adults.

3.2. Quantitative observations

3.2.1. Latency

Fig. 2 shows the individual mean latency of saccades in the two conditions tested respectively for children and for adults. The range of the mean latency in children is 186–270 and 185–289 ms for saccades to LEDs and for saccades to words respectively; in adults it is 197–245 ms for saccades to LEDs and 200–240 ms for saccades to words. The group mean latency is 218 ± 10 and 224 ± 11 ms, respectively, for saccades to LEDs and to words in children, and 215 ± 6 and 223 ± 5 ms in adults. At individual level, no significant difference is observed on the mean latency values between the two conditions. The ANOVA test shows no significant effect of the type of subject (children versus adults), or of the type of condition (LEDs versus words).

Thus, latency of rightward saccades to predictable LEDs is similar to that of rightward saccades to words; moreover latency in both conditions is similar in 7 years old children and in adults.

3.2.2. Binocular coordination of saccades

Fig. 3A shows the mean amplitude of the disconjugacy of saccades (absolute values) expressed as a percentage of saccade amplitude in the two conditions (LEDs and words), respectively in children and in adults.

In children, the percentage of disconjugacy ranges from 11% to 25% for saccades to LEDs and between 9% and 25% for saccades to words. The mean percentage of disconjugacy is 18 ± 1% and 16 ± 2% in the two conditions, respectively. At the individual level no child shows a significant difference between the two conditions.

In adults, the percentage of disconjugacy is small and ranges between 5–9 and 4–8%, respectively, for saccades to LEDs and saccades to words; the mean percentage of disconjugacy is 7 ± 0.6% for saccades to LEDs and 6 ± 0.5% for saccades to words. At the individual level no adult shows a significant difference in the disconjugacy between the two conditions.

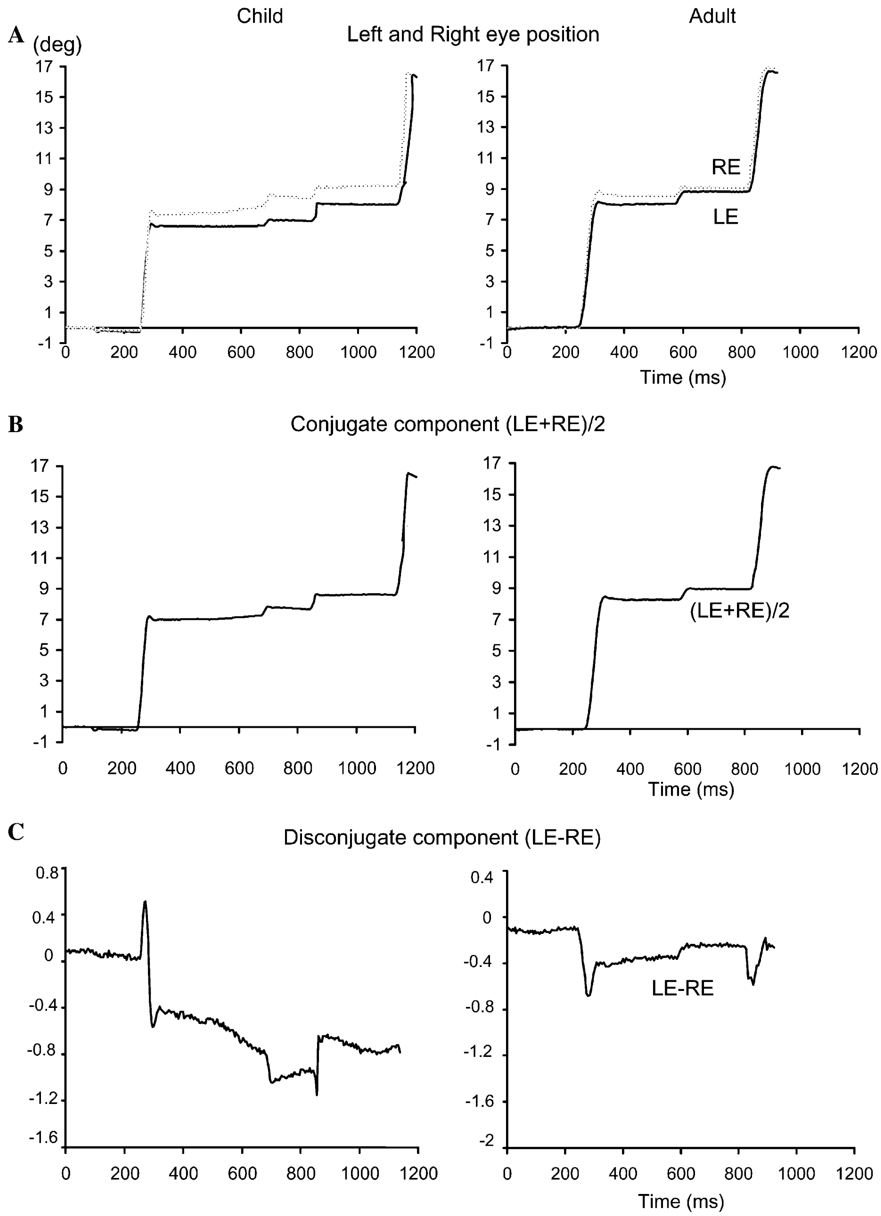

Fig. 1. Binocular recordings of saccade during reading a word from a child and an adult. (A) Individual eye position, the left eye (dark traces) and the right eye (gray traces); the word appeared at time zero. (B) Conjugate component (LE + RE)/2. (C) disconjugate component (LE − RE). Positive inflection of the signal indicates right direction, or convergent disconjugacy.

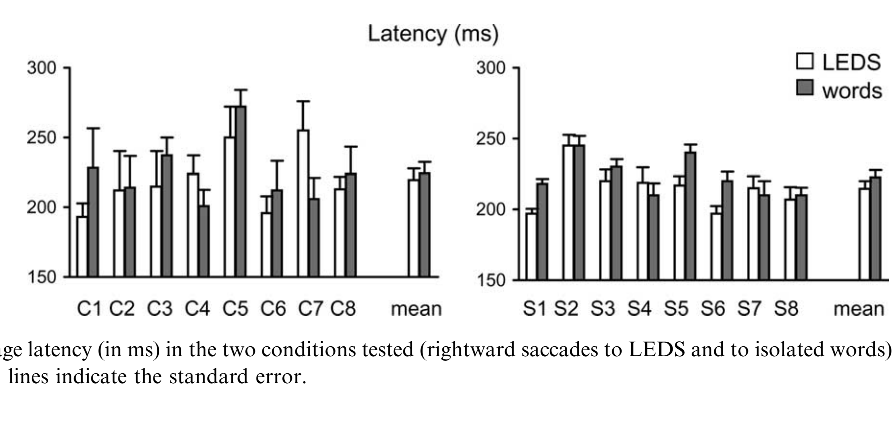

Fig. 2. Individual average latency (in ms) in the two conditions tested (rightward saccades to LEDS and to isolated words) for children (C1–C8) and adults (S1–S8). Vertical lines indicate the standard error.

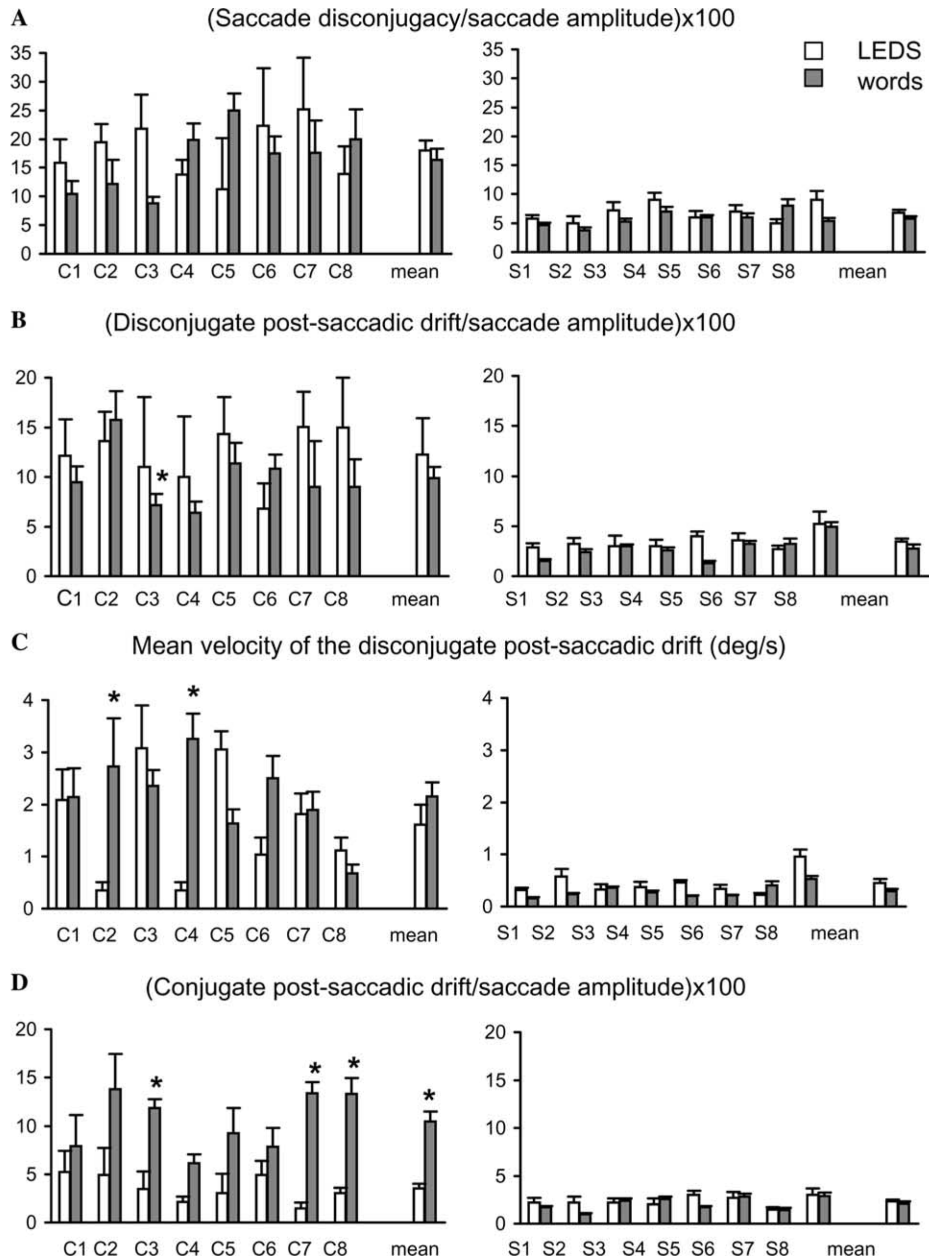

Fig. 3. Individual average disconjugacy of saccades (A), of the disconjugate post-saccadic drift (B), of the mean velocity of the disconjugate drift 80 ms after the saccade offset (C) and of conjugate drift (D) for children (C1–C8) and adults (S1–S8); values are shown for each subject in the two conditions tested: rightward saccades to LEDs and rightward saccades to isolated words. Asterisks indicate a significant difference between the two conditions. Vertical lines indicate the standard error.

The ANOVA shows a significant main effect of group ($F_{(1,14)} = 119.83$, $p < 0.0001$). There is no significant effect of the condition ($F_{(1,14)} = 0.59$, $p = 0.45$) and there is no significant interaction between group and condition ($F_{(1,14)} = 0.03$, $p = 0.86$).

In summary, children show under both conditions (saccades to LEDs and saccades to words) significantly larger disconjugacy with respect to adults; furthermore, for both children and adults the disconjugacy of saccades to LEDs is similar to that of saccades to words.

3.2.3. Disconjugate post-saccadic eye drift

Fig. 3B shows the disconjugate component of the post-saccadic drift in the two conditions for children and adults. The individual percentage of the disconjugate drift component is larger for saccades to LEDs for six of the eight children but the difference reaches significance only for child C3. The range of drift disconjugacy is 7–15 and 6–15%, for the LED and for the reading condition, respectively. The group mean percentage is 12 ± 3% and 9 ± 1%, in the two conditions respectively.

In adults the amplitude of the disconjugate post-saccadic drift is smaller, it ranges between 3% and 5% for the LED condition and 1–5% for the word condition. At the individual level, no adult shows a significant difference between the two conditions. The mean percentage of the disconjugate drift is 3.4 ± 0.3% in the LED condition and 2.7 ± 0.4% in the word condition.

The ANOVA shows a significant effect of group ($F_{(1,14)} = 87.72$, $p < 0.0001$); while there is no significant effect of the condition ($F_{(1,14)} = 2.60$, $p = 0.30$) and there is no significant interaction between group and condition ($F_{(1,14)} = 1.63$, $p = 0.22$).

In sum, the disconjugate component of the post-saccadic drift in children is similar in the two tested conditions and significantly larger from the values observed in adults.

3.2.4. Mean velocity of the disconjugate post-saccadic eye drift at 80 ms

Given the importance of the stability of fixation immediately after a saccade for efficient visual analysis and word identification, we examined further the mean velocity of the disconjugate post-saccadic drift during the first 80 ms after the saccade offset. The mean velocity of the drift for each child and each adult in the two conditions is shown in Fig. 3C. In children the mean velocity shows an idiosyncratic pattern: indeed, for three children (C2, C4, and C6) mean velocity is larger in the reading condition with respect to the LED condition, and in two of them (C2 and C4) the difference reaches significance; child C5 shows a large mean velocity in the LED condition, whereas the mean velocity in the other children is similar in the two the conditions. In children, mean velocity ranges between 0.3 to 3°/s in the LED condition and from 0.6 and 3°/s in the word condition. At the group level the mean value is 1.6 ± 0.4°/s and 2.1 ± 0.3°/s for the two conditions, respectively.

In adults the mean velocity of the drift is very small and similar in the two conditions; all individual values are smaller than 0.9°/s. The mean value is 0.4 ± 0.08°/s in the LED condition and 0.3 ± 0.04°/s in the word condition.

The ANOVA shows an effect of group ($F_{(1,14)} = 56.90$, $p < 0.0001$); the mean velocity is higher for all children at least for the word reading condition. There is no significant effect of condition ($F_{(1,14)} = 0.49$, $p = 0.49$) and there is no significant interaction between group and condition ($F_{(1,14)} = 1.55$, $p = 0.23$).

In summary, mean velocity of the disconjugate drift during the first 80 ms after the end of the saccade in children could be different in the two conditions (LEDs or words); most important, mean velocity of the drift in children is substantially higher than in adults.

3.2.5. Conjugate post-saccadic eye drift

Fig. 3D shows the conjugate component of the post-saccadic drift in the two conditions for children and adults. The amplitude of the conjugate drift of saccades to LEDs is smaller than that of saccades to words for all children and reaches significance for three of them (C3, C7, and C8). The range of the percentage of the conjugate drift is between 1% and 5%, while that for saccades to words is between 6% and 13%. The group mean percentage of conjugate drift is 3 ± 0.5% for saccades to LEDs and 10 ± 1% for saccades to words.

In adults, conjugate drift is very small and similar for the two conditions; it ranges between 1% and 3% for both saccades to LEDs and saccades to words. The mean value of the conjugate drift is similar in the two conditions (2 ± 0.2%).

The ANOVA shows a significant effect of the group ($F_{(1,14)} = 67.26$, $p < 0.0001$). Moreover, there is a significant effect of the condition ($F_{(1,14)} = 27.66$, $p < 0.0001$) and a significant interaction between group and condition ($F_{(1,14)} = 32.66$, $p < 0.0001$).

In conclusion, for all children the conjugate component of the drift tends to be larger in the word condition but it reaches significance in three children only. In contrast, the drift is smaller in the LED condition and similar to the values observed in adults.

3.2.6. Duration of fixation

Fig. 4 shows the group mean of the duration of fixation after the principal saccade and before the corrective

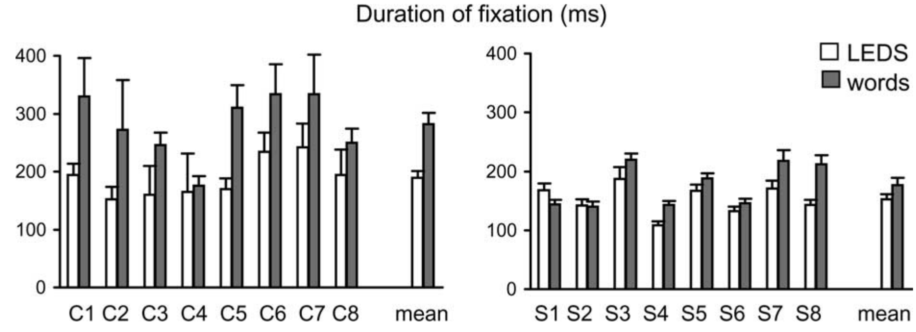

Fig. 4. Individual average duration of fixation (ms) before the corrective saccades in the two conditions for children (C1–C8) and adults (S1–S8). Vertical lines indicate standard error.

saccade in the two conditions tested respectively in children and adults. In both conditions, children have longer duration fixation compared to adults. In children, the mean duration is 189 ± 12 and 281 ± 19 ms, respectively, in LED and word conditions while in adults it is only 152 ± 13 and 176 ± 9 ms, respectively.

The ANOVA shows a significant effect of group ($F_{(1,14)} = 17.20$, $p < 0.001$). There is also a significant effect of condition ($F_{(1,14)} = 9.88$, $p < 0.007$) but there is no significant interaction between group and condition ($F_{(1,14)} = 1.92$, $p = 0.18$).

In conclusion, children show longer duration of fixation in both conditions compared to adults; moreover, duration of fixation is longer after saccades to words than after saccades to LEDs for the two groups of subjects.

4. Discussion

The main findings of this study are as follows: (i) saccade latencies are similar in children and in adults and also similar in the two conditions tested (LEDs or isolated words presented at predictable location); (ii) the disconjugacy of the saccade is significantly larger in children than in adults in agreement with the study of Yang and Kapoula (2003); moreover, disconjugacy does not depend on condition and stimulus (LEDs or words); (iii) the disconjugate component of the post-saccadic drift is significantly larger in children than in adults; the mean velocity of the disconjugate post-saccadic drift at 80 ms after the saccade offset tends to be higher in children than in adults and its value is, on overall, similar for LEDs and words. The only influence of the task is a leftward conjugate drift in children that is higher for words than for LEDs; (iiii) duration of the fixation after the saccade is longer in children than in adults; moreover, in children duration fixation is significantly longer when fixating a word than a LED. Next we will discuss the physiological significance of these findings.

4.1. Saccade latency to predictable targets

Several studies dealing with latency of saccades to unpredictable target-LEDs reported longer latency in children than in adults (Fukushima et al., 2000; Munoz et al., 1998; Yang et al., 2002). The longer saccade latency found in children with respect to adults has been attributed to underdeveloped cortical structures, particularly the frontal lobe, for which maturation, as suggested by EEG study (Anokhin, Birbaumer, Lutzenberger, Nikolaev, & Vogel, 1996) and by fMRI investigation (Luna & Sweeney, 1999) is very slow and is completed only at approximately 15 years old. In the present study the position of the target (LED or word) was predictable; we found similar latency values in children and adults. Moreover, our latency values are similar to those reported in the recent study of Vitu et al. (2004), using the same task of word reading (about 228 ms for adults). Attention skills that, as suggested by Duhamel, Colby, and Goldberg (1992) and by Wurtz, Goldberg, and Robinson (1980) involving parietal and frontal lobes, are less needed when saccading to predictable target locations. This would explain the shorter latencies observed here in children. In other oculomotor tasks such as that used by Yang et al. (2002) or during anti-saccades (see Munoz et al., 1998), the latency difference between children (<10–12 years) and adults is more evident because target unpredictability stimulates more attention and visual cortical resources that are still developing during childhood.

One could also argue that subjects learn to initiate rapidly saccades to the right side due to reading training. To explore further this possibility, we measured the latency of saccades to LEDs to the left side that were also predictable. The mean latency of leftward saccades was 223 ± 14 and 217 ± 13 ms in children and in adults, respectively; these values are not statistically different from latency values of saccades to the right. The findings are compatible with previous studies in adults (Weber & Fischer, 1995) showing that the latency distribution for saccades to the right and to the left side is nearly symmetric. Finally, the observation that latency was similar for the two conditions (LEDs and words) indicate no influence of the task on latency.

4.2. Poor binocular coordination during and after the saccades in children

This study extends the finding of Yang and Kapoula (2003) showing that the quality of binocular coordination during and after the saccades to target-LEDs at near distance is poorer in children than in adults. The novelty here is that this disconjugacy exists for both saccades to LEDs and isolated words. Indeed, under both conditions tested (saccades to LEDs and saccades to words), children show large disconjugacy of about 17% and 15% of the saccade amplitude, respectively during and after the saccade, while in adults these disconjugacy values are small (only 7% and 2%).

The results on adults contrast those from the study of Heller and Radach (1999) as they indicate that saccades remain well coordinated regardless of the type of the task (saccades to LEDs, or saccades to isolated words). Note however that in the present task adults have to read a single word and not a text as in the experiment of Heller and Radach (1999). An important question is whether our observations for single word reading are relevant for text reading in terms of requirement good binocular motor control. Single word reading and the response for the content of the word is a sub-process of the reading activity, thus our results are informative for text reading as well. Moreover, on the basis of the good stability of binocular coordination found here in adults, we doubt that reading of text is a situation provoking loose of binocular control. However, further studies of binocular control of saccades during reading text lines are needed. Finally, it could be possible that the results of Heller and Radach (1999) are due to subject recruitment given that in adults problems with vergence abnormalities are frequent. Indeed, note that in the present study, young adults were carefully selected with prior orthoptic screening excluding vergence problems.

4.3. Consequences of poor binocular coordination in children during reading

Saccades are poorly coordinated in children, consequently just at the end of the saccades the eyes possibly do not fixate the same character. Furthermore, after the saccade during the fixation the disconjugate drift is significantly higher in children than in adults, and its velocity during the first 80 ms after the saccade can reach 3°/s (see for example child C1, C2, C3, C4, and C6 in Fig. 3C). Such high drift velocity could threaten visual acuity transiently. Indeed, Westheimer and McKee (1975) reported that visual acuity degrades if the image slips on the retina with a velocity higher than 2°/s. Reduced visual acuity could slow down word reading and could explain our observation of significant longer duration of fixation in children compared to adults. We suggest that lower quality of vision caused by the large disconjugate drift delays linguistic processing. Levy-Schoen and O'Regan (1979) reported that fixation duration decreases during reading with age and reaches adult level at 11 years of age. This is also the age at which the quality of binocular coordination at near attains adult quality (Yang & Kapoula, 2003). On the other hand, Luna, Thulborn, and Munoz (2001) examined the brain activity (by fMRI) in 8–30 years old subjects during saccade tasks and they showed that the activation of cortical structures (e.g., frontal and parietal cortex) involved in eye movement control is low relative to adults and it increases during childhood and adolescence; cortical structures (left temporal and parietal cortex) involved in linguistic processing are also developing with age (Simos et al., 2001; Turkeltaub, Gareau, Flowers, Zeffiro, & Eden, 2003). Thus, the longer fixation duration could also be related to general cortical development. Most likely there is a mutual interaction between cortical development, poor binocular motor control and slow linguistic processing.

Are children reading with one eye? Recall that the children here studied have normal single vision and normal ocular alignment (see TNO score of stereoacuity). Consequently it is very unlikely that they suppress vision from one eye during reading. Nevertheless, further studies combining visual psychophysic techniques and eye movements could help and consolidate the point that the child is reading with both eyes simultaneously.

Reading with one eye could be better only for children with poor vergence control and problems with binocular vision. Stein, Richardson, and Fowler (2000) found that reading capability of dyslexic children having poor vergence control was improved by monocular occlusion. However, for normal children binocular vision is apparently still used, and as suggested by Yang and Kapoula (2003) learning adaptive mechanisms are in progress to render binocular motor control better and thus to improve the quality of binocular vision.

4.4. Leftward drift of the eyes during word fixation in children

During reading of isolated words children show larger, mostly leftward conjugate drift than when fixating LED-targets. Such leftward drift drives the eyes towards the beginning of the word. This finding is in line with the observation of Vitu (2000) comparing reading capabilities in children and in adults while reading text. Children make more frequent regressive saccades within the same word perhaps because in children the word recognition strategies are not completed developed yet. However, we can not exclude that the larger conjugate drift observed in the word than in the LED condition could simply be due to stimulus differences, particularly to the larger size of the target-word compared to the target-LED. To explore this issue further, we could use different stimuli for the reading task, such reading non-meaning words, or reading simple letters.

In conclusion, for both children and adults proprieties of binocular coordination during and after saccades are stable and do not change according to the type of task. Most important, this study shows poor binocular control of saccades in children, substantial disconjugate drift during fixation and increased leftward drift when reading words. All these imperfections could contribute to slowness of reading, as shown here by the longer fixation duration on words.

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