

Latency of saccades and vergence eye movements in dyslexic children

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Abstract The goal of this study was to explore the latency of eye movements both in direction and in depth in dyslexic children. Sixteen dyslexic (mean age: 11.12 ± 1.08 years) and 14 non-dyslexic children (mean age: 12.08 ± 0.99 years) were tested. Two different paradigms (simultaneous and gap) were used to elicit pure saccades at far and at near distance, pure vergence (convergence and divergence) and combined saccade–vergence movements. Horizontal eye movements from both eyes were recorded simultaneously by a photoelectric device (Oculometer, Dr. Bouis). The mean latency of saccades at far distance (pure or combined) is significantly longer in dyslexics, regardless of the paradigm used. For both dyslexic and non-dyslexic children, latencies in the gap paradigm are shorter. Moreover, the occurrence of express latencies for divergence (pure or combined) is significantly higher for dyslexics. Difficulties in both voluntary and reflexive control shifts of visual attention from near to far distance in dyslexics could be at the origin of these findings.

Keywords Saccades · Vergence · Combined movements · Dyslexia · Children · Gap effect

Introduction

The latency of an eye movement is the period between the appearance of a new stimulus and the starting of the eye movement. During this time interval, several processes occur such as the shift of visual attention to the new stimulus, the disengagement of oculomotor fixation and the computation of the new parameters (see Fischer and Ramsperger 1984; Findlay and Walker 1999); these processes involve different cortical and sub-cortical areas (for a review, see Leigh and Zee 2006).

The latency of saccades in children has been extensively studied (e.g., Ross et al. 1994; Munoz et al. 1998; Fukushima et al. 2000; Klein and Foerster 2001). In the last few years, our group extended these studies to different types of eye movements in natural space: saccades at far and at near distance, convergence, divergence and combined saccade–vergence movements (Yang et al. 2002; Bucci et al. 2005). Yang et al. (2002) reported that in children as well as in adults, the latency is different for the different types of eye movements: the latency of saccades at far distance is longer than that of saccades at near distance; the latency of convergence is longer than that of divergence; the latencies of the saccade and the vergence components of combined movements are longer than those of the corresponding pure movements. The authors suggested the existence of specific mechanisms for triggering saccade, convergence and divergence movements; moreover, attention, sensory and oculomotor factors could be involved differently for the initiation of saccades at far versus at near distance.

It is well known that the latency of saccades depends on the fixation task: it is shorter in the gap paradigm (first introduced by Saslow 1967) in which the target appears after a gap period following the offset of the fixation point. Saccade latencies in this task are in general shorter than

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those in the simultaneous paradigm. The mechanism by which this paradigm decreases saccade latencies remains controversial. The latency decrease generally occurs in slow regular (180–400 ms) and fast regular (120–180 ms) latencies, as was found by Kingstone and Klein (1993), Reuter-Lorenz et al. (1991), Tam and Stelmach (1993) and Wenban-Smith and Findlay (1991). On the other hand, “express” saccades (with latencies between 80 and 120 ms) occur more frequently in the gap paradigm and may form a distinct population as observed by Fischer and Ramsperger (1984). Note, however, that the emergence of express saccades in humans is subject-dependent and thus is not systematically observed (Reuter-Lorenz et al. 1991; Wenban-Smith and Findlay 1991). Decrease of saccade latencies could be due to facilitation of the disengagement of fixation and attention by the offset of the fixation point (Reuter-Lorenz et al. 1991; Kingstone and Klein 1993). This idea is integrated in the model of Findlay and Walker (1999), who suggested that there is a decrease in fixation activity during the stimulus offset that promotes rapid saccade initiation.

Bucci et al. (2005) studied the gap effect in 7-year-old children and reported frequent express latencies (80–120 ms) only for saccades at near distance and for divergence, while for saccades at far and convergence such latencies were rare. Interestingly, for these children, divergence showed a high occurrence of anticipatory latencies similar to that reported for adults by Coubarde et al. (2004). All these findings suggested that the initiation of saccades at near and of divergence is more reflexive, while that of saccades at far and of convergence is more voluntary. This idea is in line with the study of Nakayama and Mackeben (1989) describing the presence of a sustained and a transient component of visual attention in the target perception.

The present study examines the gap effect in dyslexic children. Prior studies exploring the latency of saccades in dyslexics only tested at a single distance: at far (1 m) or at intermediate (57 cm) viewing distance. We will now present their findings briefly. Dossetor and Papaioannou (1975) and Pirozzolo (1979) showed that the latency of saccades was longer in dyslexics than in non-dyslexics. In contrast, Adler-Grinberg and Stark (1978) and Black et al. (1984) found no latency difference between dyslexics and non-dyslexic subjects. Using different saccade paradigms (gap and overlap, i.e., temporal overlapping of the fixation and of the target), Fischer and Weber (1990) studied the latency distribution of saccades at an intermediate viewing distance (57 cm); 15 dyslexic children (aged 9–11 years) and 5 dyslexic teenagers (aged 15–17 years) were compared with 9 non-dyslexic children and 8 non-dyslexic teenagers of similar age. The authors reported longer mean latencies and larger standard deviation for dyslexics. Biscaldi et al. (1994) studied both dyslexic children and teenagers and

reported shorter mean latencies and more express saccades with respect to control subjects; this was the case for both gap and overlap tasks. Such subjects were called “express makers”. According to these authors, abnormal function of the fixation system, which is most likely modulated by attentional mechanisms, could be responsible for the generation of a large number of express saccades in dyslexics. In other words, the engagement of attention to the fixation point and its inhibitory effect on the saccade system could be deficient in dyslexics.

Recently, Bednarek et al. (2006) compared the latency of saccades at 50 cm viewing distance in 10-year-old dyslexics and in age-matched controls. They reported significantly reduced saccade latencies in dyslexics compared to the control group; they did not report express latencies in dyslexics, but a high occurrence of anticipatory latencies. When the attention shift was facilitated by a cue (see paradigm introduced by Posner 1980), saccade latencies were no different between the two groups of children. The authors compared their findings with those of earlier studies (Fischer and Weber 1990 and Biscaldi et al. 1994) and also proposed a deficit of the attentional system in dyslexics. Bednarek et al. shared the hypothesis of Facoetti et al. (2003) according to which dyslexics may have difficulty in narrowing the focus of attention.

All prior studies, dealing with saccades only, showed longer latency or shorter latency in dyslexics and the effect of the viewing distance was not clearly considered. Note that the latency of vergence and of combined movements in dyslexics has never been studied. The goal of the present study is to examine further the latency of saccades at far and at near distance, of convergence and divergence, and of combined saccade–vergence movements, in a group of dyslexic children and in a group of age-matched control children. Two different paradigms, simultaneous and gap are used; the occurrence of express latencies for each type of movements is also examined.

Materials and methods

Subjects

A total of 16 dyslexic children participated in the study. Dyslexic children were recruited from the pediatric hospital where they are referred for a complete evaluation of their dyslexia state with an extensive examination including neurological/psychological and phonological capabilities. For each child, the time of reading a text, its comprehension and the capacity of reading word/pseudowords was evaluated by using the L2MA battery (Chevrie-Muller et al. 1997). This is the standard test developed by the Applied Psychology Centre of Paris and is used everywhere in

France. Inclusion criteria were: scores on this test beyond two standard deviations and a normal mean intelligence quotient (IQ, evaluated with WISC III), i.e., between 85 and 115. The mean age of the dyslexic children was 11.12 ± 1.08 years, the mean IQ was 104 ± 7 and the mean reading age was 8.4 ± 1.2 years. A carefully selected age-matched control group (mean age: 12.08 ± 0.99 years) of 14 non-dyslexic children was selected. These children had to satisfy the following criteria: no known neurological or psychiatric abnormalities, no history of reading difficulty and no visual stress or any difficulties with near vision. IQ and reading measurements were not available for these children, but they were selected by the director of the school on the basis of their school performances; their scores in French (reading, understanding, orthography), mathematic and foreign languages were all beyond the mean score of the class. Recruitment of controls, based on school performance alone, has been used by others (Stein et al. 1987; Stein et al. 1988; Riddell et al. 1990).

Both non-dyslexic and dyslexic children underwent an ophthalmologic examination accompanied by orthoptic evaluation of their visual function (see Table 1); their results were compared to those from a large population of normal children. All children had normal binocular vision (60 s of arc or better), which was evaluated with the TNO random dot test (Netherlands Organisation of Applied Scientific Research Test of stereoacuity). Visual acuity was normal ($\geq 20/25$) for all children. The near point of convergence was abnormal (between 8 and 12 cm) in 31% of dyslexics, while it was normal (< 7 cm) for all non-dyslexic children. Moreover, an orthoptic evaluation of vergence fusion capability using prisms and Maddox rod was done at far and at near distance: for dyslexics the divergence amplitude was limited in 25 and 81% of the cases, respectively, at far and at near distance, while for non-dyslexic children, limited divergence was observed only at near distance in 36% of the cases. Convergence amplitude was abnormal in 31 and 12% of dyslexics (at far and near distance, respectively) and in the normal range for all but one non-dyslexic child at far distance (subject C8). Phoria (i.e., latent deviation of one eye when the other eye is covered, using the cover–uncover test) was abnormal in 19% of dyslexic children at far as well as at near distance; while the phoria was in normal range for all but one non-dyslexic child at far (subject C2) and at near distance (subject C6). In sum, orthoptic evaluation showed a tendency of poor vergence, particularly divergence, in dyslexic children in line with another study on a larger population of dyslexic and non-dyslexic children (Kapoula et al. 2007).

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 the children's parents after the procedure of the experiment was explained.

Oculomotor paradigm

Spatial arrangement

The spatial arrangement is shown in Fig. 1a. A computer controlled the LED display. LEDs were placed in two iso-vergence circles at different distances (at 20 and 150 cm) from the child. Three LEDs were placed on the circle closest to the child, one at the center and the others at $\pm 20^\circ$. The required mean vergence angle for fixating any of these three LEDs on the near circle was 17° . Five LEDs were placed on the circle most distant from the child: one at the center, two at $\pm 10^\circ$ and two at $\pm 20^\circ$; fixation to any of these LEDs required a vergence angle of 2.3° .

Three types of eye movements were elicited: pure saccades rightward or leftward, pure vergence along the median plane (convergence or divergence) and combined movements. At the beginning of each trial, a fixation LED was lit up at the center of one of the two circles (far or close). When the target LED was on the same circle, it called for a pure saccade (rightward or leftward) at far (150 cm) or at close (20 cm) viewing distance. When the target LED was on the center of the other circle, it called for a pure vergence eye movement along the median plane (convergence or divergence), and when it was lateral and on the other circle, the required eye movement was a combined saccade and vergence eye movement. The required saccade amplitude was always 20° and the required vergence change along the median plane (for pure vergence) or along lateral axes (for combined movements) was 15° .

Temporal arrangement

Two temporal paradigms (gap and simultaneous) were used (see Fig. 1b). With the gap paradigm at the beginning of each trial, a fixation LED was lit up at the center of one of the circles, which remained lit for 2.5 s. Then it was turned off, and a target LED appeared 200 ms later (gap period). The target LED appeared for 1.5 s. A delay of 0.5 s was introduced before the next trial. This type of paradigm was used to favor express movements.

With the simultaneous paradigm, after a 2.5-s fixation period, the central LED was switched off and simultaneously the target LED was switched on for 1.5 s. A delay of 0.5 s was introduced before the next trial.

Procedure

Children were in a dark room, seated in a chair with the head stabilized by a forehead and chin support. He/she

Table 1 Clinical characteristics of dyslexic children (a), non-dyslexic children (b) tested and normal subjects from other studies (Ygge et al. 1993; von Noorden and Campos 2002) (c)

Subject (years)	Corrected Visual acuity	Stereo acuity (TNO)	NPC (cm)	Hetero phoria (pD)	Diver (pD)	Conver (pD)
<i>(a) Dyslexic children</i>						
D1 (10)	LE: 20/20	60"	5	Far 2 X	Far 8	Far 25
	RE: 20/20			Near 4 X	Near 12	Near 40
D2 (10)	LE: 20/20	60"	8	Far ortho	Far 6	Far 16
	RE: 20/20			Near ortho	Near 10	Near 30
D3 (10)	LE: 20/20	60"	10	Far ortho	Far 4	Far 2
	RE: 20/20			Near ortho	Near 10	Near 20
D4 (10)	LE: 20/20	60"	12	Far 2 X	Far 2	Far 6
	RE: 20/20			Near 6 X	Near 6	Near 10
D5 (10)	LE: 20/20	60"	5	Far ortho	Far 4	Far 10
	RE: 20/25			Near ortho	Near 6	Near 30
D6 (10)	LE: 20/20	60"	5	Far ortho	Far 2	Far 25
	RE: 20/20			Near ortho	Near 8	Near 25
D7 (11)	LE: 20/20	60"	5	Far 4 E	Far 2	Far 35
	RE: 20/20			Near 1 E	Near 10	Near 40
D8 (11)	LE: 20/20	60"	5	Far 2 E	Far 4	Far 25
	RE: 20/20			Near 6 E	Near 6	Near 40
D9 (11)	LE: 20/20	60"	10	Far ortho	Far 2	Far 4
	RE: 20/20			Near ortho	Near 14	Near 16
D10 (11)	LE: 20/20	60"	10	Far ortho	Far 4	Far 16
	RE: 20/20			Near ortho	Near 12	Near 35
D11 (12)	LE: 20/25	30"	5	Far ortho	Far 8	Far 25
	RE: 20/25			Near ortho	Near 20	Near 30
D12 (12)	LE: 20/20	60"	5	Far ortho	Far 4	Far 6
	RE: 20/20			Near ortho	Near 14	Near 16
D13 (12)	LE: 20/20	60"	5	Far ortho	Far 4	Far 20
	RE: 20/20			Near 4 X	Near 12	Near 40
D14 (12)	LE: 20/20	60"	7	Far ortho	Far 8	Far 25
	RE: 20/20			Near 4 E	Near 12	Near 40
D15 (13)	LE: 20/20	60"	5	Far 3 X	Far 14	Far 40
	RE: 20/20			Near 3 X	Near 17	Near 40
D16 (13)	LE: 20/20	60"	7	Far 3 E	Far 8	Far 10
	RE: 20/20			Near 3 X	Near 14	Near 14
<i>(b) Non-dyslexic children</i>						
C1 (11)	LE: 20/25	60"	5	Far 5 X	Far 8	Far 12
	RE: 20/20			Near ortho	Near 12	Near 40
C2 (11)	LE: 20/20	30"	7	Far 4 E	Far 4	Far 16
	RE: 20/20			Near 3 X	Near 17	Near 16
C3 (11)	LE: 20/20	30"	6	Far 1 E	Far 6	Far 16
	RE: 20/20			Near ortho	Near 8	Near 20
C4 (11)	LE: 20/20	60"	3	Far ortho	Far 4	Far 16
	RE: 20/20			Near 3 X	Near 18	Near 25
C5 (11)	LE: 20/20	60"	6	Far ortho	Far 6	Far 14
	RE: 20/20			Near 2 X	Near 20	Near 30
C6 (12)	LE: 20/20	60"	3	Far 1 E	Far 4	Far 12
	RE: 20/25			Near 3 E	Near 8	Near 20
C7 (12)	LE: 20/20	30"	3	Far 1 E	Far 6	Far 14
	RE: 20/20			Near ortho	Near 4	Near 15

Table 1 continued

Subject (years)	Corrected Visual acuity	Stereo acuity (TNO)	NPC (cm)	Hetero phoria (pD)	Diver (pD)	Conver (pD)
C8 (12)	LE: 20/25	60"	5	Far ortho	Far 4	Far 6
	RE: 20/20			Near 3 X	Near 17	Near 25
C9 (12)	LE: 20/20	60"	4	Far ortho	Far 4	Far 14
	RE: 20/20			Near 4 X	Near 14	Near 15
C10 (13)	LE: 20/20	15"	4	Far ortho	Far 4	Far 16
	RE: 20/20			Near ortho	Near 17	Near 25
C11 (13)	LE: 20/20	60"	6	Far ortho	Far 4	Far 16
	RE: 20/20			Near ortho	Near 17	Near 20
C12 (13)	LE: 20/25	30"	6	Far 3 X	Far 6	Far 20
	RE: 20/25			Near 6 X	Near 8	Near 40
C13 (13)	LE: 20/20	60"	6	Far ortho	Far 8	Far 16
	RE: 20/20			Near 3 X	Near 22	Near 30
C14 (14)	LE: 20/20	60"	4	Far 3 X	Far 10	Far 20
	RE: 20/20			Near 6 X	Near 20	Near 30
				<i>(c) Normal subjects from other studies</i>		
		60"	>7	Far 3 X-ortho	Far 4–10	Far 11–17
				Near 6 X-ortho	Near 17–25	Near 15–27

Bold characters indicate abnormal orthoptic values relative to references shown in (c)

NPC near point of convergence (in cm), heterophoria and vergence fusion amplitude (in prism diopters), measured clinically

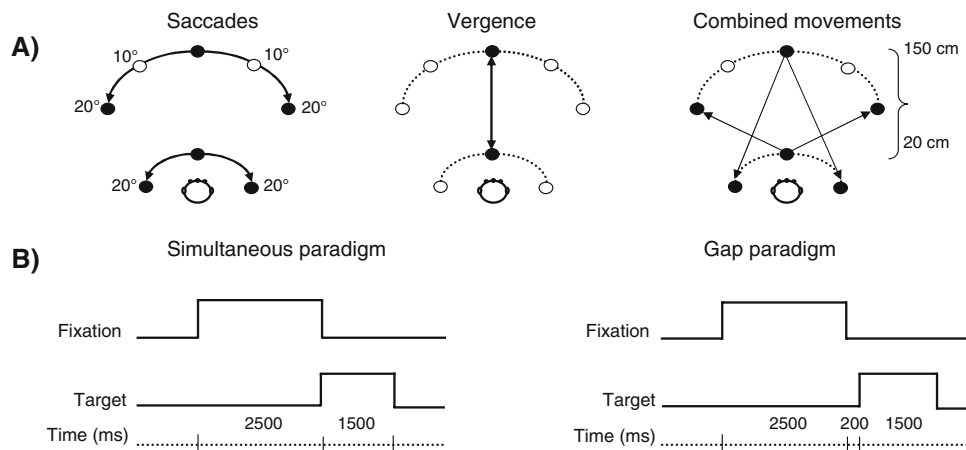


Fig. 1 Spatial arrangement (a); different types of eye movements elicited depending on the combination of the central fixation target and the target LEDs: pure saccades of 20° at far (150 cm) and at near (20 cm) distance, pure vergence (convergence and divergence) along the medi-

an plane and combined saccade—vergence movements. Pure saccades of 10° at far distance were stimulated in the calibration task only. Temporal arrangement (b); schematic diagram of the temporal arrangement used in the two different paradigms (simultaneous and gap)

faced a horizontal surface at eye level where the LEDs were positioned; viewing was binocular. Each child performed four blocks of 36 trials each, two with the gap and two with the simultaneous paradigm; each block was separated by a few minutes of rest.

In each block, the three types of trials (saccades, vergence and combined saccade—vergence movements) were interleaved randomly. Each block contained six saccades at far viewing distance (three rightwards and three leftwards), six saccades at close viewing distance (three rightwards and three leftwards), six pure convergence (along the median plane), six pure divergence, six saccades combined with divergence and six saccades combined with convergence.

Blocks of gap and of simultaneous paradigm were randomly ordered. Calibration was done before and after each block.

Calibration task

Children performed a sequence of saccades to the target LED, moving from 0° to ±10° or 0° to ±20° on the far isovergence circle. During each of these trials, the target LED remained lit at each location for 2 s. Children were instructed to fixate the target LED as accurately as possible; the duration of the target LED presentation was sufficiently long to allow accurate and stable fixation.

The calibration factors were extracted from these recordings.

Eye movement recordings

Data collection was controlled via REX software (provided online at <http://www.tchain.com> by Timothy C. Hain, Northwestern University Medical School, Chicago, III). Horizontal eye movements from both eyes were recorded simultaneously with a photoelectric device, Oculometer Dr. Bouis (Karlsruhe, Germany). This system has a resolution of 2 min of arc and a linear range of 20°. There is no obstruction of the visual field with this recording system (see Bach et al. 1983). Eye-position signals were lowpass filtered with a cutoff frequency of 200 Hz and digitized with a 12-bit analog-to-digital converter; each channel was sampled at 500 Hz.

Data analysis

Calibration factors for each eye were extracted from the eye positions during the calibration procedure; a polynomial function with five parameters 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 disconjugate vergence signal (left eye – right eye). Markers were placed automatically at different points of the eye-position signals. For each type of eye movements (saccade, vergence and combined movements), we measured the latency, that is the time between the onset of the target LED and the beginning of the movement in millisecond. For combined movement, the latency was measured for each component (saccade and vergence).

The onset of the conjugate saccadic component was defined as the time when the eye velocity reached 5% of the saccadic peak velocity. The onset of the vergence signals (for pure vergence movements and for the vergence component of combined movements) was defined as the time point when the eye velocity exceeded 5°/s. The upper limit of latency was set to 700 ms as used in our previous study (Bucci et al. 2005). Anticipatory movements, those with latencies shorter than 80 ms, were not included for calculating the mean values. Express latency for vergence (pure and combined with saccades) was defined as having the same latency as express saccades (between 80 and 120 ms, arbitrary range defined by Fischer and Ramsperger 1984); this is consistent with other studies (Bucci et al. 2005; Coubarde et al. 2004; Takagi et al. 1995).

We performed a non-parametric analysis with the Mann–Whitney's *U*-test to compare the two groups of children (dyslexics and non-dyslexics). At the individual level, the Wilcoxon's test was used in order to test for difference between the two paradigms (gap and simultaneous).

Finally, the Fisher's exact probability test (2×2 contingency table) was employed to test whether the occurrence of express movements, for the gap and for the simultaneous paradigm, was different between the two populations (dyslexics and non-dyslexics).

Results

Mean latencies of eye movements: difference between non-dyslexic and dyslexic children

Figure 2 shows the group mean latency values for each type of eye movement for both groups of children, in the simultaneous and in the gap paradigm. For all types of eye movements recorded and for both paradigms, the mean latencies of dyslexics are longer than those of non-dyslexics. However, in a few cases only such lengthening reaches statistical significance. In the simultaneous paradigm, the mean latency of dyslexics is significantly longer for saccades at far distance ($Z = 2.13$, $P < 0.03$) and for the saccade components of movements combined with convergence and divergence (respectively, $Z = 2.12$, $P < 0.02$ and $Z = 2.18$, $P < 0.02$). In the gap paradigm, the mean latency is significantly longer for saccades at far distance ($Z = 2.16$, $P < 0.03$) and for the saccade component of movements combined with convergence ($Z = 2.46$, $P < 0.01$).

Next, we will examine in more detail the latency difference for the two groups of children in the two paradigms used and the occurrence of express movements.

Saccades at far and at near distance

For both groups of children, the mean latency of saccades at far and at near distance is shorter in the gap (mean 199 ± 7 and 236 ± 17 ms for saccades at far and 165 ± 7 and 207 ± 13 ms for saccades at near, respectively, for non-dyslexics and dyslexics) than in the simultaneous paradigm (mean 236 ± 6 and 280 ± 15 ms for saccades at far and 193 ± 7 and 215 ± 11 ms for saccades at near, respectively, for non-dyslexics and dyslexics). The decrease of the latency in the gap paradigm is statistically significant ($Z = 4.63$, $P < 0.001$ and $Z = 3.42$, $P < 0.006$ for saccades at far distance; $Z = 2.90$, $P < 0.003$ and $Z = 2.54$, $P < 0.01$ for saccades at near distance, respectively, for non-dyslexics and dyslexics). Is the short latency reported in the gap paradigm due to a higher rate of express saccades? For both populations, the express saccades are significantly more frequent in the gap than in the simultaneous paradigm (for non-dyslexics: $P < 0.04$ and $P < 0.003$, respectively, for saccades at far and at near distance; and for dyslexics $P < 0.04$ and $P < 0.003$, respectively, for saccades at far and at near distance).

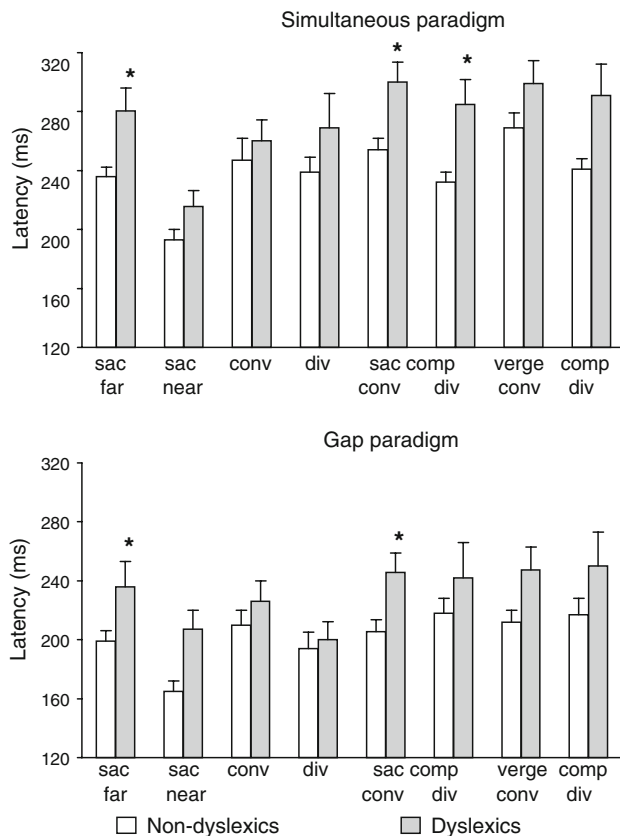


Fig. 2 Mean latency of different types of eye movements in the simultaneous and gap paradigm for non-dyslexic (white bars) and dyslexic (gray bars) children. Vertical lines indicate standard error. Latency values significantly different between the two groups of children are marked by asterisks (Mann–Whitney’s *U*-test was applied)

Convergence and divergence

For both non-dyslexics and dyslexics, the latencies of convergence and divergence in the gap paradigm (mean 210 ± 10 and 226 ± 14 ms for convergence and 194 ± 11 and 200 ± 12 ms for divergence, respectively, for non-dyslexics and dyslexics) are significantly shorter than in the simultaneous paradigm (mean 247 ± 15 and 260 ± 14 ms for convergence and 239 ± 10 and 269 ± 23 ms for divergence, respectively, for non-dyslexics and dyslexics; $Z = 2.88$, $P < 0.003$ and $Z = 3.89$, $P < 0.001$ for convergence; $Z = 3.16$, $P < 0.001$ and $Z = 5.42$, $P < 0.001$ for divergence, respectively, for non-dyslexics and dyslexics). For non-dyslexics, the occurrence of express vergences (convergence and divergence) is not significantly different between the two paradigms; for dyslexic children the occurrence of express convergence is not increased by the gap paradigm, while the occurrence of express divergence is significantly increased in the gap paradigm ($P < 0.003$).

Combined movements

In the gap paradigm, the mean latency decreases for saccades combined with convergence as well as for saccades combined with divergence for both groups of children (mean of saccades combined with convergence 205 ± 8 and 246 ± 13 ms in the gap paradigm and 254 ± 8 and 300 ± 13 ms in the simultaneous paradigm, respectively, for non-dyslexics and dyslexics; while the mean latency for saccades combined with divergence is 218 ± 10 and 242 ± 24 ms in the gap paradigm and 232 ± 7 and 285 ± 17 ms in the simultaneous paradigm, respectively, for non-dyslexics and dyslexics). Such decrease is statistically significant ($Z = 5.13$, $P < 0.001$ and $Z = 4.50$, $P < 0.001$ for saccades combined with convergence; $Z = 2.10$, $P < 0.05$ and $Z = 4.39$, $P < 0.001$ for saccades combined with divergence, respectively, for non-dyslexics and dyslexics).

The gap increases the occurrence of express movements for both non-dyslexic and dyslexic children; however, their increase is statistically significant only in dyslexic children ($P < 0.05$ for saccades combined with convergence, and $P < 0.007$ for saccades combined with divergence).

The mean latency of the vergence components of combined movements is also significantly shorter in the gap paradigm (mean 212 ± 8 and 247 ± 15 ms for the convergence component and 217 ± 11 and 250 ± 23 ms for the divergence component, respectively, for non-dyslexics and dyslexics) than in the simultaneous paradigm (mean 269 ± 10 and 298 ± 16 ms for the convergence component and 241 ± 7 and 291 ± 21 ms for the divergence component, respectively, for non-dyslexics and dyslexics). The decrease is statistically significant for both types of eye movements ($Z = 4.64$, $P < 0.003$ and $Z = 3.86$, $P < 0.001$ for the convergence component; $Z = 2.73$, $P < 0.006$ and $Z = 3.10$, $P < 0.001$ for the divergence component, respectively, for non-dyslexics and dyslexics).

The occurrence of express movements for the convergence component of combined movements does not significantly increase in the gap paradigm for non-dyslexics or for dyslexics. However, the occurrence of express movements for the divergence component is significantly higher in the gap paradigm with respect to the simultaneous paradigm for both non-dyslexics ($P < 0.04$) and dyslexic children ($P < 0.01$).

In conclusion, for both groups of children (non-dyslexics and dyslexics), the gap paradigm decreases significantly the mean latencies of all horizontal eye movements in the natural environment.

Next, we will examine further the occurrence of express eye movements in the simultaneous and in the gap paradigm for both groups of children tested.

Table 2 Percentage of express movements recorded in the simultaneous and in the gap paradigm for each non-dyslexic children (a) and dyslexic children (b)

	Pure movements								Combined movements							
	Sacc far		Sac near		Conv		Div		Sac comp				Vergence comp			
									Conv		Div		Conv		Div	
	S	G	S	G	S	G	S	G	S	G	S	G	S	G	S	G
<i>(a) Non-dyslexic children</i>																
C1																20
C2																50
C3																67
C4		14		12												14
C5																20
C6																50
C7		12														25
C8																25
C9		12		57												75
C10		14														
C11																40
C12		25														28
C13																17
C14																20
Mean		6		5												34
SE		2		4												8
<i>(b) Dyslexic children</i>																
D1																14
D2																22
D3																12
D4																20
D5																43
D6																28
D7																11
D8																27
D9																14
D10																11
D11		33		17												30
D12	9	40		8												9
D13		17														25
D14		36														70
D15																22
D16																10
Mean	1	12		2												15
SE		4		1												4

Bold characters indicate the percentage of express movements statistically different between the two groups of children (Mann–Whitney's *U*-test)

Express eye movements

Table 2 shows the percentage of express movements reported in the simultaneous and in the gap paradigm for each non-dyslexic and dyslexic child examined. In the simultaneous paradigm, one can observe at the individual level that, for all but one non-dyslexic child (C6), express movements are quite rare. In contrast, the occurrence of

express movements has a tendency to increase in the gap paradigm for the majority of the children.

Dyslexic children make few express movements in the simultaneous paradigm: one child only (D12) has a tendency to make up to 25% of express movements. In contrast, the frequency of express movements increases with the gap paradigm (between 11 and 75%) for the majority of the children.

Table 3 Percentage of anticipatory movements recorded in the simultaneous and in the gap paradigm for two groups of children

	Saccades		Sac comp		Verg comp		
	Far	Near	Con	Div	Con	Div	
<i>Simultaneous paradigm</i>							
Non-Dyslexics							1 left eye
Dyslexics	2		1	1		1	
<i>Gap paradigm</i>							
Non-Dyslexics	5	2	2	26	8	5	2 13
Dyslexics	14	18	5	15	2	5	2 5

Bold characters indicate the percentage of anticipatory movements statistically different between the two groups of children (Mann–Whitney’s *U*-test)

An interesting observation is that express latencies in dyslexics occur for many types of eye movements, while for non-dyslexics such latencies occur for fewer subtypes of eye movements (see Table 2). The Fisher exact probability test (2×2 contingency table) shows a significantly higher frequency of express movements in the gap paradigm for dyslexics with respect to non-dyslexics ($\chi^2 = 5.85$, $P < 0.01$). In contrast, in the simultaneous paradigm, the occurrence of express movements is not statistically different in the two groups of children ($\chi^2 = 2.41$, $P = 0.12$).

Frequency of anticipatory movements

The percentage of anticipatory movements for the two paradigms is shown in Table 3. In the simultaneous paradigm, anticipatory movements are rare in both non-dyslexic and dyslexic children; in contrast, anticipatory latencies occur more frequently in the gap paradigm. For non-dyslexics, anticipatory divergence, pure or combined, occurs in 26 and 13%, respectively; for the other types of eye movements, anticipatory latencies are less frequent (ranging between 2 and 8%). Dyslexics show frequent anticipatory latencies for saccades at far and at near distance and for pure divergence (14, 18 and 15%, respectively); for the other types of eye movements, anticipatory latencies are less frequent ($\leq 5\%$).

Discussion

The main findings of this study are as follows: (1) The mean latency of all eye movements tends to be longer in dyslexic children than in age-matched non-dyslexic children; the difference is significant for saccades at far distance (pure and combined) for both paradigms used. (2) For both non-dyslexic and dyslexic children, the gap paradigm reduces the mean latency of all types of eye movements

significantly. (3) The occurrence of anticipatory and express latencies is rare in the simultaneous paradigm for non-dyslexic and dyslexic children; in contrast, in the gap paradigm, anticipatory and express latencies are significantly more frequent. (4) For dyslexics, express latencies occur for a larger variety of eye movements, particularly for divergence (pure or combined), while for non-dyslexics such latencies occur mostly for saccades at near.

Increased saccade latency in dyslexic children

Previous studies from our group dealing with latency of saccades at different viewing distance in normal children (Yang et al. 2002; Bucci et al. 2005), as well as in children with vertigo (Bucci et al. 2004) and in children with strabismus (Bucci et al. 2006), showed that saccades at far distance naturally have a longer latency with respect to saccades at near distance; the same difference occurs for adults and aged subjects. Multiple mechanisms could explain the longer latency at far distance: sensory, oculomotor and attentional (see Yang et al. 2002). It is likely that initiating a saccade at a far distance would require more involvement of parietal–frontal pathways believed to be activated for voluntary saccade triggering (Pierrot-Deseilligny et al. 1995, 2002). The finding of significantly longer latencies for saccades (pure and combined) starting from far distance suggests that dyslexic children may have problems with the initiation of more voluntary eye movements.

In summary, our results allow us to reconcile the contradictory findings regarding eye movement latency in dyslexics reported in the section “Introduction” (e.g., Dossetor and Papaioannou 1975 and Bednarek et al. 2006) given that the distance at which a saccade is made seems to influence its latency. In other words, the different latency values found in dyslexics in the above-cited studies could be due to the different viewing distance used (1 m versus 50 cm). Furthermore, the apparently paradoxical finding of the presence of both increased latencies and decreased latencies (due to the high occurrence of express movements) observed in dyslexics can be reconciled to the fact that regular latencies and express latencies are believed to correspond to different mechanisms or modes of saccade initiation (voluntary versus reflexive saccades, e.g., Pierrot-Deseilligny et al. 1995). Indeed, these authors suggested that several cortical areas (e.g., posterior parietal cortex, frontal cortex) are activated for triggering voluntary eye movements; in contrast, for triggering express movements the visual information from the occipital cortex is sent directly to the brainstem. Moreover, Isa and Kobayashi (2004) made the hypothesis according to which in the superior colliculus occurs the switching between a long, cortical circuit (to trigger voluntary movements) or a short, brain-

stem circuit (for reflexive eye movements). Most likely, for dyslexics, the visual attention has an important role for switching between these two modes of eye movements initiation.

Gap effect in dyslexics

It is well known that the gap paradigm has a double effect: the decrease of mean eye movement latencies and the emergence of express movements (Saslow 1967; Fischer and Ramsperger 1984). This study shows that the decrease of the mean latency due to the gap paradigm is similar in dyslexics to the one observed in non-dyslexics. We also show that the decrease occurs for all types of eye movements in the natural space examined (saccades at far and at near distance, convergence, divergence and combined saccade–vergence movements).

For convergence, express latencies are rare for both groups of subjects; this is in agreement with previous studies in normal children (Bucci et al. 2005) as well as in normal adults (Coubard et al. 2004). Similarly, the finding of high rates of anticipatory and express latency for divergence in children is in line with the above-cited studies.

Fischer and Breitmeyer (1987) advanced the hypothesis according to which the state of the visual attention “engaged” or “disengaged” at the time of the onset of the saccade target could be responsible of the triggering of an express or a voluntary saccade. In other words, if the visual attention is “disengaged”, express saccades occur. On the contrary, if visual attention is already “engaged” when the command to make a saccade is given, saccade latency is longer because of the time needed to switch attention from an “engaged” state to a “disengaged” state. Note, however, that others researchers (Kingstone and Klein 1993; Walker et al. 1995) did not share this hypothesis because their findings showed the importance of oculomotor disengagement and a limited role of attention in the gap effect. Thus, the mechanisms underlying the occurrence of express saccades are still controversial. Recently, Pratt et al. (2006) examined further the role of attention in the gap task; they introduced a new paradigm in which the subject had to saccade to a target under a gap condition while attending to a second peripheral target that was always present. They reported longer latencies relative to the standard gap condition when attention and fixation were coupled. Pratt et al. concluded that attention could modulate the activity of fixation cells in the SC; such modulation could be higher when attention is allocated to fixation.

The knowledge on cortical structures involved in the control of vergence movements in humans has progressed recently. A PET study of Hasebe et al. (1999) showed that many cortical areas (the bilateral temporo-occipital junc-

tion, the left inferior parietal cortex and the right fusiform gyrus) are activated prior to vergence movements. An EEG study of Tzelepi et al. (2004) also showed an increased central bilateral and posterior activation prior to divergence and convergence movements. Other studies from our group using transcranial magnetic stimulation (e.g., Coubard et al. 2003; Yang and Kapoula 2004; Kapoula et al. 2005) showed that both the right and the left parietal cortex are involved in the initiation of vergence movements. Thus, the same cortical oculomotor areas are involved in the initiation of saccades and vergence eye movements. Moreover, these structures are also known to subtend shifts of visual attention (see Rizzolati et al. 1987 and Corbetta 1998).

More express latencies in dyslexics

The novel finding is that express latencies occur for a larger variety of eye movements in dyslexics, particularly for divergence. One could make the hypothesis that express latencies found in dyslexics could be due to a higher activation of their attention. This idea is in line with the thinking of Mackeben and Nakayama (1993) suggesting that express latencies could be based on mechanisms involving an unusually rapid shift of attention. Our observations suggest that such a hypothetical unusually rapid shift of attention is more spatially extended in dyslexics.

A final point to discuss is the possible link between the fast initiation of divergence and the limitations of clinically assessed divergence. Indeed, the clinical findings of dyslexics reported in this study (see Table 1) show a frequently reduced amplitude of divergence, measured with a bar of prisms; this finding is in line also with a prior study dealing with a large population of dyslexics (Kapoula et al. 2007). Express triggering of divergence means that the movement starts before the sensory processing of uncrossed disparity is achieved and this could be the reason why clinically measured divergence amplitude is reduced. Further studies on latency and accuracy characteristics of divergence elicited with prisms in dyslexics are needed.

In conclusion, this study shows that dyslexic children have longer latencies for saccades starting from a far point and have frequent express divergence latencies. We attribute these findings to problems of voluntary and reflexive control of attention to targets in 3D space.

Finally, the new message coming out from this study is the importance to examine at the same time in children several types of eye movements (saccades, vergences and combined saccades vergence movements). Indeed, it should be noted that the natural movements made for looking successfully at different objects in 3D space normally involve both saccades and vergence components.

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