POOR BINOCULAR COORDINATION OF SACCADIES DURING READING IN CHILDREN WITH VISUAL DEFICITS

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ABSTRACT

Purpose: Eye movements are important for stabilizing and orienting gaze in space and for various other activities as reading. During reading, the vergence angle between the two eyes need to be well adjusted to each word distance; and therefore saccades and vergence movements must be well coordinated in order to read the text properly. Without such
coordination, reading may be compromised. In the present study, we examined the quality of binocular saccade coordination during reading in children with binocular visual impairment.

**Methods:** Binocular eye movements were recorded during reading silently a text with a videooculography system in three groups of children: (i) twelve children (from 7.3 to 13.4 years old) with vergence insufficiency (distant near point of convergence and/or low convergence fusional amplitude); (ii) ten children with strabismus with binocular vision (from 7.6 to 15.9 years old); (iii) eight children with strabismus without binocular vision (from 6.8 to 16 years old). Data were compared to age-matched control children with normal ocular motor capabilities.

**Results:** Binocular coordination during and after the saccades is significantly poorer in the three groups of children as compared to control age-matched groups; the duration of fixation is longer in the three groups of children with respect to control group, but it is significantly longer only in the two groups of strabismic children.

**Conclusions:** Such findings support the hypothesis of a tight relationship between the saccade and vergence systems for controlling the binocular coordination of saccades during reading. Furthermore binocular vision plays an important role for binocular saccade yoking.

**Keywords:** Binocular coordination, saccades, vergence, reading, strabismus, vergence insufficiency

**INTRODUCTION**

Reading is a daily task used frequently, needing saccades from the left to the right and several fixations on the words. Given the close distance at which reading is performed the angle between the two visual axes need to be adjusted and the two eyes have to converge appropriately in order to fuse the word and understand its meaning. The large majority of studies dealing with reading were limited to record eye movements from one eye only (see review from Rayner, 1998), and only recently during the last decade researchers started to explore the quality of binocular coordination during reading task by recording movements from both eyes.

Bassou, Granić, Pugh, and Morucci (1992) were the first to record binocular eye movements in ten years old children while reading a text. They showed that saccades of the two eyes were highly disconjugated in these children. These authors suggested that ocular movements during reading do not always follow Hering’s law, according to which both eyes are well yoked.
because they receive equal innervations. The authors pointed out that poor binocular control in children could interfere with learning to read. Note however, that due to the low resolution of the recording system used (i.e. an EOG device), these results were only qualitative.

Blythe et al. (2006) compared binocular coordination during reading a text in twelve children (from 7 to 11 years old) and in twelve young adult subjects (18-21 years old). They measured the binocular coordination at the beginning and at the end of the fixation, and they found that children showed significantly larger disconjugate fixations than adults. These differences between children and adults suggest that children’s ocular motor control is immature and it develops during childhood.

An immaturity of the ocular motor saccade and vergence systems interaction has been also proposed by our group (Bucci, Nassibi, Gerard, Bui-Quoc, and Seassau, 2012) exploring the quality of binocular coordination during reading in groups of dyslexic and non dyslexic children from 8 to 12 years old. According to our results, reading skills mature with time, and it is hypothesized that cortical structures (e.g. frontal and parietal cortex) involved in eye movement control as well as those involved in linguistic processing (i.e. left temporal and parietal cortex) are developing during childhood and adolescence (Luna et al. 2008; Simos et al. 2001; Turkeltaub et al. 2003).

All these findings show that saccade and vergence interaction, necessary for a good binocular coordination during and after the saccades, is still developing in children under the age of 12, and someone could ask whether a deficit in vergence or saccade ocular motor systems could lead to poor binocular coordination. A previous report of our group (Bucci et al. 2006) comparing the binocular coordination of saccades to target-LEDs at near (30 cm) and far (150 cm) distances in a population of fifteen children (from 10 to 15 years) with vergence deficits reported poor binocular coordination for saccades to near targets (when a convergence of the two eyes were required in order to fuse the target-LED). This study -even if it was not dealing with reading task- suggests a fine relationship between the saccade and the vergence system that could interfere for a good learning of reading.

Another population of children which could show difficulties for learning to read is strabismic population given that for their deviation vergence capabilities are very scarce. To our knowledge, there are few studies dealing with binocular motor control in children with strabismus. Recall that approximately 2% of children under 7 years old develop strabismus (von Noorden and Campos, 2006) and in many cases, it is responsible for abnormal alignment of the eyes and abnormal binocular vision. Previous works showed
that in children with strabismus the accuracy of saccadic and vergence eye movements was poor and the velocity of convergence movements was also abnormally slow (Bucci et al. 2009). Such findings could be due to impairment in the central structures related to sensory disparity inputs occurring in strabismic subjects.

The purpose of the present study is to further examine binocular coordination during and after saccades through a reading task in different groups of children with different level of vergence deficiency. We examined a group of children with vergence insufficiency and strabismic children with and without binocular vision. Given that binocular capabilities are fundamental for vergence driven inputs we make the hypothesis that the quality of binocular saccade control might be worst in the last group of children.

METHODS

Subjects

Three groups of children participated in this study: (i) twelve children (mean age: 10.25 ± 1.82 years) with normal vestibular function but vergence insufficiency at the orthoptic examination; (ii) ten children with strabismus with binocular vision (mean age: 10.7 ± 0.8) and (iii) eight children with strabismus without binocular vision (mean age: 9.6 ± 1.2).

Three age matched groups of children with normal binocular vision and vergence ranges were also recruited. All children were native French and had no known of reading difficulties.

The investigation adhered to the principles of the Declaration of Helsinki and was approved by our Institutional Human Experimentation Committee. Written consent was obtained from the children's parents after an explanation of the experimental procedure.

Ophthalmological and Orthoptic Tests

All children underwent ophthalmological and orthoptic examination to evaluate their visual function. Clinical data of the three groups of children are shown in Table 1 (A: children with vergence insufficiency; B: children with strabismus with binocular vision; C: children with strabismus without binocular vision).
The visual acuity was measured for each eye separately at far distance (5m) with the Monoyer chart. The heterophoria (i.e. the latent deviation of one eye covered when the other is not covered) or the heterotropia (i.e. the manifest deviation of one eye) were measured at near distance by using the cover-uncover test. The measurement of fusional amplitude of convergence and divergence was done at near distance (30cm) by using a base-out and a base-in prism bar. The near point of convergence (NPC) was also examined by placing a small accommodative target at 30 cm in the midplane in front of the child and moving it slowly towards the eye until one eye lost fixation. The stereacuity threshold based on disparity detection was evaluated with the TNO random dot test for stereoscopic depth discrimination.

The monocular visual acuity was normal (≥20/20) for all children.

Clinical characteristics of children with vergence insufficiency are shown in Table 1A.

Table 1A. Clinical characteristics of children with vergence insufficiency

<table>
<thead>
<tr>
<th>Children (years)</th>
<th>Glasses correction</th>
<th>Phoria (pD)</th>
<th>Divergence (pD)</th>
<th>Convergence (pD)</th>
<th>NPC (cm)</th>
<th>TNO (sec of arc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1(7.3)</td>
<td>RE : -6.25 (-2.50)</td>
<td>-12</td>
<td>12</td>
<td>12</td>
<td>7</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>LE : -4.00 (-50)</td>
<td>15</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C2(8.6)</td>
<td></td>
<td>-4</td>
<td>8</td>
<td>20</td>
<td>10</td>
<td>30</td>
</tr>
<tr>
<td>C3(8.6)</td>
<td>RE : +3.00</td>
<td>-6</td>
<td>8</td>
<td>30</td>
<td>0</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>LE : +3.50</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C4(8.7)</td>
<td></td>
<td>-6</td>
<td>8</td>
<td>20</td>
<td>10</td>
<td>30</td>
</tr>
<tr>
<td>C5(9.1)</td>
<td>RE : +0.50</td>
<td>-12</td>
<td>20</td>
<td>18</td>
<td>6</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>LE : +0.50</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C6(9.9)</td>
<td></td>
<td>-4</td>
<td>16</td>
<td>20</td>
<td>1</td>
<td>60</td>
</tr>
<tr>
<td>C7(10.7)</td>
<td></td>
<td>-8</td>
<td>18</td>
<td>25</td>
<td>10</td>
<td>60</td>
</tr>
<tr>
<td>C8(11.8)</td>
<td>RE : +0.25 (-50)</td>
<td>-4</td>
<td>20</td>
<td>25</td>
<td>9</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>LE : +0.50</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C9(12)</td>
<td></td>
<td>-8</td>
<td>10</td>
<td>6</td>
<td>9</td>
<td>30</td>
</tr>
<tr>
<td>C10(12.3)</td>
<td></td>
<td>-2</td>
<td>16</td>
<td>30</td>
<td>8</td>
<td>60</td>
</tr>
<tr>
<td>C11(12.5)</td>
<td></td>
<td>-6</td>
<td>16</td>
<td>25</td>
<td>12</td>
<td>60</td>
</tr>
<tr>
<td>C12 (13.4)</td>
<td></td>
<td>6</td>
<td>10</td>
<td>45</td>
<td>0</td>
<td>30</td>
</tr>
</tbody>
</table>

LE, left eye; RE, right eye. Phoria is negative in the case of exophoria, positive in the case of esophoria and zero in the case of orthophoria. These values are given in prism diopters (pD). Phoria and vergence fusional amplitude are measured at near (30 cm) distance with the orthoptic technique. These values are given in prism diopters (pD). Near point of convergence (NPC) is measured in centimeters. The binocular vision is evaluated with the TNO test for stereoscopic depth discrimination; this value is given in seconds of arc.
In the literature, normative data for orthoptic examination varied greatly (Rouse et al., 1998; Rouse et al., 1999; Rainey, 2002; van Noorden and Campos, 2002; Jeanrot and Jeanrot, 2003, Espinasse-Berrod, 2008; Dusek, 2011). We based our criteria on our normal values calculated in our clinical research center on a population of 81 children aged from 5 to 17 years old presenting no vestibular pathology and no neurological or ophthalmologic pathology (see Table 2). According to these normal values, all children who suffered from vertigo and headaches have abnormal vergence fusional amplitude. Five of them (C1, C2, C3, C4, C9) have both convergence and divergence insufficiency; six children (C5, C6, C7, C8, C10, C11) have only convergence insufficiency and one child (C12) only has divergence insufficiency.

Table 1B. Clinical characteristics of strabismic children with binocular vision

<table>
<thead>
<tr>
<th>Children (years)</th>
<th>Glasses correction</th>
<th>Angle of strabismus (prism D)</th>
<th>TNO (sec of arc)</th>
<th>Type of strabismus</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1 (7.6)</td>
<td>RE: -1.25 (-0.75),155° LE: -1.50 (-1.00),150°</td>
<td>30 X'-X'T</td>
<td>40</td>
<td>Intermittent exotropia</td>
</tr>
<tr>
<td>C2 (8.6)</td>
<td>RE: -1.25 (-1.00),140° LE: -0.50 (-2.00),0°</td>
<td>30 X'-X'T</td>
<td>60</td>
<td>Intermittent exotropia</td>
</tr>
<tr>
<td>C3 (9.3)</td>
<td>RE: +1.00 (-0.25),75° LE: +1.00 (-0.25),90°</td>
<td>12 X'-X'T</td>
<td>60</td>
<td>Intermittent exotropia</td>
</tr>
<tr>
<td>C4 (9.4)</td>
<td>RE: +0.75 (-0.25),175° LE: +0.75</td>
<td>25 X'-X'T</td>
<td>40</td>
<td>Intermittent exotropia</td>
</tr>
<tr>
<td>C5 (9.7)</td>
<td>RE: +6.50 LE: +7.50</td>
<td>10 X'-XT</td>
<td>40</td>
<td>Intermittent exotropia</td>
</tr>
<tr>
<td>C6 (10.5)</td>
<td>RE: -1.00 LE: -1.00</td>
<td>35 X'-XT</td>
<td>60</td>
<td>Intermittent exotropia</td>
</tr>
<tr>
<td>C7 (11.3)</td>
<td>RE: +5.75 (-2.25),170° LE: +6.00 (-2.50),0°</td>
<td>12 E'T</td>
<td>400</td>
<td>Accommodative esotropia</td>
</tr>
<tr>
<td>C8 (11.4)</td>
<td>RE: 0.00 LE: 0.00</td>
<td>18 X'-X'T</td>
<td>60</td>
<td>Intermittent exotropia</td>
</tr>
<tr>
<td>C9 (13.8)</td>
<td>RE: +0.25 LE: +0.25 (-0.25),0°</td>
<td>30 E'-E'T</td>
<td>240</td>
<td>Accommodative esotropia</td>
</tr>
<tr>
<td>C10 (15.9)</td>
<td>RE: +4.25 (-0.25),45° LE: +3.75 (-0.50),135°</td>
<td>10 E'-E'T</td>
<td>60</td>
<td>Accommodative esotropia</td>
</tr>
</tbody>
</table>

LE, left eye; RE, right eye. X'-X'T, intermittent exotropia measured at near distance (30cm); E'-E'T, accommodative esotropia measured at near distance (30 cm), O'; orthophoria measured at near distance (30 cm). Other notes are as in Table 1A.
Ten children with strabismus (Table 1B) had binocular vision that for the majority of them was in normal range (≤60 seconds of arc with the TNO test); two children only had reduced binocular vision of about 400” and 240” of arc. The majority of these children (7/10) had intermittent divergent strabismus, while the other three children (C7, C9 and C10) had partially accommodative esotropia.

Clinical characteristics of eight children with strabismus without binocular vision are shown in Table 1C. Three children had congenital esotropia while the other five children had accommodative esotropia.

**Table 1C. Clinical characteristics of strabismic children without binocular vision**

<table>
<thead>
<tr>
<th>Children (years)</th>
<th>Glasses correction</th>
<th>Angle of strabismus (prism D)</th>
<th>TNO (sec of arc)</th>
<th>Type of strabismus</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1 (6.8)</td>
<td>RE: -1.75 (-2.25) 15° LE: -1.25 (-1.75) 30°</td>
<td>55 E’T + 10 HTG</td>
<td>--</td>
<td>Congenital esotropia</td>
</tr>
<tr>
<td>C2 (7)</td>
<td>RE: +1.75 (-1.00) 165° LE: +0.75 (-1.00) 165°</td>
<td>25 E’T</td>
<td>--</td>
<td>Congenital esotropia</td>
</tr>
<tr>
<td>C3 (7)</td>
<td>RE: +2.25 LE: +5.75</td>
<td>35 E’T</td>
<td>--</td>
<td>Accommodative esotropia</td>
</tr>
<tr>
<td>C4 (7.3)</td>
<td>RE: +6.75 (-2.00) 15° LE: +7.25 (-2.00) 10°</td>
<td>45 E’T</td>
<td>--</td>
<td>Accommodative esotropia</td>
</tr>
<tr>
<td>C5 (8.9)</td>
<td>RE: +1.25 LE: +1.00 (-1.00) 75°</td>
<td>40 E’T</td>
<td>--</td>
<td>Congenital esotropia</td>
</tr>
<tr>
<td>C6 (9.4)</td>
<td>RE: +6.00 (-0.50) 140° LE: +5.00 (-0.50) 20°</td>
<td>30 E’T</td>
<td>--</td>
<td>Accommodative esotropia</td>
</tr>
<tr>
<td>C7 (13.9)</td>
<td>RE: +2.25 (-0.50) 145° LE: +2.00</td>
<td>45 E’T</td>
<td>--</td>
<td>Accommodative esotropia</td>
</tr>
<tr>
<td>C8 (16)</td>
<td>RE: +5.50 (-2.00) 0° LE: +5.75 (-2.25) 0°</td>
<td>6 E’T</td>
<td>--</td>
<td>Accommodative esotropia</td>
</tr>
</tbody>
</table>

LE, left eye; RE, right eye. X’-X’T, intermittent exotropia measured at near distance (30 cm); E’-E’T, accommodative esotropia measured at near distance (30 cm), O’; orthophoria measured at near distance (30 cm). Other notes are as in Table 1A.

**Table 2. Clinical characteristics of age matched control groups**

<table>
<thead>
<tr>
<th></th>
<th>Phoria (pD)</th>
<th>Divergence (pD)</th>
<th>Convergence (pD)</th>
<th>NPC (cm)</th>
<th>TNO (sec of arc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean ± SE</td>
<td>-4 ± 5</td>
<td>16 ± 4</td>
<td>35 ± 13</td>
<td>3 ± 4</td>
<td>56 ± 19</td>
</tr>
<tr>
<td>Range</td>
<td>0 to -7</td>
<td>13 to 19</td>
<td>26 to 44</td>
<td>0 to 5</td>
<td>15 to 120</td>
</tr>
</tbody>
</table>

Notes as in Table 1A.
Visual functions were also evaluated for the age matched control children and the mean values (with respective range) of their clinical characteristic are shown in Table 2.

**Reading Task**

The reading paradigm is similar to those used by Bucci’s group in previous studies on reading task (Bucci et al. 2012; Lions et al., 2013; Seassau and Bucci, under revision) and consisted of a four lines text extracted from a book for children, containing 40 words and 174 characters. The text was 29° wide and 6.4° high; mean character width was 0.5° and the text was written in black “courier” font on a white background. Each age group had to read a different text. Figure 1 show each of these texts: an extract from “Jojo Lapin fait des farces”, Gnid Bulton, Hachette Ed., for 6-to-9-year-olds (Figure 1A); an extract from “Bagarres à l’école”, Marc Cantin et Eric Gasté, Castro Cadet ed., for 10-to-12-year-olds (Figure 1B); and an extract from “La guerre des boutons”, Louis Pergaud. Folio Ed., for 13-to15-year-olds (Figure 1C).

![Figure 1. Reading task respectively used for children with a reading age of 6-9 years (A); 10-12 years (B), and 13-15 years (C).](image-url)
Texts come from three different books that are frequently used by French teachers in different class levels (7–9, 10–12, and after 13 years old). These age-specific texts have been used to ensure that all words were well-known and easily understood by the children.

Children were asked to read the text silently. When they were done, they raised a finger and were asked to describe the text read. This allowed the experimenters to check that the text had indeed been read and understood.

Eye Movement Recordings

Eye movements were recorded with the Mobile Eyebrain Tracker (Mobile EBT®., e(eye)BRAIN, www.eye-brain.com), an eye-tracking device CE marked for medical purpose. The Mobile EBT® benefits from a high frequency camera that allows it to record both the horizontal and vertical eye positions independently and simultaneously for each eye. Recording frequency was set up to 300 Hz.

The precision of this system is typically 0.5°; in a controlled setting such as the one we used, it reaches 0.25°. The recording system does not obstruct the visual field, and the calibrated zone covers an horizontal visual angle of ± 22°.

Procedure

Children were asked to seat in a comfortable chair adjusted for height, in a dark room, with their face resting on a forehead and chin support, under binocular viewing condition. Children were in front of a PC screen of 22” with a resolution of 1920x1080 and a refresh rate of 60 Hz, at 60 cm distance from the screen.

Calibration was done at the beginning of the reading task. During the calibration procedure, children were asked to fixate a grid of 13 points (diameter 0.5 deg) mapping the screen. Point positions in horizontal/vertical plans were: -20.9°/12.2° ; 0°/12.2° ; 20.9°/12.2° ; -10.8°/6.2° ; 10.8°/6.2° ; -20.9°/0° ; 0°/0° ; 20.9°/0° ; -10.8°/-6.2° ; 10.8°/-6.2° ; -20.9°/-12.2° ; 0°/-12.2° ; 20.9°/-12.2°. Each calibration point required a fixation of 250 ms to be validated. A polynomial function with five parameters was used to fit the calibration data and to determine the visual angles. After the calibration procedure, the reading task was presented to the child.
Data Analysis

Methods are similar to those used in a prior study (see Bucci et al. 2012 and Lions et al., 2013). Briefly, the software MeyeAnalysis (provided with the eye tracker, see www.eye-brain.com) was used to extract saccadic eye movements from the data. It determined automatically the onset and the end of each saccade by using a ‘built-in saccade detection algorithm’. All detected saccades are verified by the investigator and corrected/discard if necessary.

For each saccade recorded in the reading task, we examined the amplitude of the conjugate [(left eye + right eye)/2] and the disconjugate components (left eye – right eye) of the eye movements. The disconjugacy was measured as the change in vergence between the beginning and the end of each saccade. We also examined the disconjugate component of the post-saccadic fixation. The duration of fixation was also evaluated.

Statistical analysis was performed by an ANOVA using the six age-groups as inter-subject factor. Next we will focus our findings on comparison between the three groups of patients (children with vergence abnormalities, children with strabismus with and without binocular vision) and their difference with respect to each of age matched group of control children.

RESULTS

The absolute mean amplitude of saccades during reading task for each group of children is shown in Figure 2. The ANOVA showed a significant group effect ($F_{(5,54)} = 5.75$, $p < 0.0002$). Post hoc comparison showed that the amplitude of saccades of the group of children with vergence abnormalities was significant smaller with respect to the other two groups of strabismic children with and without binocular vision ($p < 0.0001$). Importantly, the absolute mean amplitude of saccades of each of these groups was similar to those reported by each age matched group of control children.

In Figure 3 is shown the mean disconjugacy during saccades for the patients and control children. The ANOVA test showed a significant effect of group ($F_{(5,54)} = 56.64$, $p < 0.0001$). Post hoc comparison showed that all three groups of patients had significantly higher disconjugacy with respect to each age matched control group (all $p < 0.001$). Furthermore, the saccade disconjugacy was significant smaller ($p < 0.01$) in strabismic children with binocular vision (mean: $0.44 \pm 0.04^\circ$) with respect to children with vergence abnormalities (mean: $0.84 \pm 0.04^\circ$).
0.05°) and to strabismic children without binocular vision (mean: 1.09 ± 0.06°).

The mean disconjugacy of the post-saccadic fixation (absolute values) for patients and control children is shown in Figure 4. The ANOVA test revealed a significant effect of group ($F_{(5,54)} = 25.49$, $p < 0.0001$). The post-saccadic fixation disconjugacy was significantly higher in patients (mean: 0.81 ± 0.33 deg) than in control children (mean: 0.32 ± 0.09 deg). Post hoc comparison showed that all three groups of patients had significantly higher disconjugacy with respect to each age matched control group (all $p > 0.001$).

Figure 2. Individual mean of saccade amplitude (in degrees) for children with vergence abnormalities, for strabismic children with and without binocular vision and for the three corresponding age-matched control groups of children. Vertical bars indicate the standard error.

Figure 3. Individual mean of saccade amplitude disconjugacy (in degrees) for children with vergence abnormalities, for strabismic children with and without binocular vision and for the three corresponding age-matched control groups of children. Vertical bars indicate the standard error.
Figure 4. Individual mean of post-saccadic amplitude disconjugacy (in degrees) for children with vergence abnormalities, for strabismic children with and without binocular vision and for the three corresponding age-matched control groups of children. Vertical bars indicate the standard error.

Note also that, similar to the saccade disconjugacy, the disconjugacy measured during the post-saccadic fixation was significant smaller ($p < 0.01$) in strabismic children with binocular vision (mean: $0.47 \pm 0.05^\circ$) with respect to children with vergence abnormalities (mean: $0.81 \pm 0.09^\circ$) and to strabismic children without binocular vision (mean: $1.15 \pm 0.11^\circ$).

The duration of the fixation reported in patients and in control groups of children is shown in Figure 5. The ANOVA test reported a significant effect of group ($F_{(5,54)} = 3.01, p < 0.01$).

Figure 5. Individual mean of fixation duration (in milliseconds) for children with vergence abnormalities, and for strabismic children with and without binocular vision and for the three corresponding age-matched groups of control children. Vertical bars indicate the standard error.
Post hoc comparison showed that the post-saccadic fixation disconjugacy was similar in the three groups of patients (mean: 379 ± 35 ms, 428 ± 20 ms and 428 ± 32 ms, respectively for children with vergence insufficiency, and strabismic children with and without binocular vision); in contrast, strabismic children only (with and without binocular vision) showed significant longer duration of fixation (all p < 0.03) with respect to age matched control group of children (mean: 318 ± 41 ms, 292 ± 28 ms and 323 ± 29 ms, respectively).

**DISCUSSION AND CONCLUSION**

The mean findings from this study were as follows: (i) while reading a text, saccade amplitude is similar in patients with visual deficits and in age matched control children; (ii) patients with visual deficits showed poorer binocular coordination during and after the saccades than control age matched children; (iii) the duration of fixation was longer with respect to age matched control children in the two groups of strabismic children only. Each of these results will be discussed below.

**Saccade Amplitude During Reading**

This study shows that saccade amplitude is similar in patients with visual deficits and in age matched control children. Several studies (Buswell, 1922; Rayner, 1986; McConkie et al. 1991) showed that younger children have longer and more frequent fixations, smaller saccades, and frequent backward saccades (regressive leftward saccades); reading capabilities increase as children grow older, leading to an improvement of these ocular motor performance (see review from Rayner, 1998).

Our findings from children with vergence abnormalities are in line with these studies given that the age of these children was younger than those of the other patients tested; as shown in the Figure 2 younger children make saccades of smaller amplitude.

With respect to strabismic children (with and without binocular vision), our data show similar saccade amplitudes between strabismic and control children; this finding is also not a surprise. Indeed, Kanonidou et al. (2010) reported similar results in strabismic amblyopic adults. In other words, strabismus does not seem to influence the amplitude of saccades. This confirms and extends our previous work dealing with saccades in this type of
population (Bucci et al. 2002; Bucci et al. 2009) showing that strabismic children were able to properly localize a target.

Taken together all these findings suggest that the cortical and subcortical structures responsible for the computation and the execution of the saccades are functional in these populations of children.

**Disconjugacy During and After the Saccades**

All three groups of patients tested (with vergence insufficiency and with strabismus with and without binocular vision) showed poor binocular coordination during and after the saccades during reading a text compared to age matched control children. These results extend the previous study of our group in children with vergence insufficiency (Bucci et al. 2006) as well as in strabismic children (Bucci et al. 2002) showing large disconjugacy during and after the saccades while saccading to targets at near distance. We hypothesized that the fine control of binocular saccade coordination is based on learning mechanisms allowing an efficient relationship between the motor command of the saccades and the vergence sub-systems.

The present results suggest that this relationship is deficient in these types of children with visual deficits. The deficiency in the vergence system that occurs in our patients could interfere with a reliable signal of vergence, thereby leading to uncoupled saccades and poor binocular saccade coordination. Our results allow us to increase knowledge on vergence and saccade interaction in reading. If such a mechanism does not work in a correct way, it could lead to impaired quality of binocular coordination during and after saccades. There is a debate on whether poor binocular coordination of saccade control could interfere with reading capabilities (in dyslexia population, for instance). Further studies are needed to examine binocular coordination in a larger population of children without vergence abnormalities and of children with reading difficulties.

Furthermore, in the present study we also show that binocular vision plays an important role in controlling binocular saccades coordination given that strabismic children with binocular vision show smaller disconjugacy than strabismic children without binocular vision. We think that during a cognitive task such as reading, binocular vision is necessary in order to bring both eyes onto the word, allowing rapid and efficient reading. Although some results show that small disparities during reading are present and well tolerated in normal populations (Blythe et al. 2006; Kirkby et al. 2008), the large
disconjugacy of saccades we observed particularly in strabismic children without binocular vision could prevent proper identification and understanding of the words.

Finally, we have to point out that the smaller disconjugacy during and after the saccades reported in strabismic children with binocular vision with respect to children with vergence insufficiency could be due to the different age of children tested. Indeed our ongoing studies (Seassau and Bucci, under revision) on binocular coordination during reading in a large population of normal children showed that disconjugacy during and after saccades decreases with age.

Consequently, in order to explore further the quality of binocular coordination in patients with vergence abnormalities and the role of binocular vision for the saccade yoking a larger population of children with similar age need to be tested.

Duration of the Fixation

Our findings show significantly longer fixations in the two groups of strabismic children only. This could be the consequence of a lower quality of vision caused by the large disconjugacy reported during the post-saccadic fixation period, delaying a proper linguistic processing. Stifter (2005) examined the reading capabilities in children with microstrabismic amblyopia and they found that normal children display a higher reading speed than amblyopic children.

Similarly, Kanonidou et al. (2010) examined reading performances in twenty subjects with strabismus and amblyopia and they found that reading speed in these patients was slower than in normal subjects. These results suggested that such abnormal reading pattern could be a strategy used by strabismic subjects to override their abnormal sensory visual input. Our findings are also in line with the study of Jainta et al. (2011) showing that during reading of a blurred text, normal adults lengthen the duration of fixation.

Our data show that binocular vision does not influence the duration of fixation given that both groups of strabismic children show similar durations of fixation. We suggest that duration of fixation depends more on the deviation of ocular axis than on an abnormal sensory visual input. Such eye deviation could lead to a longer fixation because of the difficulty in identifying each word.
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REFERENCES


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