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Are changes in the stomatognatic system able to modify the eye balance in dyslexia?

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ABSTRACT

Objectives: To clarify the link between eye muscle function and oral information by comparing 21 dyslexic readers (DR) and 14 normal readers (NR).

Methods: Changes in vertical heterophoria (VH) were measured using the Maddox Rod Test performed according to oral modifications and postural conditions. The Spearman correlation was used to assess whether reading delay was correlated with the lability index.

Results: Overall, 50% of NR children and 81% of DR experienced at least one variation in visual perception ($p = 0.053$). Among DR, the less reading delay they had, the higher their index of lability ($p = 0.026$), whereas there was no significant correlation among NR. Changes in the Maddox Test were more frequent in DR than in NR after the addition of sensory and postural stimuli, except for one specific posture. For sensory stimuli, the mean lability index was 1.35 in NR and 4.19 in DR, ($p = 0.001$). For postural stimuli, it was 0.71 and 2.61, ($p = 0.003$).

Conclusions: It is possible to modify visual perception by changing sensory or mechanical stimuli. Changes are more frequent in DR than in NR. Postural control can be improved with guided oral stimulations.

Significance: These results reinforce the importance of professional cooperation in the care of dyslexic readers.

1. Introduction

Developmental dyslexia is a specific learning difficulty that primarily affects the skills involved in accurate and fluent reading and spelling. It is generally considered to be the result of specific impairments relative to phonological representation. It is characterized by difficulties with processing speed, working memory and rapid naming, and is not influenced by exogenous factors such as lack of intelligence or educational access. Dyslexia affects around 10% of the population and is categorized into three distinct clinical types[1]:

i) Surface: difficulty in recognizing the visual form of written words, especially if they are irregular,
ii) Phonological: a specific inability to handle speech sounds and the graphene-phoneme conversion,
iii) Mixed: the most frequent type, combining surface and phonological anomalies.

Previous studies have emphasized that children with dyslexia may have multi-deficit disorders including deficits in the auditory, visual and motor system.[2] Among dyslexics, abnormal motor skills can be expressed by anomalies in body tone and posture.[3,4] Other peculiarities can affect the fine motor skills, especially the ocular and oral muscles.[5,6]

Reading is a complex oculomotor and cognitive activity whose exact mechanisms are still poorly understood. Eye movements must be very precise to allow the visual capture of written words by fixing the center of both retinas (fovea) at a particular location within the word designated as the center of gravity of the word.[1] Concerning muscular function, this position is coded from the efferent oculomotor control information and from the afferent proprioceptive information originating in the eye muscles, although the relative importance of each of these two elements remains unknown.[7] Ocular proprioception, which depends on the trigeminal nerve, is primarily used for error correction and to modulate visual attention.[8] Abnormal ocular muscle function could be responsible of binocular dyscoordination during reading.[9] In

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dyslexia, coordination disorders affect horizontal but also oblique and vertical eye movements.[9]

Fine oral articulatory movements are crucial for the appropriate production of sounds when reading aloud. Beyond their local motor action, they also have an important role in the perception of sound units.[10] That is why, according to the motor theory of speech perception proposed by Liberman, abnormal oral muscle function could play a role in phonological dysfunction which is one of the main characteristic of dyslexia.[11]

This idea is at the origin of the motor-articulatory feedback hypothesis of developmental dyslexia which suggests that phonological awareness may be linked to an abnormal production of intended oral articulatory gestures.[12] We thus attempted to clarify the link between eye muscle function and oral information, using two indicators: *heterophoria*, taken as a measure of coupling of the eyes during a visual task and *dental information* as a trigeminal mechanical input.

The purpose of this exploratory study was to compare a group of dyslexic readers (DR) to a group of normal readers (NR) in order to answer the following questions:

1. Is it possible to modify visual perception by modifying oral sensory information?
2. Do these changes vary for DR and NR?
3. Is there a difference in response when the stimuli is sensory or mechanical?
4. Is there a relationship between the lability of the visual axes and changes in oral, spinal or podal positions?
5. Could the mouth be a link between the ocular and phonological signs of dyslexia?

2. Subjects and methods

2.1. Participants

Children were recruited during pediatric ophthalmological consultation. Exclusion criteria were: a history of neurological, psychiatric or genetic disease, delayed or abnormal psychomotor development, IQ below 85, orthodontic treatment in progress, children under psychotropic treatment (especially drugs from the phenylethylamine group or anti-epileptics). After consent was obtained from the children and their parents, they were tested within the guidelines of the declaration of Helsinki. Children with a visual acuity of 20/20 in both eyes with no refractive error and no organic abnormalities of the anterior or posterior segments were retained. Children with the following visual features were excluded: strabismus with or without surgery, orthoptic rehabilitation in progress, re-educated amblyopia, stereopsis > 100 s. The inclusion criteria for the dyslexic children were a documented diagnosis of dyslexia and a score of at least 24 months of reading delay on the WWIT/TIME 3 test (Written Word Identification Test).[13] This test identifies the decoding skills and the comprehension and spelling of 40 words for children aged 7 to 15. In the group of dyslexic children only, the use of the Odedys Battery helped classify the type of dyslexia.[14]

Children were recruited from consecutive consultations. A total of 35 children fulfilled the inclusion criteria: 21 DR children (11 males and 10 females) participated in the study and were compared with a group of 14 NR children (9 males and 5 females). The average delay in reading months was 11 ± 9 months in the DR group. Odedys tests found mixed dyslexia for all the dyslexic children.

2.2. Experimental procedure

To sensitize the action of oral stimulation on the ocular muscles, the parallelism of the visual axes is weakened by manipulating the fusion of the two retinal images. The coordinated position of the two eyes is indeed linked to a coupling between the control of the ocular motricity (efference copy and muscle proprioception) and the retinal fusion. When the latter is impaired, the eye axes tend to deviate slightly. This deviation is called heterophoria. The parallelism of the ocular axes is almost perfect in the vertical plane (0.12° of deviation) and the natural compensation possibilities are very low. This is why we studied vertical heterophoria (HV) while the oral information changed, either by sensorimotor variations in the tongue or lips, or by mechanical variations of the dental occlusion. As the eyes and the mouth are established sensors influencing the postural regulation, we also investigated the influence of four different bodily positions on lability.[15,16]

2.2.1. Vertical heterophoria measurement

Changes in vertical heterophoria were observed using a Maddox Rod Test which has been used for more than a century in ophthalmology.[16] It is performed with a red Maddox rod, consisting of 17 biconvex cylinders that have enough convergence to transform the image of a point of white light into a red line perpendicular to the cylinder axis (Movie 1). When the cylinders are vertical, the patient sees two dissociated images from the same light source: a red horizontal line through the Maddox rod and a colorless spot of light in direct vision. The light is placed four meters from the subject (the Frankfurt plane being horizontal) at eye level. It is important that the light be very small (diameter = 1–2 mm) so that the red line caused by the Maddox rod is as thin as possible. The test is performed for each of the two eyes starting with either the right or left and leaving a time of one second between each eye so as to provide a moment of binocular fusion. The child must reply, without changing the position of the tongue, by directing the thumb horizontally, up or down indicating that the red line has been seen respectively in the exact center, above or below the light (Fig. 1). The test procedure is very easy for the clinician and the child. Clinically, it is an inexpensive and effective way to detect very small variations in the vertical stability of both eyes when retinal fusion is changed. Its effectiveness is comparable to other, more invasive methods.[17] The Maddox rod test is a conventional tool to dissociate binocular vision by modifying retinal fusion. Indeed this test forces the brain to perceive two different images even though the visual input has the same temporal and spatial characteristics (one single light spot located in one single place). In this situation, both eyes tend to dissociate and lose their parallelism with appearance of a heterophoria. Depending on the position of the red screen, it is possible to break the parallelism of the visual axes in the horizontal or vertical direction or even in torsion in the frontal plane. We chose to study vertical deviation because ocular motor compensation is very weak in this plane.

Supplementary video related to this article can be found at https://doi.org/10.1016/j.jobcr.2019.03.005

2.2.2. Oral modifications

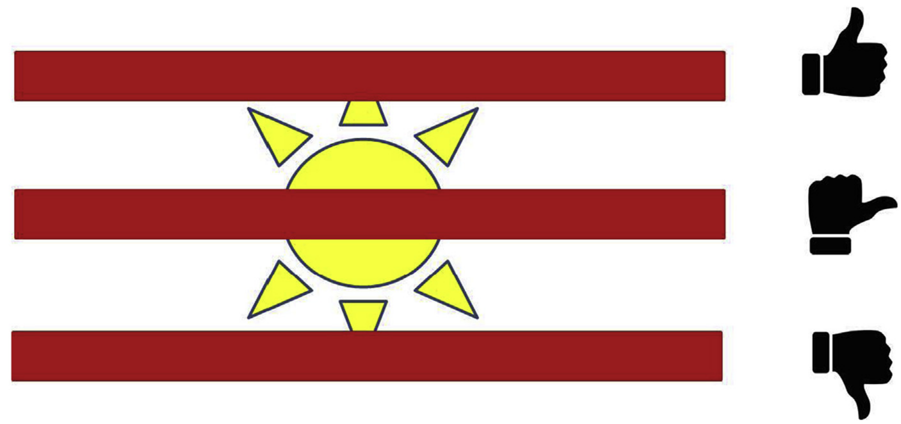
The test was performed using five well-defined oral conditions (Movie 1).

- Three conditions that do not affect dental occlusion:
  - the tip of the tongue firmly touching the central retro-incisor papillae
  - the lips tightly closed
  - the tip of the tongue planted against the lower incisors
- Two conditions that modify dental occlusion:
  - dental rolls between the molars
  - use of a dental splint.

2.2.3. Postural modifications

The five oral modifications described were done in four different postures:

- child sitting in a spontaneous and natural position without plantar support
- sitting straight up without plantar support
- standing in a natural position to add the information from the



Notes: Thumb up represents red line above the light, horizontal thumb represents red line strictly in the center of the light, and thumb downward represents red line under the light.

Fig. 1. How to indicate the position of the red line without changing information from the mouth.

plantar sole with the mouth also in a natural position
- standing with a foam insole between the foot and the ground to decrease exteroceptive plantar information

At the end of the test, in each postural condition, an index of lability was created. It matches the number of times, as a result of a modification, that the VH changed when compared with the previous situation (see example Table 1). For each postural condition the index is thus between 0 and 5:

- 0 corresponds to no modification of the position of the red line,
- 5 corresponds to a modification of position of the red line in front of the right eye and/or the left eye for each of the oral stimulations, the result being compared to the position just before. Whether the line is above, below, or in the center of the light is not taken into account.

2.3. Statistical analysis

All studied parameters were collected for the 35 children. Univariate analyses that compared the characteristics of DR and NR children were done with i) Chi2 test for qualitative variables, ii) Student's T test for quantitative variables after validation of homoscedasticity using Bartlett's test. The normality of distribution was assessed with Shapiro-Wilk test. The Spearman correlation coefficient was used to assess whether reading delay was correlated with lability index. $P < 0.05$ was considered statistically significant. All statistical analyses were performed with Stata Statistical Software V.1.5.

3. Results

The proportion of DR and NR children did not significantly vary with sex (55% DR in boys vs 67% in girls, $p = 0.486$). Mean age was 125.0 months (SE ± 7.1) for normal readers and 134.6 months (SE ± 4.8) for dyslexics ($p = 0.258$).

Overall, 69% of children presented at least one change in visual perception using the Maddox Rod Test when the oral information was modified, whatever the stimulation. This proportion was 50% in NR and 81% in DR ($p = 0.053$). Considering the whole population, the index of lability varied significantly with the group of children: it was on average 9.76 (95% CI: [7.04–12.47) in DR and 4.21 (95% CI: [1.33–4.97]) in NR ($p = 0.007$).

We tested the relation between reading delay and index of lability: in DR, the Spearman correlation coefficient was 0.483 ($p = 0.026$). Among DR, the less reading delay they had, the higher their index of lability. In NR, there was no statistical correlation between literacy level and index of lability.

The proportion of children whose results on the Maddox Rod Test changed was significantly higher in the DR group than in the NR group after the introduction of sensory stimuli: tongue normally held in the mouth ($p = 0.002$), tongue firmly touching the central retro-incisor papillae ($p < 0.001$), and lips tightly closed ($p = 0.005$). The tip of the tongue pushing against the lower incisors had no significant effect ($p = 0.091$) (Table 2). The results were similar after the introduction of mechanical stimuli: dental occlusion modified by dental rolls between the molars ($p = 0.009$) or using a dental splint ($p = 0.004$).

The response to the Maddox Rod Test similarly varied whether the stimuli were sensory or mechanical. For the three tests, the mean lability index was 1.35 (95% CI: [0.38–2.33]) in normal readers and 4.19 (95% CI: [3.01–5.36] in dyslexics, ($p = 0.001$). For mechanical stimuli, the mean was 0.71 (95% CI: [0.01–1.44]) for NR, and 2.61 (95% CI: [1.70–3.53] for DR, ($p = 0.003$). The index of lability was thus 2 to 3 times higher in dyslexic children whatever the type of stimuli.

The lability caused by changes in the spinal and podal sensors differed for a given oral condition.The proportion of DR presenting at least 1 modification of VH with the Maddox test was significantly higher than for NR when the oral modifications were performed in patients sitting in natural position ($p = 0.005$), sitting straight up ($p = 0.036$), or standing in a natural position with the mouth also in a natural position ($p = 0.035$) (Table 3). Standing with a foam insole between the foot and the ground had no significant influence. Conversely, the lability caused by changes in the oral sensor differed for a given spinal or podal condition.

4. Discussion

The main results of this study strongly suggest that manipulation of oral conditions modify visual perception and that changes affect differentially dyslexic children than normal readers.

Global effect of oral stimulations on the visual axis: Using the Maddox rod test, which weakens the binocular balance, we demonstrated for the first time that it is possible to modify visual perception by changing the oral sensory information for 69% of dyslexic and non-dyslexic children. Changes were significantly more frequent in the dyslexic population, and the variation (lability) was drastically higher in dyslexics. The

Table 1
Example of calculating the index of lability (postural condition = sitting in natural position without oral modification).

	Condition: Sitting in natural position with no oral modification	Tip of the tongue firmly touching the central retro-incisor papillae	Lips tightly closed	Tip of the tongue planted against the lower incisors	Dental rolls between the molars	Use of a dental splint	Index of lability
	H H	H O	H O	H h	H H	H H	
Points for lability index	0	1	0	1	1	1	Σ = 4

Note: Each time that the type of VH changes as a result of the stimulation of one sensor (when compared to the previous stimulation) gives 1 point.
Abbreviations: O, line in the middle of the light; h, line over the light; H, line under the light.

Table 2
Comparison between normal readers and dyslexics readers for changes in vertical heterophoria measured using a Maddox Rod Test according to oral conditions.

	Normal Readers	Dyslexic Readers	p value*
Tongue held normally in the mouth			
0 change	86%	33%	
≥1 change	14%	67%	0.002
Tongue firmly touching the central retro-incisor papillae			
0 change	93%	24%	
≥1 change	7%	76%	0.000
Lips tightly closed			
0 change	71%	24%	
≥1 change	29%	76%	0.005
Tongue pushing against the lower incisors			
0 change	57%	29%	
≥1 change	43%	71%	0.091
Dental rolls between the molars			
0 change	79%	33%	
≥1 change	21%	67%	0.009
Dental splint			
0 change	79%	29%	
≥1 change	21%	71%	0.004

* Chi2 test.

Table 3
Comparison between normal readers and dyslexic readers for changes in vertical heterophoria measured with the Maddox Rod Test according to spinal and podal then oral sensors.

	Normal Readers	Dyslexics Readers	p value*
Spinal and podal sensors			
Sitting in natural position			
0 change	71%	23%	
≥1 change	29%	76%	0.005
Sitting straight up			
0 change	64%	29%	
≥1 change	36%	71%	0.036
Standing in a natural position			
0 change	64%	28%	
≥1 change	36%	72%	0.035
Standing with a foam insole between the foot and the ground			
0 change	50%	24%	
≥1 change	50%	76%	0.110
Oral sensor			
Sensory			
0 change	50%	19%	
≥1 change	50%	81%	0.053
Mechanical			
0 change	71%	29%	
≥1 change	29%	71%	0.001

*Chi2 test.

mechanism of the variation of the ocular axes remains unclear. The quality of the images was not changed during the oral manipulation. However, it should be noted that the quality of the binocular balance depends not only on the fusing of the retinal images of both eyes but also on maintaining the tone of the ocular muscles. This tone is regulated by the internal monitoring of the innervations sent to the muscles (efference copy) with the afferent proprioceptive discharge.[18] The role of eye proprioception discharge is enhanced for visual localization when there is a conflict with the oculomotor plan perception, as was the case in our study.[8] Because proprioceptive information from the eye muscles is carried by the upper branch of the trigeminal nerve, it is therefore not so surprising that oral changes may interfere when ocular balance is unstable because of changes in retinal fusion.

Specific effects of oral stimulations on visual axis: each of the oral stimuli led to a huge difference between normal readers and dyslexics, except for inferior incisor stimuli. Three of the oral modifications were located exclusively in the anterior part of the mouth and were chosen because their effect is supposed to be more sensory than mechanical:

1) the tip of the tongue firmly touching the central retro-incisor papillae stimulates recovery of a corporal postural reflex related to contact with the lingual and palatine mucosa,[19]
2) the stimulation of the facial nerve with lips tightly closed has an antagonistic action on the trigeminal nerve (Bratzlavsky reflex),[20] 3) the tip of the tongue planted against the lower incisors mechanically stimulates the periodontal ligaments that may be involved in one aspect of the feeling of body ownership.[21]

Compared to stimuli involving the tongue and the lips, the action of the other stimuli was located further back between the molars (dental rolls) or the entire dental arch (splint). They are supposed to have a stronger action on the temporo-mandibular joint and its proprioceptive sensors, and modify occlusion intensely. Their action is obviously more mechanical, and the stimulation of the periodontal ligaments is more global and less precise. However, in our study, the effect on the visual axis was not different. This suggests that any action in the mouth is likely to have an impact on visual perception when the binocular balance is unstable.

Oral stimulations and posture regulation: the lability of the ocular effect depends on changes on spinal and podal sensation. This dependence was significantly more marked for dyslexic children and higher after oral stimulation. These results suggest the existence of links between eye stability, trigeminal information and postural regulation. They also suggest that these links could be more unstable in dyslexia. Postural adjustments use feed-back and feed-forward mechanisms. Feed-back information includes several types of afferent inputs: exteroceptive (skin sensitivity in the feet), proprioceptive (especially from the cervical, hip, ankle, and knee joints), vestibular (utriculus, sacculus, semicircular canals), and visual (retinal and muscle proprioception). For visual inputs, retinal flow, efference copy and extraocular muscle afferent information consecutive to eye movements operate congruently.[16] Interestingly, the presence of small vertical eye deviation like VH can alter postural balance in young healthy adults and VH correction improves postural stability.[22] Thus the appearance of a small vertical deviation of ocular axes during oral changes could be one of the mechanisms connecting the mouth modifications and postural imbalances. This phenomenon could be explained by the narrow relationship between the muscles of the eye and mouth in the trigeminal nerve nucleus. Indeed, the sensory neurons of extraocular muscles are present as along with the primary afferent neurons associated with muscles for chewing, tooth pulp, and periodontal ligaments.[23] There are also direct links between the trigeminal nucleus and the superior colliculus which receives visual, somesthetic, and proprioceptive afferent fibers and is involved in posture control and gaze movements.[24]

The link between VH and sensory oral modification is interesting because in the scientific literature, the relationship between the stomatognathic system and posture regulation is mainly centered on the responsibility of malocclusion or temporomandibular joint pathology, that is to say mechanical dysfunction.[25] The stomatognathic system, which is composed of muscle and ligament structures linked to the cervical region, is considered a functional complex known as the "cranio-cervico-mandibular system".[26] A change in the position of the mandible may affect the center of foot pressure (COP) position and gait stability.[27] In this case, proprioceptive and periodontal afference is sometimes said to be responsible, but mostly the mechanism is thought to be predominantly mechanical though it has been shown that anesthesia of the lower branch of the trigeminal nerve causes postural imbalance.[28] Nevertheless, the importance of mechanical stomatognathic factors is not always recognized because some studies do not find any relationship between posture, asymmetrical malocclusion or different dental positions, and temporomandibular disorders.[29] We showed that a change in posture modifies the behavior of the eyes during oral stimulation, suggesting more complex interferences between posture, mouth and eyes. They exist even if the stimulation modifies the occlusion or the position of the temporomandibular joint only slightly. Our results suggest that sensory stimuli are as active as the mechanical disturbances. It would be interesting to simultaneously compare the effect of sensory and mechanical stimuli on the posterior and the anterior arches.

We found that the effect of changes in oral stimuli on vision was greater in the group of dyslexic children than in the group of normal readers. The difference increased between the two groups of children when proprioception was modified in the back. Using a global approach, some clinical studies reinforce the possibility of a link between posture deficits and dyslexia,[30] but co-occurrence of postural deficits and dyslexia do not prove their interdependency, and postural regulation of dyslexic children has been the subject of several studies with somewhat contradictory findings. Indeed, many studies have demonstrated impaired automatization of balance control in dyslexic children and adults,[31] but others have failed to replicate this result.[32] Despite such discrepancies, there is a consensus that motor difficulties are frequent in the dyslexic population. This postural instability could indicate that such children lack the ability to assimilate multiple sensorimotor inputs. Interestingly, postural control can be improved by the use of very low-power oblique prisms (0.5°) to correct VH.[33] Our study suggests that this improvement could also be obtained with guided oral stimuli. It also suggests that therapeutic adjustments in the mouth could have a damaging effect on ocular stability and on postural regulation. These results reinforce the importance of inter-professional cooperation, especially in the care of children with specific learning disabilities.

Oral stimuli, VH and dyslexia: the majority of dyslexic children have both visual and phonological disorders. Imprecise eye movements, difficulty with visual recognition, and phonological disturbances are usually considered to have a neurodevelopmental origin.[1] Heilman has proposed that the mouth could play a role in the emergence of the phonological problems of dyslexic children who are unaware of the position of their articulators during speech.[12] The inability to associate the position of their articulators with speech sounds may impair the development of phonological awareness and the ability to convert graphemes to phonemes. The high level of oculomotor lability found in our study when the position of the tongue is changed might help to understand the presence of both visual and phonological disorders in dyslexia. It could also explain why some dyslexics have more difficulty reading aloud.[34] On the other hand, there is no association between the position lability of the ocular axes during oral stimulation and the level of delayed reading in dyslexics. This lability must be considered above all as a clue depending on the stability of general proprioceptive information. It does not intervene directly in the ability to read as it was demonstrated in a previous study.[35]

This study has highlighted the interdependence of the position of the visual axes and the trigeminal information that comes from the mouth when the fusion of the retinal images is manipulated. This is more marked for dyslexic children than for normal-reader children. This phenomenon varies according to posture. Our study opens a new field of research on the relations between oral sensory perception, visual perception and postural regulation.

Disclosure

The authors report no conflicts of interest in this work.
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