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Visual Training Helps Improve Reading in Dyslexic Children with Abnormal Crowding

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Authors' contributions

This work was carried out in collaboration between all authors. Author CA designed the study, managed the bibliographic search and wrote the first draft of the manuscript. Authors EB and LC recruited the patients and performed the experimentation. All authors read and approved the final manuscript.

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ABSTRACT

Aims: To evaluate the effectiveness of visual training aimed at improving the visual function in dyslexic children suffering from increased crowding.
Study Design: Single-masked crossover pilot study.
Place and Duration of Study: University of Turin and the Gradenigo Hospital, Department of Ophthalmology, Turin, between March and November 2014.
Methodology: 14 reading-impaired children (8-11 years) with increased paracentral crowding underwent a visual training devised to improve reading fluency by reducing lateral masking. Patients were asked to recognize trigrams of letters with different inter-letter spacing displayed at variable eccentricities on both sides of the fixation point (trigram training). Since any visual task chosen as a placebo could show some rehabilitative effect, placebo training was replaced by a period of reading practice, when reading exercises were recommended to be done at home.
Results: After two weeks of training, in the recruited sample reading rate for words increased from 1.88 syl/sec (SD:±0.74) to 2.19 syl/sec (±0.86). Reading rate for non-words improved from 1.13 (±0.39) syl/sec to 1.28 (±0.42) syl/sec. No significant improvement was found after the period of

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reading practice both at words and non-words. Analysis of variance showed a significant reading exercise x trigram training effect both for words (P= .0004) and non-words (P= .0001) in the recruited sample of disabled readers.
To confirm the ameliorative effect of training (not being involved a placebo), a second, smaller sample has been administered the reading practice before the treatment.
In this second group no substantial change in reading fluency was found after two weeks of reading practice, whereas after the trigram training reading rate improved by 11.8% at words and 29% at non-words despite, probably due to the small size of the second sample, results did not reach statistical significance.
Conclusion: Trigram visuoperceptive training demonstrated to be effective in improving reading rate in dyslexic children suffering from reinforced crowding. The ameliorative effect of the rehabilitation is found to be sharper in patients showing abnormal crowding compared to the non-classified dyslexics trained in a previous study. Interdisciplinary rehabilitative approach of developmental dyslexia should therefore consider also visuoperceptive rehabilitation aimed at normalizing lateral masking.

Keywords: Dyslexia; visual training; crowding; reading rate; trigram.

1. INTRODUCTION

Developmental dyslexia is a specific reading disability that affects approximately 4-10% of the scholar population [1,2]. A growing body of evidence is supporting the potential role of the visual function in the pathogenesis of this clinical condition. Apart from arguable evidence on abnormal motion perception [3-9], contrast sensibility deficits (see Skottun, [10] for a review), longer visual persistence time [4,11-16], or unstable binocular fixation [17-19], increased crowding seems to play an important role at least in a subtype of patients [20-26].

Crowding or lateral masking is the physiological phenomenon that makes neighboring letters unrecognizable if they are as close as to fall within a spatial interval, called *critical spacing*. According to the Bouma's law, the extent of the critical spacing (in degrees) is roughly half the eccentricity, so that the least spacing between letters required to make each character recognizable is 0.5φ (where φ is the eccentricity [27]). Even if increased crowding is typical of amblyopic subjects (see for example Levi et al. [28]), many studies found critical spacing to be abnormally wider around the fixation point also in a proportion of dyslexic children [20-26]. In these subjects the distance between adjoining letters in the paracentral region needs to be about one and a half wider compared to normal readers in order to make such letters recognizable [23].

In a previous study [29], we have suggested wider critical spacing in dyslexics to be related to anisotropic spatial relationship perception: the perception of the visual space "shrunk" along the horizontal axis would lead to perceived reduction of the distance between characters so as to make them falling within the boundary of the critical region. As a matter of fact, increasing interletter distance tends to improve reading rate and accuracy in dyslexic patients but not in normal readers [29,30]. Larger critical spacing is claimed to prevent from reading fluently by reducing the number of characters recognizable at each fixation, that is to say the so called *visual span* [31]. Since lateral masking increases with eccentricity, the visual span narrows the more the farther from the fixation point: this is the reason why in normal subjects peripheral reading speed would remain slower compared to central reading, even after the print size has been scaled.

Enlargement of the visual span is be achievable by training crowding in the peripheral visual field: intensive practice in recognizing the letters of trigrams displayed 10 deg above and below the fixation point, in fact, is found to be effective in making the visual span at those positions wider, thereby in making peripheral reading rate faster by 41% in a group of adult normal subjects [32]. Even if weaker, training benefits has been reported also in older adults [33].

If visual training focused on crowding is found to be effective in narrowing the critical spacing, therefore in enlarging the visual span and finally in increasing the peripheral reading rate in normal readers, it is worth wondering whether a similar practice can improve the reading rate of dyslexic children as well.

In a recent investigation [34], we have reported the results of the *Trigram* training, a visual training designed to improve parafoveal crowding based on the paradigm adopted in previous surveys [32,33]. In the dyslexic sample reading fluency improved after 2 weeks of *Trigram* training, while it did not change after the placebo. And yet, after the crossover the ameliorative effect tended to fade, making the outcome of the rehabilitation somehow uncertain.

In order to address this effect, we argued that the prominent phonological impairment affecting the recruited sample could mask the lexical improvement provided by the visuoperceptive training.

Moreover, the placebo we had chosen, consisting of repeated contrast sensitivity testing, could to a certain extent act as a weak rehabilitative procedure itself, biasing the statistical outcome.

The aim of the present survey is addressing these issues. The effect of the *trigram* training has been investigated in a sample of dyslexics with prevalent visuoperceptive impairment, that is to say with increased paracentral crowding.

In addition, to avoid any potential ameliorative effect of a putatively placebo treatment, the placebo training we adopted in the previous survey has been replaced by daily reading practice to be done at home.

2. EXPERIMENTAL DETAILS

2.1 Participants

From the Neuro-Ophthalmology Center of the University of Turin 14 dyslexic children (12 males, 2 females) aged 8-11 years (median 9 years) with increased paracentral crowding were recruited. The diagnosis of dyslexia, was based on its operational definition, i.e. lexical age reduced of at least 2.5 years with reading rate and accuracy below the second standard deviation compared to normal age-matched readers, normal intellectual ability and normal or above normal IQ, with visual acuity 60/60 and no behavioural or auditory impairment problems [3].

Selection criteria were: presence of developmental dyslexia as assessed by the neuro-psychiatrist at the reading battery of Zoccolotti [34], average to above-average intellectual ability, normal IQ as measured by Wechsler Intelligence Scale for Children (WISC-R), performance equal to normal readers in other academic subjects, best corrected visual acuity (BCVA) ≥ 60/60, increased paracentral lateral masking.

Exclusion criteria were general or ophthalmological diseases, hyperopia/myopia >2D, astigmatism > 1.5D, eso/exotropy, poor convergence, auditory impairment, Attention Deficit Hyperactivity Disorders (ADHD), behavioral problems, poor collaboration.

Children were enrolled after verifying the presence of abnormal crowding via trend analysis performed on their reading rate as a function of interletter spacing. The procedure has been previously described in detail [29,34,35] and will be summarized in the next section.

The parents were contacted by phone and their informed consent was obtained after explanation of the aim, nature and possible consequences of the study.

2.2 Materials and Methods: Procedure for Reading Performance Assessment

In order to better characterize the global reading performance of the subjects, before and after the treatment and the period of reading practice reading rate for words and non-words was estimated presenting trials made of words or strings nonsense with variable interletter spacing, ranging from 0.2 to 0.51 deg (distance computed center-to-center). The sample of words was chosen according to the age of the children.

More in detail, to test reading performance 22 presentations were displayed in randomized order on a high-resolution LCD screen at a viewing distance of 70 cm. Each presentation was made of 4 words placed side by side on the same line and made of 3, 4, 3 and 2 syllables (font Free Monospace), or 5 non-words made of, 2, 2, 2, 3 and 3 syllables. The subject was required, without being urged to the best performance, to read aloud each word in binocular conditions. Each presentation remained visible on the screen the time necessary to be read. Luminance of the letters was 0.3 cd/m^2, luminance of the background was 85 cd/m^2. Mean character size was 0.4 deg at the viewing distance (70 cm). At each trial words or non-words were presented at a different value of interletter spacing, that is 0.2, 0.23, 0.25, 0.27, 0.28, 0.31, 0.36, 0.4, 0.44, 0.47 or 0.51 degrees, in random order. Two trials were presented per each interletter spacing, and the best performance was then selected automatically by the instrument. The *cumulative reading rate* (CRR) was then computed by averaging each best estimate [29,34,35]. Indeed, we believe the CRR accounts for the reading performance of the subject suffering from reinforced crowding in a more comprehensive way compared to the standardized reading measure. By averaging reading rate values from narrower- to wider-than standard spacing, in fact, we expect CRR to be a more veridical index of reading performance compared to the conventional 0.4 deg-spacing: as a matter of fact, the latter does not consider the higher-than expected difficulty of such patients to read in more demanding conditions (spacing lower than 0.4 deg) or, in turn, the higher-than expected facilitation in reading strings with interletter spacings wider than 0.4 deg.

The judgment of abnormal crowding is based on trend analysis performed on reading rate as a function of interletter spacing. According to the procedure described in detail by one of us [35], it is assumed that progressive increase of the distance between letters reduces lateral masking between adjoining characters, so that reading rate improves. When the spacing between the characters of the string becomes wider than the parafoveal critical spacing of the reader, his/her reading rate is expected to remain stable. The spacing at which such improvement ends is taken as the parafoveal critical spacing of the reader. In a previous population study we have computed the parafoveal critical spacing in a large number of schoolchildren aged 8-10 years according to this paradigm. Its extent was lower than 0.4 deg (see Aleci, [35] for detailed informations).

In Fig. 1 the difference between expected and measured critical spacing in the sample is depicted. Median parafoveal critical spacing was 0.47 deg (range:0.44-0.51).

2.3 Training Procedure

The training used in the experiment (we will refer to as *trigram training*) has been described in a previous paper [34]. In brief, triplets of Sloan letters (in randomized combination) are displayed for 200 msec along the horizontal meridian on the left and right side of the fixation point, at different values of eccentricity (in a fixed order: right 2,4,6,8,10 deg, then left 2,4,6 deg, in total 45 presentations per locus) and with different values of spacing. Luminance of the stimuli was 0.3 cd/m^2, luminance of the background was 85 cd/m^2. The size of the letters is scaled according to the eccentricity so as to be well beyond the recognition threshold at every tested locus. The exam is performed binocularly.

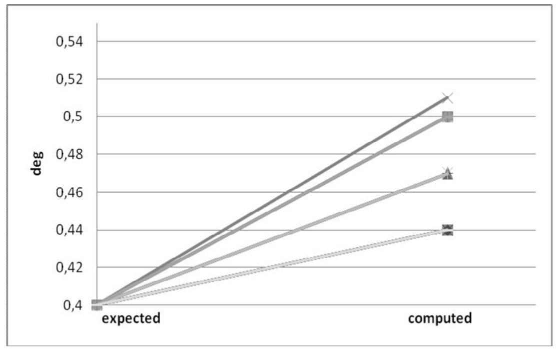

Fig. 1. Expected and computed critical spacing in the recruited sample

Trial after trial subjects are asked to look steadily at a central mark (an emoticon changing at each presentation in order to help stable fixation) and at the same time to recognize the three letters making up the trigram displayed paracentrally. No feedback is provided. During the training session fixation is checked by a second operator and the subject is constantly promped to look steadily at the central emoticon. The trial is repeated in case a shift of fixation were detected by the second operator.

In the previous as well as in the present experiment each subject underwent 1 session (average duration: 15 minutes) per day (in the morning) for 5+5 consecutive days (two weeks from Monday to Friday). Therefore, in total each patient was administered 3600 trials. Session after session spacing between the letters of the trigram is progressively reduced, making therefore the task even more demanding.

At each session the distance between the three letters is computed by the software as a multiplicative proportion of the critical spacing (center-to-center of the letters), according to the Bouma’s law. The widest interletter spacing is 1.32 (φ/2) at the first session (day 1) and it is reduced at each session till to 1.05 (φ/2) at day 10. After the last session reading exercises were recommended to be done at home daily 15 minutes a day for two weeks (*reading practice*). Lexical performance at the end of the trigram training (T1) and of the reading practice (T2) was then measured and compared.

All authors hereby declare that the experiment has been examined and approved by the ethics committee and has therefore been performed in accordance with the ethical standards laid down in the 1964 declaration of Helsinki. All applicable institutional and governmental regulations concerning the ethical use of human volunteers were followed.

3. RESULTS

All the recruited children completed the rehabilitation program.

At the end of the training (T1) cumulative reading rate for words increased from 1.88 syl/sec (SD:±0.74) to 2.18 syl/sec (± 0.86). Cumulative reading rate for non-words improved from 1.13 (±0.39) syl/sec to 1.28 ((±0.42) syl/sec. The pre-treated group then underwent the reading practice at home. At the end of the reading practice (T2) cumulative reading rate changed from 2.18 to 2.23 syl/sec (±0.96) when subjects were asked to read words, from 1.28 to 1.29 ((±0.40) syl/sec when they were required to read non-words.

Repeated measures analysis of variance performed respectively on CRR for words and non words showed significant effect of the trigram training compared to the reading practice (F:10.64 , *P*= .0004, and F:13.35, *P*= .0001, respectively).

Reading rate improved by 16% at words and by 13.2% at non words (Tukey-Kramer multiple comparison test, words: $q_{3.51}$=5.20, p<.01, non-words $q_{3.51}$=5.20, p<.001); in turn, no further increase in lexical speed was found after the reading practice (only 1.8% of improvement at words, 0.7% of improvement at non-words: Tukey-Kramer $q_{3.51}$=0.81 and $q_{3.5}$=0.26, p>.05 in both reading tasks).

Is should be noted that the effect of the trigram training remained stable after two weeks (Tukey-Kramer $q_{3.51}$=6.01 and $q_{3.5}$=6.46, p<.001 in both reading tasks: Fig. 2, upper left panel and Table 1).

To further ascertain if the effect of the treatment lasts over time, 8 children (median age: 9 years) of the recruited sample were recalled and re-evaluated four weeks after the trigram training (T3).

In the sub-sample reading rate improvement is found to be overall stable when tested with word as well as non-words. In fact, words reading rate at T3 decreased just by 3% compared to T2, being this slight loss not significant (Tukey-Kramer $q_{3.94}$=1.03, p>.05). In turn, the gain remained significant compared to T0 (Tukey-Kramer $q_{3.94}$=5.06, p<.01).

Likewise, non-words reading rate at T3 decreased just by 1.7% compared to T2 (Tukey-Kramer $q_{3.94}$=0.44, p>.05: Fig. 2, upper right panel and Table 1).

Finally, to confirm the ameliorative effect of training (not being involved a placebo), a second, smaller sample (5 subjects, age:8-10 years) was administered the reading practice before the treatment (*reverse group*). Inclusion and exclusion criteria were the same as the main sample. The members of this second sample belonged to the same socio-cultural contest as the main group.

In the reverse group reading fluency was unchanged after two weeks of reading practice (from 2.20 [±0.86] to 2.19 [±0.77] syl/sec) when tested with words, while improvement by 11.8 % (2.45 [±0.65] syl/sec) was obtained at the end of the trigram training.

A similar trend is found at non-word testing: reading rate was roughly the same after the reading practice (from 1.14 [±0.46] to 1.19 [±0.44] syl/sec), whereas an appreciable improvement (1.47 [[±0.38], that is 29%) was computed at the end of the training (Fig. 2, lower panel and Table 1).

Despite the sizeable increase in reading speed after the trigram administration compared to the reading practice, in the reverse group the trend did not reach a significant level both at words and non-words testing (Repeated measures ANOVA: F=2.41, p=.1 and F=1.28, p=.3, respectively). It is arguable the lack of significance to be due to the small size of the enrolled sample.

The results of the experiment are summarized in Table 1.

4. DISCUSSION

It s well known that increased crowding affects the ability to read fluently, so that on the one hand reading rate is considered a main marker of the success of the remediation program in amblyopic subjects [36,37], on the other hand crowding is found to be stronger in the paracentral region of the visual field in many disabled readers. Upon this basis, rehabilitating crowding could help improve the lexical function.

Indeed, many studies have confirmed the effect of visual training in improving crowding both in the peripheral or paracentral visual field of normal subjets [32,38-42], see Huurneman et al. [43] for a review).

Recently, we argued that if training peripheral crowding is effective in improving peripheral reading speed of normal readers, training parafoveal crowding could be effective in increasing the reading rate of dyslexics as well.

So, in a previous investigation a sample of dyslexic children had been trained by means of a rehabilitation paradigm based on the presentation of trigrams, similar to the technique used to train the peripheral crowding of normal readers in the aforementioned studies [34]. Unlike the former, the triplets of letters were displayed at different eccentricities along the horizontal axis closer to the fixation point, and the effect was evaluated by testing the lexical performance with a sample of words and non-words.

In that study some evidence was found that visual training aimed at reducing the effect of crowding may improve the lexical function of dyslexics. In fact, when tested with words, reading rate improved after the treatment (from 1.54 syl/sec [±0.60] to 1.74 syl/sec [±0.64], *P*=.001).) but not after the placebo. The improvement lasted at least for two weeks. When tested with non-words, reading rate improved two weeks after the treatment (CRR from 0.94 [0.68-1.55] syl/sec to 1.03 [0.85-1.63], but not after the placebo. Results, however, revealed to be quite controversial, as the ameliorative effect of the training was not confirmed after the crossover (group G2). Two main possible explanations for such equivocal finding have been advocated, namely:

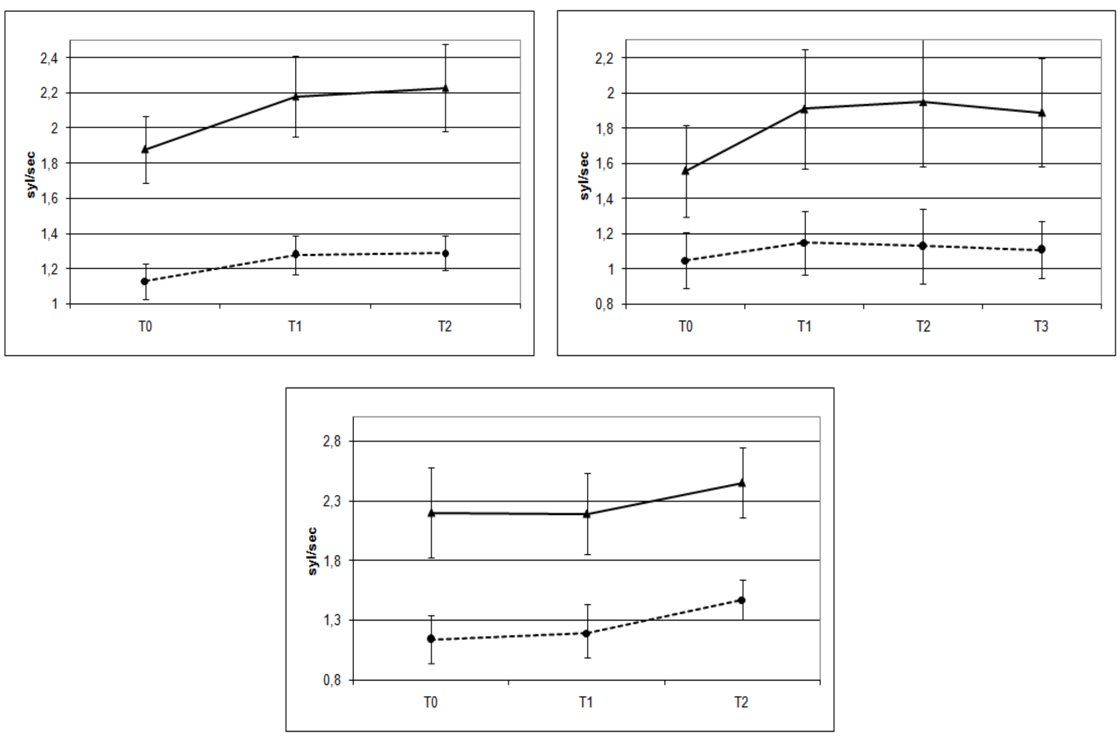

Fig. 2. Upper left panel: reading rate for word (continuous line) and non words (dotted line) after the trigram training (T1) and the reading practice (T2). Upper right panel: effect of the training after 4 weeks in the sub-sample. Bars are standard error of the mean. Lower panel: Reading rate for word (continuous line) and non words (dotted line) in the reverse group. T0=baseline, T1=after the reading practice, T2=after the *Trigram* training

Table 1. Results from the main sample, after prolonged observation, and from the reverse sample. In brackets is standard deviation

	Main sample		**gain vs T0**		**Prolonged observation**			**Reverse sample**		**gain vs T0**	
Phase	**W**	**NW**	**W**	**NW**	**W**	**NW**	**Phase**	**W**	**NW**	**W**	**NW**
T0	1.88 (±0.74)	1.13 (±0.39)			1.56 (±0.73)	1.01 (±0.41)	T0	2.20 (±0.86)	1.14 (±0.46)		
T1 (AT)	2.18 (±0.86)	1.28 (±0.42)	16%	13.2%	1.91 (±0.96)	1.15 (±0.50)	T1 (ARP)	2.19 (±0.77)	1.19 (±0..44)	0%	4.3%
T2 (ARP)	2.23 (±0.96)	1.29 (±0.40)	2.2%	0.7%	1.95 (±1.06)	1.13 (±0.48)	T2 (AT)	2.45 (±0.65)	1.47 (±0.38)	11.8%	29%
T3 (4AT)					1.89 (±0.88)	1.12 (±0.45)	(±0.)				
p	*.0004*	*.0001*			*T2 vs T3: >.05*	*T2 vs T3: >.05*		*>.05*	*>.05*		

1. The presence of a strong phonological impairment in the enrolled group. Such phonological impairment could mask the lexical improvement provided by the visuoperceptive training. In other terms the recruitment criteria of the sample did not consider a preliminary classification aimed at focusing the treatment on "visual" dyslexics, i.e. those patients mainly characterized by defective visuospatial component;
2. Repeated contrast sensitivity testing chosen as a placebo could to a certain extent act as a (albeit weak) rehabilitative procedure itself, biasing the statistical outcome.

In the present study these two putative flaws have been ruled out by selecting a group of dyslexics with increased parafoveal crowding. In addition, the administration of the placebo by the operator has been replaced by simple reading practice to be done at home.

The results are in line with the finding of our previous survey, but the ameliorative effect of the training looks sharper. In fact, the improvement provided by the *trigram* training was more evident in the group of disabled readers with reinforced lateral masking compared to the non-selected dyslexic sample of our previous investigation: reading rate improved by 16% at words and by 13.2% at non words compared, respectively, to 13% and 9.5% as found in the not classified sample.

In turn, after the period of reading practice the gain was negligible, being considerably lower compared to the lexical improvement measured at the end of the putative placebo (contrast sensitivity testing) period adopted in our previous survey (actual gain: 2.2% vs 6.3% at words and 0.7% vs 3.9% at non-words (Fig. 3).

This finding seems to indirectly confirm that contrast sensitivity repeated testing may have some ameliorative effect on the lexical function, therefore biasing the outcome of our first investigation.

The fact remains that even in dyslexics with increased lateral masking the reading improvement after the training is just slightly greater compared to the unselected dyslexic population. As a possible explanation for such unexpectedly mild difference is that in the non-selected sample of our previous study some of the children could suffer from abnormal crowding to a certain extent. However, from our results it is arguable that the visual share responsible for the reading disability is no more than 10-16%, even in selected patients suffering from increased lateral masking, being the rest of the share due to linguistic and phonological alterations. Moreover, the gain is consistently lower compared to the effect of a similar training strategy on the peripheral reading of normal subjects [32]. As already advanced, this discrepancy could depend on the lack in the dyslexic population of the automatisms that normal readers have learned during their normal lexical development, as well as on the different paradigm employed to assess reading performance [34].

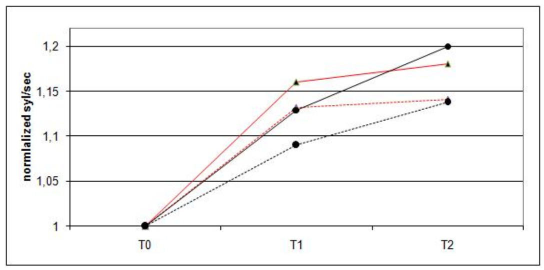

Fig. 3. Amount of improvement (gain) at words and non words in the present study (red lines) compared to the previous investigation [34: Aleci et al. 2013: dark lines). Continuous lines: words, dotted lines: non-words. T1: at the end of the trigram training, T2: at the end of the reading practice (actual study) or of the putative placebo (contrast sensitivity testing, previous experiment [34])

Without doubt the lack of fixation monitoring via eye-tracker is probably the main flaw of the procedure, even if for a similar training paradigm "little detectable differences between observers with and without eye-movement monitoring" has been reported [32]. In addition, the effect of the training has been considered for a restricted interval (4 weeks) of time and in a limited sample. To better understand this crucial aspect, next studies should iconsider longer follow ups, involving more patients. Finally, to confirm the effective improvement provided by the rehabilitative strategy, in subsequent cross-over investigations the *reverse"* group should be more consistent.

5. CONCLUSION

In conclusion, visual training focused on crowding should be considered in dyslexics affected by abnormal lateral masking. Treatment of dyslexia that ignore this possible additional tool runs the risk of making the rehabilitative action a blunt bullet.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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