Instability of Fixation in Dyslexia: Development – Deficits – Training

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ABSTRACT

Background: While eye movements as a necessary prerequisite for natural viewing become more and more important as a part of the neurological diagnostic evaluation, the utilization of fixation is not as well established. This paper discusses two different and independent types of instability of fixation which can only be recognized by recording and analyzing specific movements of the eyes that include: (i) binocular instability (slow movements of the two eyes with different velocities mostly of opposite sign) and (ii) simple instability (small involuntary conjugate saccades (intrusions) during periods of fixating a stationary fixation point).

Methods: A prosaccade task with overlap conditions is utilized which requires periods of stationary fixation as well as saccades to a new stimulus target. This allows the quantitative determination of the appropriate variables.

Results: The diagnostic data from children diagnosed with dyslexia are compared with those of age-matched control subjects. An optomotor therapy procedure with one eye covered reduced the binocular instability by 50%, while the simple instability was reduced by 20%.

Conclusion: The results indicate that the two types of fixation instability are independent from each other. Both may contribute to problems of visual processing of those with dyslexia and possible other learning problems.

Keywords: Eye movements, fixation, binocular vision, saccades, dyslexia, binocular instability, training.

Introduction

Under natural viewing conditions and various other situations, it is necessary to maintain fixation at a certain point. Fixation must be stopped, however, when another saccade is generated. This applies not only monocularly but binocularly. The binocular neurons in striate cortex are highly sensitive to small disparities[1] and both eyes must stay in place for proper stereo vision to occur. Fixation therefore is an active process in the brain, which stays under voluntary control but may be also working automatically. The role of fixation in the diagnosis of the quality of vision has been neglected for a long time. Today, there is plenty of evidence that fixation is an active neural process. Neurons whose activity is related to fixation were found in the supplementary eye fields,[2] in the frontal eye fields,[3] in the posterior and inferior parietal cortex,[4-6] in infero-temporal cortex,[7] in striate cortex,[8] in substantia nigra pars reticulata,[9] and in the brain stem.[10]

This multi-representation of fixation in different brain areas emphasizes the functional significance of this basic optomotor function for vision. Especially, the activity of neurons in the frontal pole of the superior colliculus is enhanced during fixation and suppressed during saccades.[11] This observation has allowed us to develop insights into the basic neurophysiological process of the optomotor cycle consisting of saccades and of the periods of fixation in between.[12] Only when the system is in a state of "disengaged" fixation from the saccade system can it generate express saccades, i.e., activation of the optomotor reflex.[13] For a more complete review see Fischer and Weber's article.[14]

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The investigation of fixation in relation to the generation of saccades as part of the optomotor cycle in human observers[15] has lead to the question of instabilities of fixation: what kinds of instabilities are possible and how can they be measured. In principle, fixation may be disturbed by small involuntary saccades (intrusive saccades) or by slow drifts of the two in different directions thereby losing the proper angle of conversion between the two eyes.

Further questions require answers as well: Is it possible that these types of instabilities of fixation decrease with increasing age of normal subjects? Is it possible that dyslexic children demonstrate such instabilities as suggested by earlier research,[16,17] and how many of them are affected? Finally, we want to know if training of fixation can reduce these instabilities. For example, reading exercises with one eye covered improved reading in children with dyslexia, who had failed the Dunlop Test.[16] The failure of this test may be a consequence of instable binocular fixation. In this case, monocular training could be used to improve the visual capacities of dyslexics. In line with this argument it has been noted that dyslexics may show a heterophoria that can interfere with the reading process as well.[18]

In a recent paper the control of saccades of dyslexic subjects was compared with that of age-matched control subjects.[19] It was found, that large proportions of dyslexics exhibit a deficit in antisaccade performance. The present paper may be considered as an extension of our knowledge about the role of eye movement control in dyslexia. It also constitutes an extension of the methods that may be used in optometry to find and to improve such deficits. The goal of the paper, however, is not to increase our theoretical understanding of the nature of dyslexia.

The raw data were collected since 1991 until 2006. This is the reason for the large number of dyslexic subjects contributing to the analysis that is presented here.

Methods

Subjects: Control subjects were recruited from local schools in the area of Freiburg, Germany. None of them had academic problems. (Diagnostischer Rechtschreibtest, DRT3/4). Dyslexic subjects were identified by low scores in reading (Züricher Lesetest), in spelling (DRT3/4), and by normal or higher scores in intelligence tests (KABC). This procedure follows the generally accepted international definition of dyslexia.

Table 1: The table gives the numbers of subjects in each group and in each age group.

Age group	7-8 y	8-9 y	11-13 y	14-17 y
Binocular Stability Controls: N=129	26	45	41	17
Dyslexics all: N=2267	587	912	615	153
Dyslexics specific: N=421	96	175	123	27
Simple Stability Controls: N=170	35	59	42	34
Dyslexics all: N=2428	635	973	653	167
Dyslexics specific: N=466	105	192	138	31

It is also agreed that dyslexia is a neurobiological not a psychological problem, but dyslexia may create psychological problems.

Age groups: all subjects of this study were 7 to 17 years old. They were divided into 4 age groups: 7-8; 9-10; 11-13; 14-17y. The range of the age groups was increased with increasing age because strong changes with age were expected at younger ages (7-10y) as compared with older ages (11-17y). The total number of subjects depended on the completeness of data for each variable (see below). Table 1 presents the numbers of subjects in each group and in each age group. Within the test groups two numbers are given. "Specific" means that only subjects with a complete diagnosis of dyslexia (see previous paragraph), including the result of an intelligence test, were accepted as members. A second group contained the subjects who had reading and/or spelling deficits, but the results of an intelligence assessment were not available. We have analyzed the binocular and the simple fixation instability of both groups separately and did not see any significant differences, indicating that intelligence has little or nothing to do with the results. Therefore, both groups were combined within the "all" group.

The number of control subjects is different for the 2 studies, because we started to collect the data for the binocular stability only after we had the technical equipment for recording the movements of both eyes.

Eye movement recording: Infrared light corneal reflection techniques were used throughout the studies (Iris Scalar or ExpressEye[20]). Both instruments allow a spatial resolution of 0.2 deg of visual angle and a temporal resolution of 1ms for each eye.

Eye movement task: The well known prosaccade task with overlap conditions was used. It requires two periods of fixation interrupted by one visually guided saccade. Each trial starts with the presentation of a fixation point for a second until a target stimulus 4 deg to the right or left was presented in addition to the fixation point. The subjects were instructed to make a saccade to the target stimulus (a prosaccade) and maintain fixation of this new fixation stimulus for another 700ms until the end of the trial. Additional details have been described earlier.[21] Altogether 200 trials were given, 100 with the target stimulus 4deg at the right and 100 trials with the target 4deg at the left in random order.

Definition of variables: The following variables were determined:

(i) Binocular fixation instability: From the position signal of both eyes the relative velocity between the right and the left eye was calculated. Given the two eyes keep the angle of convergence constant, the relative velocity should be zero. Significant deviations from zero indicate that the angle of convergence is changing and therefore the binocular stability is lost as long as the velocity becomes zero again. In this way periods of binocular instability were determined and added up during each trial. Each trial was assigned the percentage of time, during which the binocular stability was lost (bdx). The percentage of trials in which the bdx exceeded 15% was assigned to each subject as a measure of binocular stability. This number is called the binocular index (Bindex). The cut-off of 15% was used on the basis of an analysis of the scatter plot of bdx versus the mean relative velocity of the two eyes within each trial (see Figure 2, lower diagram). The extremely strong correlation of the variables is lost at bdx-values above 15%.

(ii) Simple fixation instability: The number of saccades that occurred before the target stimulus was presented was counted. These saccades interrupted fixation at a point in time when no saccades should be made at all. The number of these intrusive saccades per trial was used as a measure for "simple" instability of fixation. These saccades occurred simultaneously in both eyes (conjugate saccades). This suggests that it is appropriate to analyze the movements of one eye only.

Training: the subjects were given a visual orientation detection task in which a small oriented stimulus (capital letter T) changed its orientation quickly in a random series of up-down-left-right movements. After the series ended, the subject had to press one of the 4 arrow keys of the training device which corresponded to the last orientation of the stimulus. This task forces the subject to maintain fixation at the small stimulus, because otherwise the chances of missing the correct orientation were large. During the daily training session 200 trials were used. The training lasted 7-15 min every day for a period of 3 weeks. The training was performed by the children at home using a small device with keys and a small LCD display. As the response of 70% or more of the trials were correct, the next session was made more difficult by shortening the presentation time. The device stored all data from all sessions. When the device was sent back the data were downloaded and analyzed to determine the compliance of the subject and to evaluate the progress made by each subject. More details have been described in an earlier paper.[21] During the training the subjects covered one eye (see results).

Analysis of data: Effects of age were investigated by correlation analysis. For each type of variable the mean value of each age group and its standard error were calculated and shown as functions of age. The corresponding mean values were also calculated for the dyslexic subjects and compared with those of the controls of the same age group. Correlation analysis and t-tests were used for statistical analysis. ANOVA were not used because of the large differences of group size.

Moreover, it was determined how many dyslexic subjects failed to reach the age norm as defined by the 16th percentile of the controls. This measure was used for two reasons: First, it is robust against deviations of the distribution of the experimental values from the Gaussian "normal" distributions. Second, the cut-off of the 16th percentile is the same as a cut-off of the mean value plus one standard deviation of a Gaussian distribution.

The Ethic Committee of the Medical Faculty of the University of Freiburg has approved the methods described above.

Results

The results will be presented in 3 sections, one dealing with the binocular instability, another with the simple instability, and the last with the effects of training on these types of instabilities of fixation.

Binocular Instability

Figure 1 shows the traces of eye movements of two single trials recorded from a single subject performing the prosaccade task with overlap conditions. The left and right eye movement can be seen as indicated. The relative velocity of the two eyes is shown by the

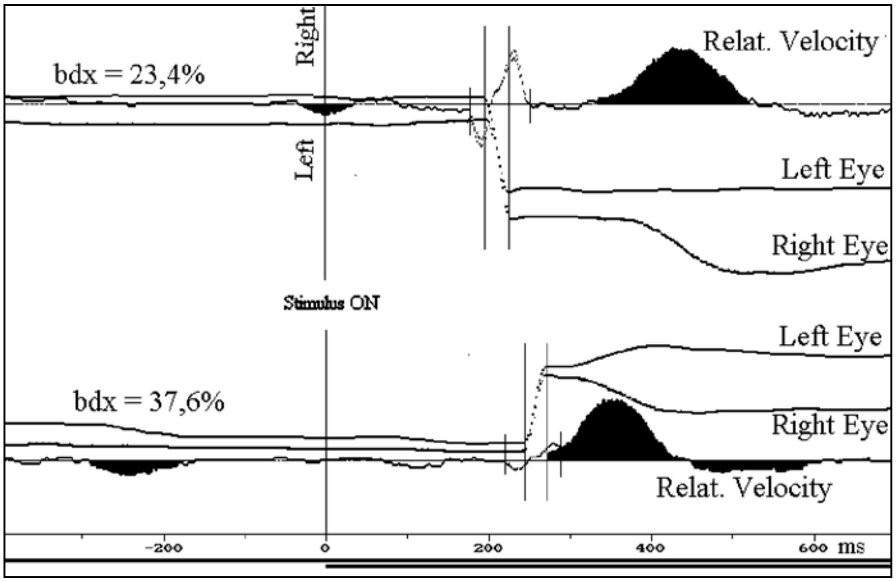

Figure 1: *The figure shows the eye movement traces from 2 trials of the same subject. Right and left eye movements can be seen as well as the relative velocity of the two eyes. The beginning and the end of saccades are marked by long vertical lines. Periods in the velocity trace, where the relative velocity was sigificantly different from zero are colored in black. The sum of the length of these periods expressed as the percentage of the trial duration serve as a measure of binocular instability in the trial (bdx). Periods shortly before and shortly after saccades (marked by short vertical lines) are excluded from this analysis.*

3rd line. During the beginning of the trial both eyes do not move very much so their relative velocity is close to zero. After the obligatory conjugate saccade, however, the right eye alone moves to the left and the relative velocity deviates significantly from zero as noted by the time periods marked in black.

The lower part of the figure depicts another trial from the same subject. In this case both eyes start moving after the saccade, with the right eye moving to the left, and the left eye to the right. The sum of the black portions of the velocity trace given as a percentage of the duration of the complete trial is assigned to the corresponding trial.

After the analysis of a complete session the data are visualized as shown by the Figure 2. The upper left diagram shows the distribution of the bdx values, the middle part shows the distribution of the relative velocity values. The lower left diagram shows a scatter plot of the velocity values versus the bdx of each trial. The strong correlation indicates, that the two variables are not independent of each other. Therefore, we decided to use the bdx only to characterize the binocular instability Bindex of each subject.

In this case the subject was assigned a Bindex of 81%, i.e., in 81% of the trials the bdx values exceeded a threshold of 15%.

The age curve of the two groups of subjects is shown in Figure 3. The figure shows the slow decrease of the instability with age. In both groups the coefficients of the linear correlation between Bindex and age were small (controls: $r = -0.13$; dyslexics: $r = -0.17$) with significance p-values above 0.15. When the total group was analyzed the regression coefficient was even smaller ($r= -0.09$), but the significance value dropped below 0.001. While this might be interpreted theoretically as a "significant" effect of age, in practice this has no meaning, because it is just the large number of subjects which causes the p-value to decline.

The binocular instability was systematically higher for the dyslexics, but there is also a large scatter in all age groups. The two-tailed test of the difference between the control and the dyslexic group reached a significance of $p=0.03$. Using the "all" group the p-value was 0.007. When counting the percent numbers of dyslexic subjects whose Bindex was larger the 16–percentile of the controls, one obtains 25% as a mean value across the 4 age groups.

Eye Dominance of Binocular Instability

As in natural stereo vision, one expects a certain amount of eye dominance to be also present in binocular instability. Therefore, in an analysis of the data of 72 control subjects and 68 subjects with dyslexia a Bindex was assigned to each eye depending on which eye caused the instability in a given trial. The difference between the right and left eye values can be regarded as a measure of eye dominance in causing the instability.

The Figure 4 shows the distributions of the differences between the right and left Bindex values. As can be seen only in a small numbers of subjects the binocular stability could be reliably assigned to one or the other eye. In most of the cases either both eyes moved simultaneously, or the right eye (on some trials) and the left eye (on other trials) caused the instability. Among the dyslexic subjects the left eye was causing the instability more often (23%) as compared to the right eye (3%). In 74% of the cases the instability was caused by both eyes. The same consideration of the

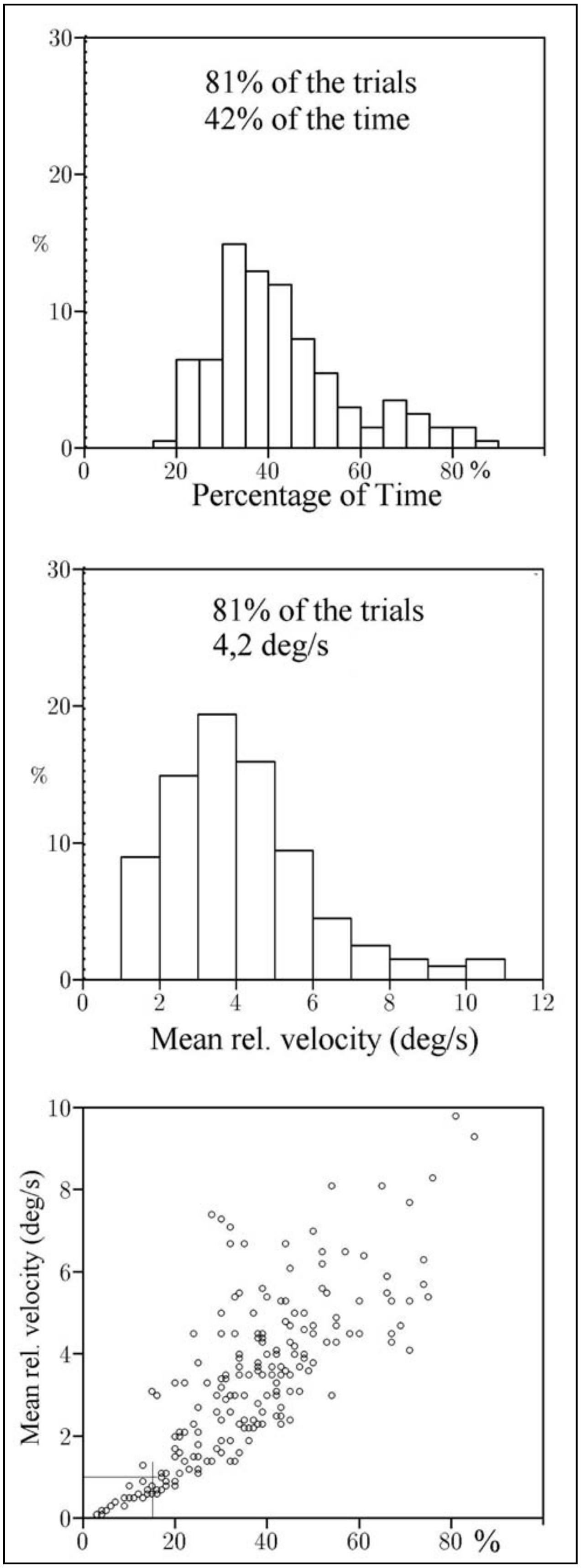

Figure 2: *The diagrams indicate how the binocular instabilities in the single trials (the bdx) were used to assign a single value Bindex to the subject. In this case the Bindex was 81%. The thin lines in the lower diagram indicates the cut-off bdx=15%. Details in the text.*

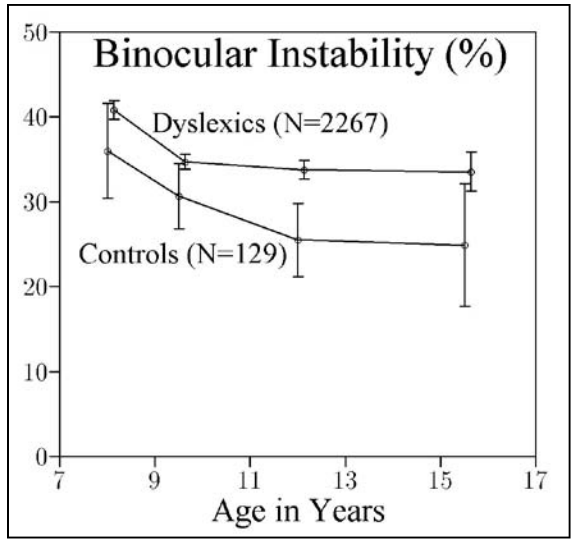

Figure 3: *The binocular instability (Bindex) as a function of age for both groups of subjects. The vertical bars indicated the size of the standard error.*

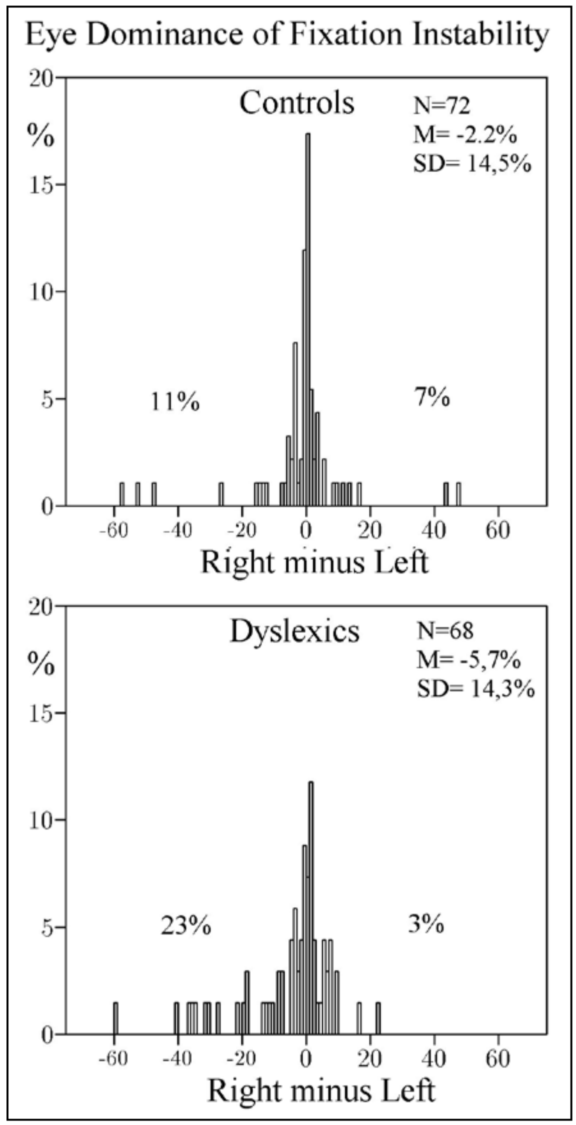

Figure 4: *The distributions of the differences between the Bindex values of the right eye and left eye.*

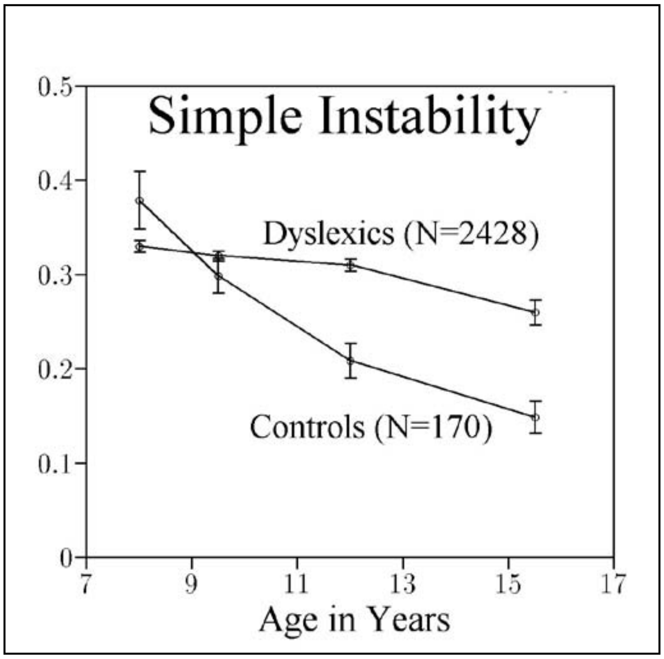

Figure 5: *Shows the simple instability of fixation for both groups as a function of age.*

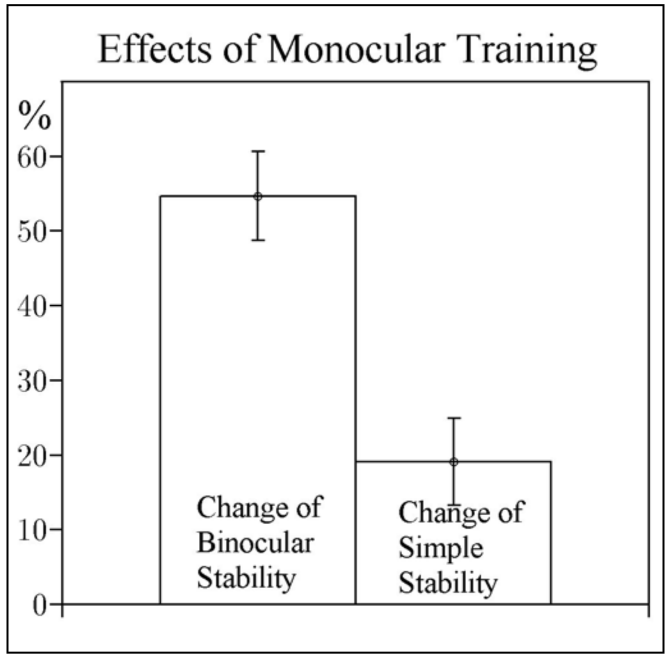

Figure 6: *The improvements of binocular and simple stability by a monocular training in percent reduction of the mean Bindex (left) and mean number of involuntary saccades per trial (right). N=27.*

data of the control group notes that 82% of the cases of binocular instability was caused by both eyes.

Simple Instability (Involuntary Intrusive Saccades)

The Figure 5 shows the age development of the simple instability of fixation. Both groups start with relatively high values of intrusive saccades. With increasing age this number decreases more for the controls than for the dyslexics. The linear regression coefficient (instability versus age) was r= -0.47 (p<0.000) for the controls and r= -0.14 (p<0.002) for the dyslexics. The results for the "all"-group was r=-0.10 (p=0.000). Unlike the binocular instability, the simple instability depends on age.

The percentage of dyslexics failing the 16th percentile increases from 10% to 20% in the 2 younger groups (16% is the value for the control group) and to 31% and 48% for the two older groups. In other words: simple instability is a problem for dyslexic children above the age of 10 years.

Independence of Binocular and Simple Instability

One may argue that both the binocular and the simple instability arise from a common dysfunction. To test this hypothesis the correlation coefficients between the two variables were calculated separately for the two groups. The coefficients were below 0.2 and did not reach significance (p>0.1). This result indicates that the two types of instability are independent from each other.

Effects of Training

Once instability was detected by using the 16th percentile criterion the question was whether or not daily practice of a visual fixation task would reduce the instability. We adopted the idea of J. Stein, who used monocular reading sessions in cases of dyslexic children who failed of the Dunlop Test.[22] We used monocular training of a fixation task.

This study was conducted with 27 dyslexic children who failed to reach the 16th percentile of the binocular fixation stability of the controls. Their simple instabilities were also measured before and after the training. The training consisted of a daily practice of a visual fixation task (see methods) for 3 weeks.

In cases where a dominance of one or the other eye was found, the "weak" eye which caused the instability most of the time was used during the training sessions. In the other cases, the left and the right eye were covered alternately from one training session to the next.

The pre- and post-training values were compared by the two-tailed student t-test. For the binocular instability the significance was p=0.0000, for the simple instability the significance was p=0.08. i.e., it failed even the 5% limit.

To see the amount of the training effects on binocular and simple stability, we calculated the percentage of differences before and after the training.

The result is shown by Figure 6: while the binocular stability was improved by about 55%, the simple stability improved by 19%. The effects on binocular fixation were very strong: 74% of the children reached values below the 16th percentile of the pre-training values.

The simple fixation stability was improved in only 41% of the children. Despite the statistical insignificance of the pre-post-difference, a number of 41% is meaningful from a practical/clinical point of view.

The scatter plot of the percentages of improvements of the binocular versus the simple stability exhibits no significant correlation. This result supports the independence of the two types of instability.

Discussion

The data presented in this paper describe two types of stability of fixation as defined by (i) a stable angle of convergence between the two eyes (binocular stability) and (ii) by the number of unwanted (involuntary, intrusive) saccades per trial (simple stability).

From age 7 to age 17 years the binocular stability shows only a tendency towards developmental improvement, but fails to reach significance in a correlation analysis. The simple stability, on the other hand, keeps improving significantly reaching its "best" value only at adult age.

These two types of stability are independent of each other, because their values do not correlate and because binocular stability can be strongly improved by training, whereas the simple instability improves only by smaller amounts. The strength of the improvements of the two types does not correlate and the time course of the development is different.

Dyslexic subjects have higher instabilities as compared with their corresponding age group. The percentage of affected subjects was 25% for the binocular instability independent of age. For the simple instabilities only the two older groups exhibit percentages of 31% and 48% of dyslexic subjects falling below the 16th percentile of the pre-training values.

Daily practice helps to improve binocular fixation by 55%, while simple stability improves by only 19%. To the extent that the binocular instability causes dynamic problems of stereo-vision, the trained subjects may have less and shorter periods of double images arriving at cortical levels of visual processing. This in turn makes it easier for them to identify letters and short sequences of letters with the result of fewer problems in reading.

But these problems are not the only ones encountered by dyslexics. A real help for dyslexic subjects may need improvements of other deficits as well. These can be deficits in the control of saccades by the frontal brain,[23] weaknesses in subitizing and number counting[24,25] as well as deficits in auditory differentiation.[26] Except for poor voluntary saccade control these are problems arising in the early processing of the neural signals on their way from the sense organs to the visual cortical structures. Therefore, the diagnosis and the therapy of these deficits do not rely on language processing and can be used irrespective of the language the subjects are speaking. Positive effects of training of saccade control on reading in dyslexic subjects have been reported in a earlier publications.[27,28]

During the period from 1991 we collected data from many children exhibiting dyscalculia and attention deficits. The preliminary analysis of this data has shown that there is little difference between these groups and those with dyslexia. This means that specific deficits in fixation are not specific to dyslexia. It rather appears that difficulties in acquiring reading, spelling, and basic arithmetic skills can be caused by combinations of deficits in the afferent channels from the sensory organs to cortical structures and/or in saccade control.

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