Article

Saccade Control in Dyslexia: Development, Deficits, Training and Transfer to Reading

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ABSTRACT

Background: Saccade control is a complex function of our brain and relies on the coordination of several subcortical, cortical, and functional areas. In the past it has been difficult to use data from saccade analysis as an additional diagnostic tool for insight into any particular patient's oculo-visual problem. With the development of technological advances and optomotor research there is now a better understanding of visually guided saccadic reactions. This article describes the development of saccade control, diagnostic data from dyslexic subjects, and the effect of daily saccadic and fixation practice and its transfer to reading skills.

Methods: All subjects were recruited from local schools. Several standard tests (reading, spelling, intelligence) were used for inclusion/exclusion of the subjects participating in the various studies. Eye movements were recorded by infrared light reflection methods. Prosaccades with overlap conditions and antisaccades with gap conditions were required in 200 trials for each task. Variables characterizing pro- and antisaccade performance were extracted for each subject. Mean values and standard deviations comparing the experimental and control subjects were calculated in each of the 4 age groups in an age range of 7 to 17 years. ANOVAs or t-test were used for statistical evaluations.

Results: The data from 114 normal control subjects show a developmental progression lasting until adult age. Among the 3230 subjects in the dyslexic group 20 to 70% (depending on age) failed the criterion of the age matched controls when looking at anti-saccade performance. Pro-saccade performance did not differentiate between the groups. Daily practice conducted by 182 dyslexic subjects improved their antisaccade performance in approximately 80% of the cases. For training subjects, it was noted that successful training transferred to the act of reading by reducing the percentage of reading errors in the experimental group (N=10) by 50% and by 20% for the control group (N=11).

Conclusion: This study suggests that deficits in antisaccade control but not in prosaccade control contribute systematically to the problems of subjects with specific deficits in acquiring reading skills and that appropriate training can reduce the percentage of reading errors.

Key Words: Eye Movement, prosaccade, antisaccade, oculomotor development, optomotor, optometric vision therapy, dyslexia, reading disabled, EZ-reader model

Introduction

Reading is a tremendously complex neural process. The human brain requires development and training to learn and use a letter language. In addition to this, many years of formal education is required to learn how to read, write and spell. By contrast spoken language is learned much earlier in life and needs less additional education. Most children learn their language by listening and repetition. In an almost trial-and-error manner, they repeat what they have heard and learn their language.

From the sensory-motor point of view, vision and the control of saccades, must function almost optimally and with few errors to provide fluent reading (the term "optomotor" is used instead of "visuomotor", because the latter applies also to eye-hand coordination or to optokinetic responses. "Oculomotor" points to the movement and the muscles of the eye.) During short fixation periods of 100 to 300ms visual information is picked up and processed in order to identify a word or a syllable before the next saccade brings the eyes to the next word unit. When looking at normal, healthy adult subjects; the control of saccades is by itself a complex process with many brain structures being involved. In principle, 3 main partially independent components have been isolated over the years of research concerning saccade programming: (1) The fixation system keeps the eyes from moving, including saccades that must be suppressed; (2) The optomotor reflex moves the eyes quickly from one position to a new visual event (express saccade); and (3) The voluntary component allows the subject to generate a saccade under individual control. The first component is provided by the parietal cortex[1] and the fixation zone of the superior colliculus.[2,3] The reflex occurs as an express saccade[4] and is mediated by the saccade related zones of the superior colliculus.[5,6] The voluntary component relies on the frontal lobe functions.[7] The frontal component is one of the keys to deficits observed in neurological and/or psychiatric patients and can be diagnosed by the relatively simple antisaccade task as reviewed earlier.[8] The task requires the subject to look to the opposite side of a stimulus appearing suddenly in the periphery. The antisaccade task was introduced into eye movement research many years ago.[9] However recently, it was used as an instrument to investigate the relationship between saccades and visual attention.[10] The introduction of a temporal gap between the offset of a central fixation point and the onset of a peripheral stimulus is called the gap-paradigm.[11] The gap reduces saccadic reaction times when compared with a no-gap condition or an overlap condition, in which the fixation point remained visible when the new stimulus was presented. The combination of the gap condition and the instruction to make antisaccades revealed interesting new aspects of saccade control[12] and its relation to visual attention.[10]

Of course, the control of saccades is not the only condition for proper reading skills, because the saccades must be coordinated with language processing, which is also an extremely complex process in the brain. The question whether poor saccade control leads to problems in reading or vice versa has been answered in opposite ways. Some authors maintain, that eye movements are the key to dyslexia[13], others claim that there is no relationship between saccade control and symptoms of dyslexia,[14] and still others reached the conclusion that poor saccade control results from poor reading skills. Even though there exist many studies on eye movements and dyslexia, the discussion and controversy continues.[15,16]

The EZ-reader model proposed by Raichle et al[17] is the most elaborate model of reading. It takes into account the experimental results of eye movement studies and their relation to linguistic aspects of reading. During each fixation period language processes must be completed, before the next saccade is generated to continue the analysis of the written text along the line of print. The authors assign the command for each saccade to the frontal lobe. This model therefore predicts that deficits in the frontal saccade command leads to problems in reading.[18] By using the antisaccade task which probes the frontal lobe function, it has been observed that the error rates during the performance of the antisaccade task is increased in dyslexic subjects in comparison with age matched control children, while the variables of a prosaccade task did not differentiate the groups.[19] Further studies have shown, that the control of antisaccades of normal adult subjects may be improved by daily practice over a some of weeks.[20] Similar improvements could also be observed in children with dyslexia[21], but the question remained, whether or not there would be a positive effect of the antisaccade training on reading skills.

This article assesses three areas: the diagnosis of deficits in saccade control, the training of saccade and fixation control, and the transfer effect of the training to reading of dyslexic children.

Methods

Participants: The participants of the control group (N=114) were recruited from schools in the Freiburg area. They had average or better grades in German reading and spelling. The participants of the experimental group performed below average in reading and/or spelling but reached average or better grades in all other domains (N=3230). A subgroup (N=624) of this large experimental group was also tested for general intelligence using the K-ABC or

the HAWIK tests to find the IQ. Children scoring below the percentile of p16 were excluded from this group. Children with a diagnosis of attention deficits (ADHD) were also excluded. All participants were 7 to 17 years old. The groups were classified into 4 age groups as can be seen in Table 1.

Eye movement recording: The movements of both eye were recorded in the horizontal direction using infrared light corneal reflection (Iris Scalar or ExpressEye[22]). The resolution was 1ms in time and 0,2 deg in space. Saccades were identified automatically by a computer program under visual control at the screen, allowing for interactive corrections and modifications. The complete description of the details are published elsewhere.[23]

Optomotor saccade tasks: There were 2 tasks for the diagnosis of saccade control. The spatial and temporal aspects are shown in the upper part of Figure 1. The upper part shows the spatial arrangements. The frames illustrate the time course of each task. The lower parts show the traces of the stimuli and the eye movements. In the prosaccade task a fixation point was shown in the centre and after one second another stimulus was presented randomly 4 deg at the right or left. This task condition is called the "overlap", because the stimulus and the fixation point overlap in time. The subject was instructed to look to this new stimulus (prosaccade).

In the antisaccade task the fixation point was also shown, but it was extinguished after a second. Only 200ms later (the gap) a new stimulus was presented randomly at the right or left. This task condition is called the "gap", because of the temporal gap between fixation offset and stimulus onset. The subject was instructed to look to the opposite side of the stimulus (antisaccade).

Variables: The variables are defined as shown in the lower parts of Figure 1. The full set of variables included reaction time (srt) of pro- and antisaccades, the percent number of express saccades in the overlap condition and the percent number of erratic saccades (perr) in the antisaccade gap task using corresponding software for counting the errors. The percentage of corrective saccades (pcor) after errors bringing the eyes to the opposite side of the stimulus and the corresponding correction time (tcor) were also determined. All variables were determined separately for left and right stimulation. The analysis presented in this article uses only selected variables as will be seen in the result section. A complete description of

Table 1. The table shows the definition and size of the 4 age groups of the control group, the dyslexics, and the training group.

	7-8y	9-10y	1-13y	14-17y
Controls (N=114)	25	34	31	24
Dyslexics (N=3230)	796	1309	897	228
Training Group (N=182)	37	73	55	17

the tasks and the definition of the variables have been given earlier.[23]

Training: The participants of the study of the effects of daily practice were recruited in the same way as for the first study. The subjects were also grouped into 4 age groups (Table 1). In addition to the classification of the experimental group described above these subjects exhibited deficits in saccade control by scoring below p16 in 2 or more variables describing antisaccade performance (see below). Their post-training data were compared with their pre-training data as well as with corresponding data of age matched control groups. The number of participants was N=182 (Table 1).

Procedure of the training: Corresponding to the three components of saccade control, the training consisted of 3 versions of a visual orientation discrimination task, which was used to investigate dynamic vision[24] i.e. to probe the mango-cellular subsystem of vision. A full description has been published earlier.[25]

Briefly: *The fixation task* required the identification of 1 out of 4 possible orientations (up, down, right, left) of a small stimulus consisting of the capital letter T. The stimulus changed its orientation between up, left, right, and down with short presentation times varying from 190ms to 90ms determining the difficulties of task. The orientation changes continued for a random period of 3 to 5 rotations before the series was stopped. The task was to indicate the orientation of the last presentation by pressing the corresponding arrow key at the training instrument. Because the stimulus was small and because of the fast rate of changes a correct identification of the last orientation the subject learns to keep fixation of the centre of the screen.

The saccade task was identical to the fixation task with the exception that the rotating stimulus was displaced to the right or left and continued to rotate at the new position for only a short time before it
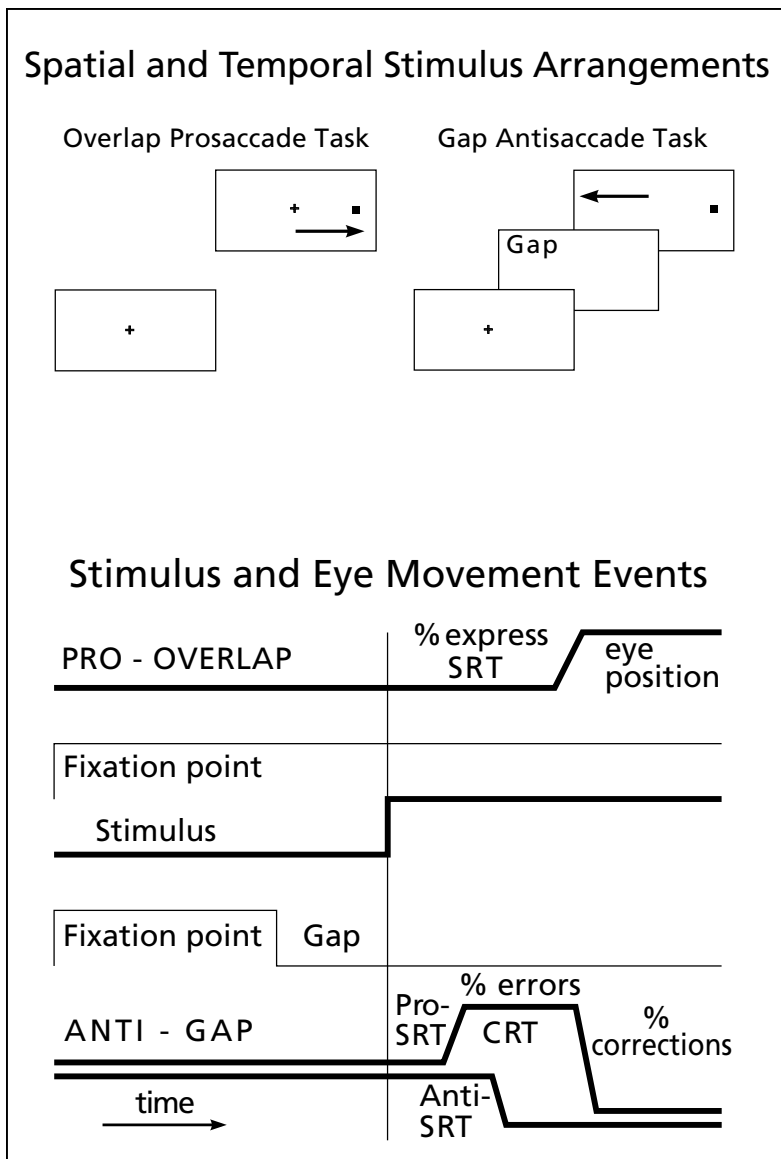
Spatial and Temporal Stimulus Arrangements

Overlap Prosaccade Task   Gap Antisaccade Task

Stimulus and Eye Movement Events

Figure 1 *The upper part shows the spatial and temporal arrangements of the fixation point and the stimulus in both the overlap paradigm combined with the instruction to make prosaccades (left) and the gap paradigm combined with the instruction to make antisaccades (right). The lower part shows schematically the traces of the fixation point, the stimulus, and the eye movement of several single trials. The drawing helps to understand the definition of the variables, which could be obtained by the analysis of the eye movement traces. For details see text. SRT = saccadic reaction time; CRT = correction time.*

Photo 1 The photo shows the front view of the training instrument. The scale of 10 cm is given below. The small stimulus can be seen in the centre but its orientation is hardly recognized.

disappeared. The best strategy of solving this visual task was to make a saccade to the new stimulus location and identify the last orientation by foveal vision.

The antitask was identical to the saccade task, but this time a large distracting stimulus (a star symbol) was presented at one side, while the small test stimulus was presented only once at the opposite side in one of the 4 orientations. Again the task was to identify the orientation of the test stimulus. The best strategy to identify the orientation requires an antisaccade with respect to the distracting stimulus to identify the orientation by foveal vision.

(Photo 1 shows the front view of the instrument. The stimulus is small and may be hard to recognize in this photograph (0.2 x 0.3 deg of visual angle at 30cm viewing distance).

The training was scheduled individually for each child depending on the individual diagnostic results obtained from the analysis of the eye movement records. The daily training required 200 repetitions and lasted between 8 and 13 minutes depending on the state of training of each subject. The training instrument controlled the difficulty of the tasks by controlling the speed by which the stimulus changed its orientation. As the subjects increased their percentages of correct identification the difficulty was increased by using faster rates of orientation changes.

Transfer to reading: The transfer of the training to reading was studied in 2 groups: the experimental group (n=11) was given the training required by the

diagnosis; the control group (n=10) had to wait until the training group finished the training. For this study only small groups were available, because all subjects were members of a group being treated for dyslexia. They had a common teacher, who would provide identical help for this group. After the training both groups received common lessons in reading for 6 weeks. During the whole duration of this study 9 children were lost (21 remained), because not all variables could be collected from each single child. There was no placebo group, because the training by itself specifically affects the components of saccade and fixation control (see Results). Reading competence was tested by counting the reading errors of a special reading task before and after the reading lessons. The reading test was specially designed for this kind of study of children of different ages.

Results

Development and Developmental Deficits: The effects of age on saccade control must be studied as a prerequisit of any diagnosis. As a well accepted variable in research of saccade control the reaction time of pro- and antisaccades is analysed first.

Figure 2 shows the age curves of the control and the experimental group. The reaction times of both pro- and antisaccades decrease with increasing age. Moreover, the two curves in the left and right diagram are overlapping in 2 or 3 age groups indicating that the reaction times hardly differentiate between the control and the experimental groups. In fact, the analysis of variance revealed no significant differences between the groups. Almost all of variance is attributed to the covariate "age". Yet, this does not mean, that all dyslexics reached normal values of prosaccadic reaction times.

However, when looking at the percentage of errors and error corrections in Figure 3 the differences between the two groups become evident. Both groups start with high percentages of errors (left side) and low percentages of corrections. Both variables are subjected to a long lasting development until adulthood is reached. The curves diverge progressively, the differences becoming largest for the oldest groups. An ANOVA with age as a covariate revealed a significant interaction term (age x error). Therefore, only participants of the same age may be compared directly.

The combined effect of errors and error corrections can be seen by calculating the percentage of misses (pmis) from the error rate (perr) and the correction rate (pcor): pmis=perr (1-pcor)/100. This variable measures the probability that an error (prosaccade to the stimulus) remains uncorrected until the end of the trial even when a second saccade was made, which failed to reach the opposite side as required by the
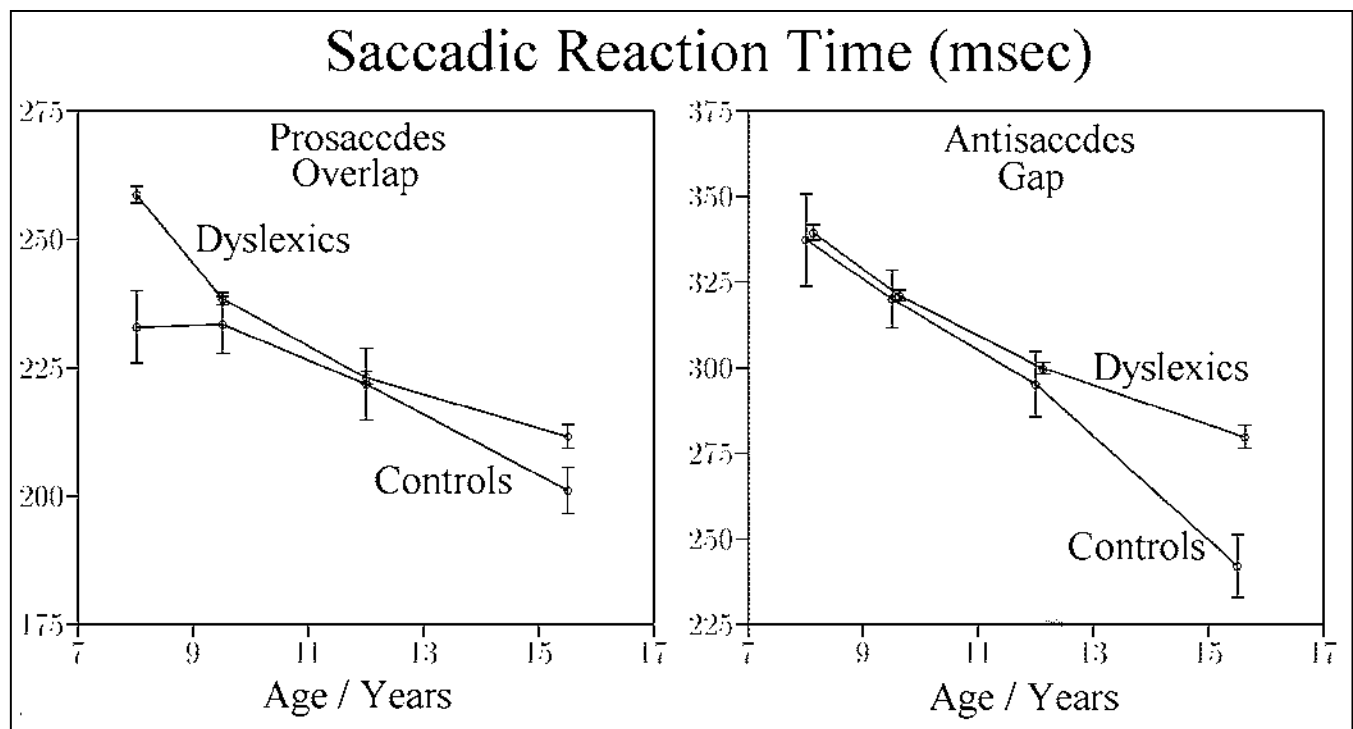

Figure 2   *The figure shows the age curves of the reaction times of the prosaccades (left side) and of the correct antisaccades (right side) for both groups of subjects.*
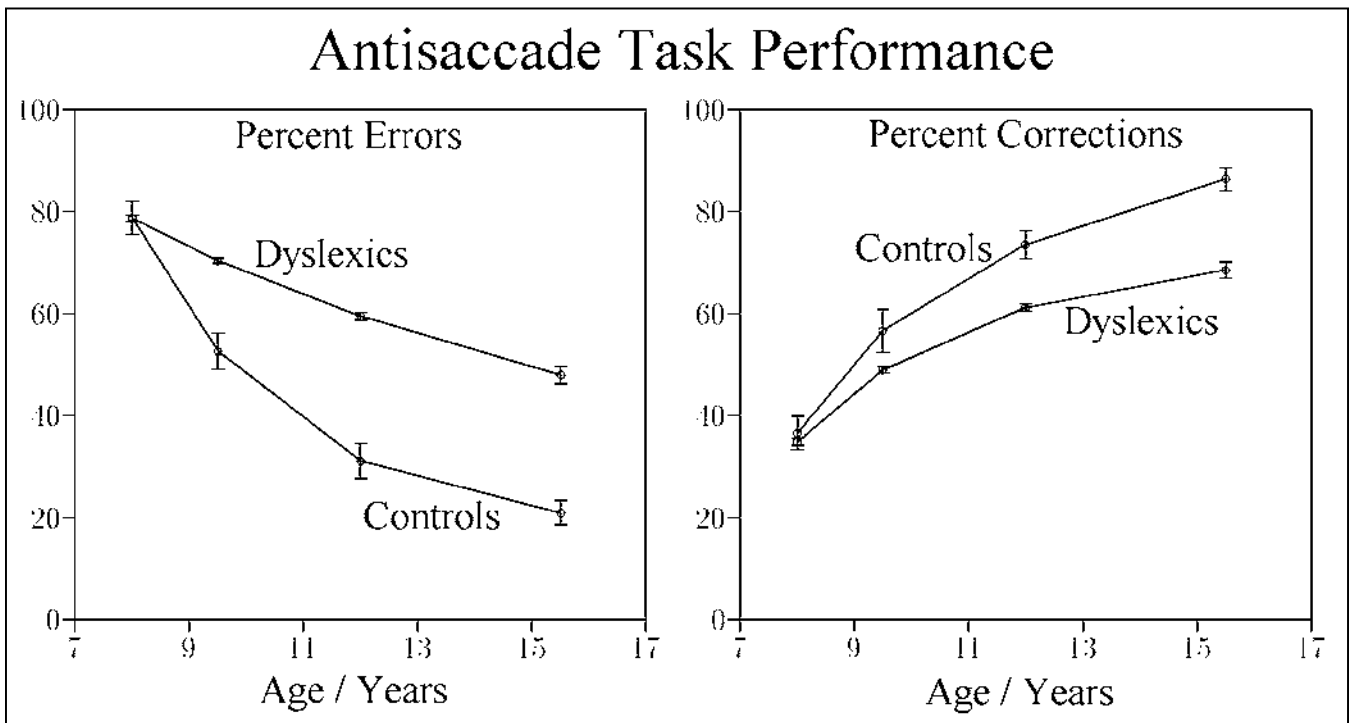
Antisaccade Task Performance

Figure 3 *The figure shows at the left the age curves of the percentage of errors occurring in the antisaccade task. The right side shows the age curves of the percentage of corrections following an error (s. Methods)*
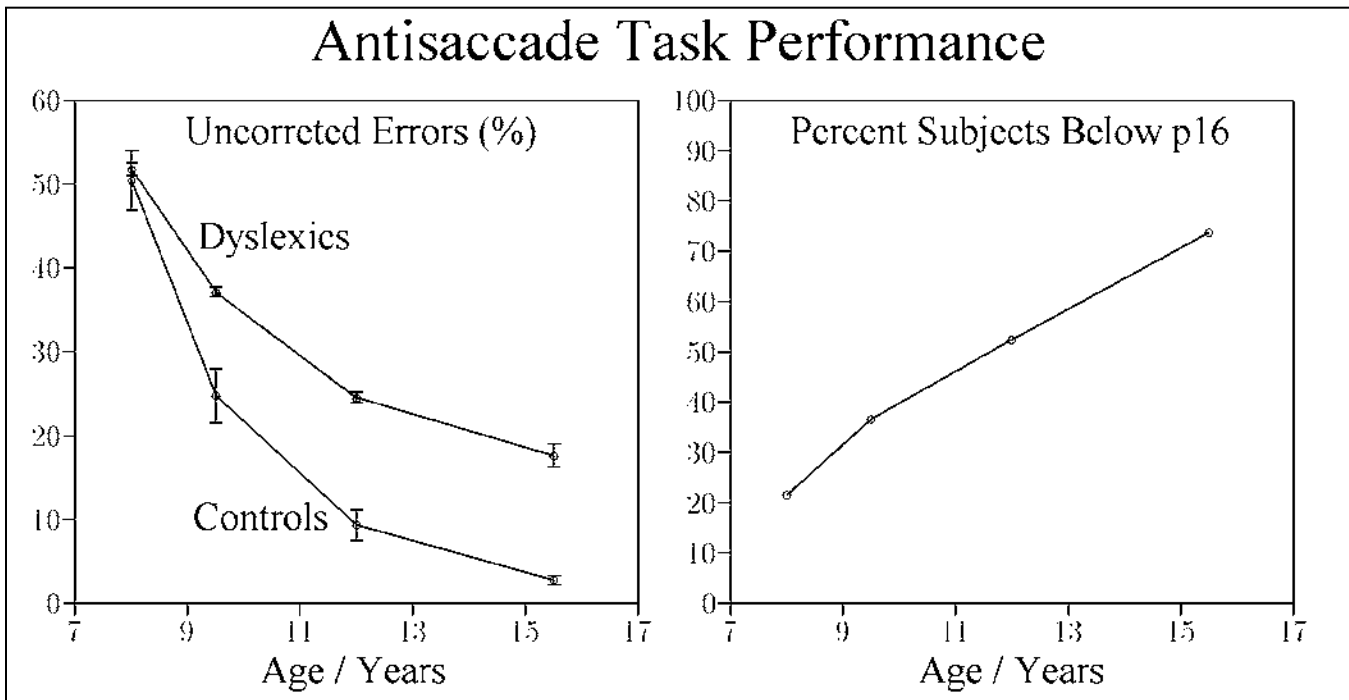
Antisaccade Task Performance

Figure 4 *The left side shows the age curves of the percentage of uncorrected errors, i. e. errors which remained uncorrected until the end of the trial or even after a second saccade, which did not bring the eyes to the required opposite side of the stimulus. The right side shows the percentage of dyslexic subjects, who failed the percentile p16. They performed poorer than one standard deviation above the mean value of the age-matched controls.*

task instruction. Figure 4 shows the age curves at the left side. An ANOVA with age as a covariate shows that age is a highly significant factor in these data.

The Figure 4 shows in the right diagram the percentage of dyslexic subjects failing the percentile

p16 of the control group of the same age. The diagram indicates that not all dyslexics contribute to the differences in the age curves. The percentage of impaired subjects increases from just above 20% to almost 70%

Training: Participants with deficits in saccade and/or fixation control were offered a specific training using a hand held device ("FixTrain™") for daily use at home. The sequence of the training was always: Fixation - Saccade - Anti, because proper fixation is a prerequisite for correct pro- and antisaccades. Pre- and post-training data were available from 182 subjects in the age range of 7 to 17 years. They were also grouped into 4 age groups. Table 2 shows the number of subjects within each group.

Figure 5 shows on the left side the age curves of the reaction times of prosaccades (overlap condition) before and after the training. No systematic effects can be seen. While some subjects became faster, because they trained the saccade task; others became slower, because they trained the fixation task. Most subjects exhibited no changes and the mean value remained the same. The reaction times of the correct antisaccades (right side) became clearly faster for the 3 younger groups. The oldest group exhibited considerable scatter in the data with a tendency to faster reaction times of the trained group as compared with the untrained group.

The most drastic training effects were obtained in the error and correction rate determined from the antisaccade task. The Figure 6 shows at the left side the combined variable pmis (percentage of uncorrected errors) before and after the training. While the pre-post differences decreased with age, the percent difference stayed the same at about 50% across the different age groups.

The right diagram of Figure 6 depicts the percentage of successful subjects, who reached the normal range of the age matched control subjects (percentile above p16). The rate of success was almost 100% for the youngest group and decreased to 65% for the oldest group. The weighted mean value of the success rate was 81%.

Specificity of the training: If the control of prosaccades is independent from the control of antisaccades one expects, that training of antisaccades does not transfer to the training prosaccades and vice versa. To test this hypothesis the pre- and post training data were analysed separately for a group of subjects, who trained the antisaccade task but not the prosaccade task and another group, who did not train the antisaccade task but the prosaccade task. The result is shown in Figure 7.

The left diagram depicts the reduction of reaction time of the prosaccades obtained from the two groups with overlap conditions. When antisaccades were trained but not saccades (A, nS) the reaction times of the prosaccades did not change. But when antisaccades were not trained but saccades were trained (nA, S) the reaction times were reduced by about 50ms on average.
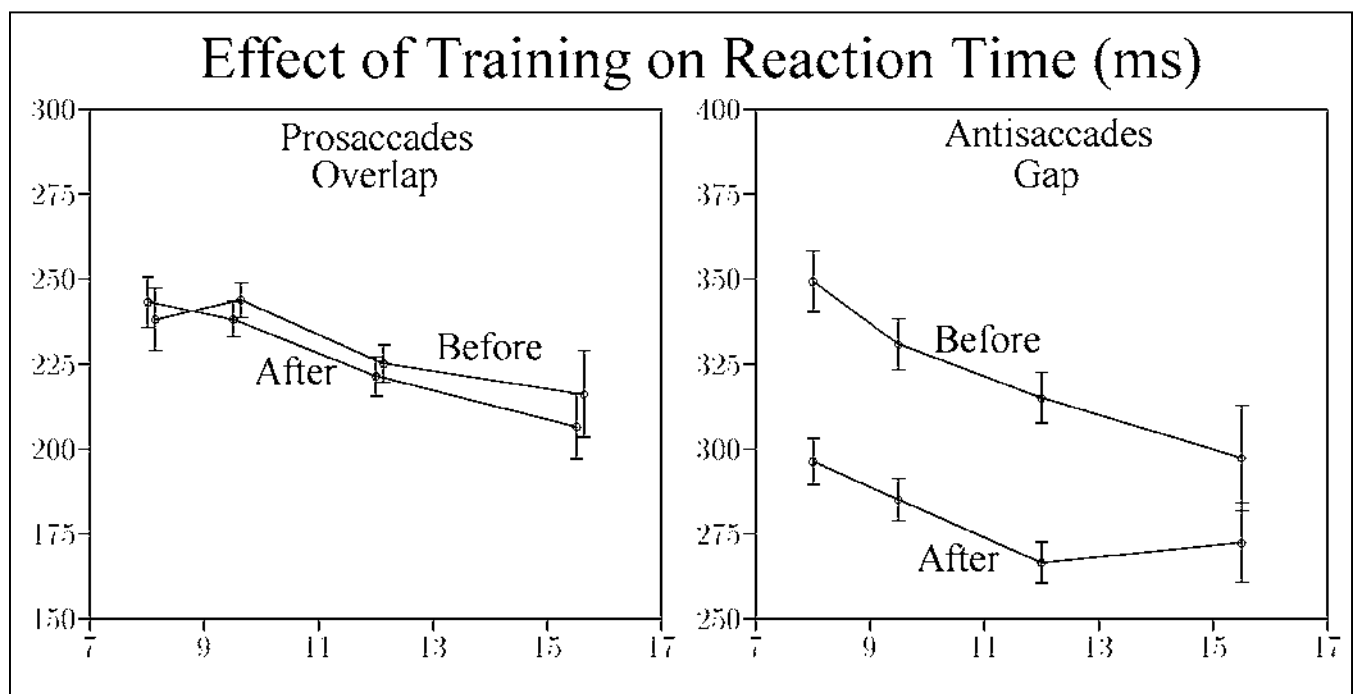

Figure 5 *The left side shows the age curves of the reaction times of the prosaccades before and after the training. The right side shows the reaction times of the correct antisaccades.*
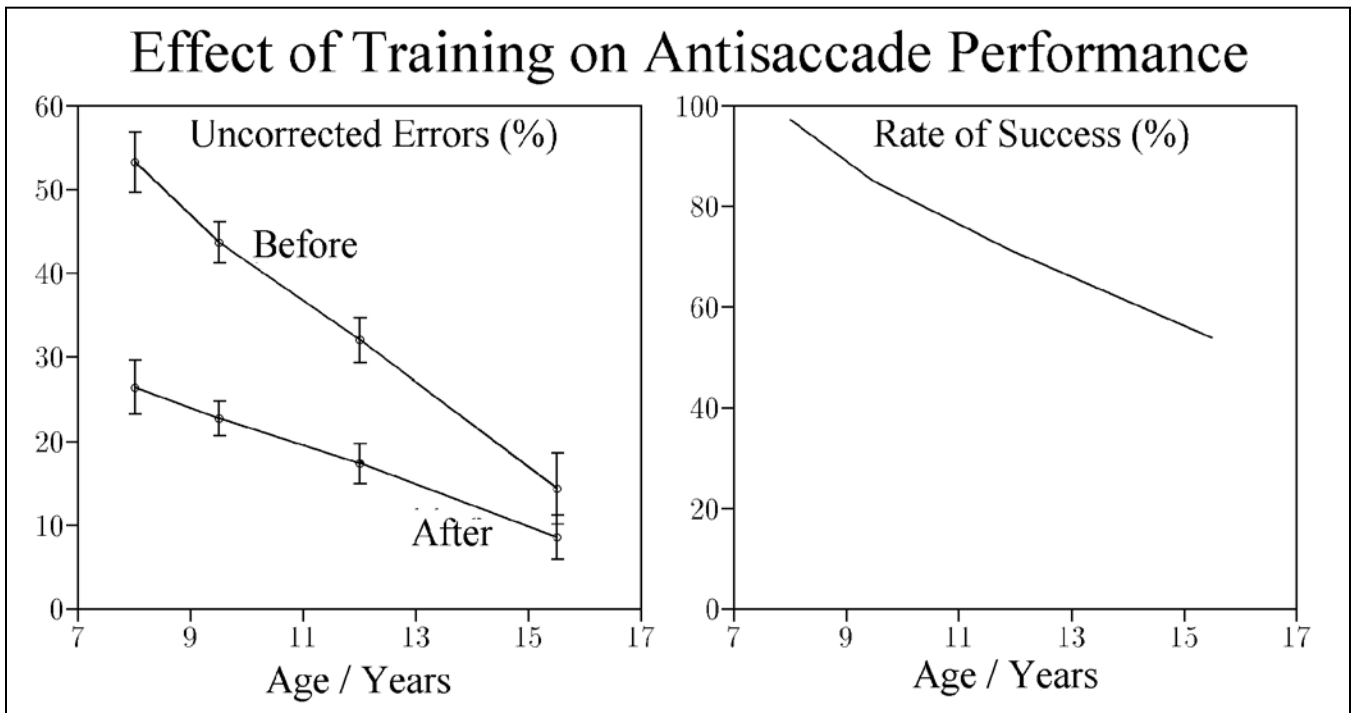
Figure 6   *The left side shows the effect of the training on the percentage of uncorrected errors. The right side shows the percentage of successful subjects, who reached the range of the age-matched controls.*
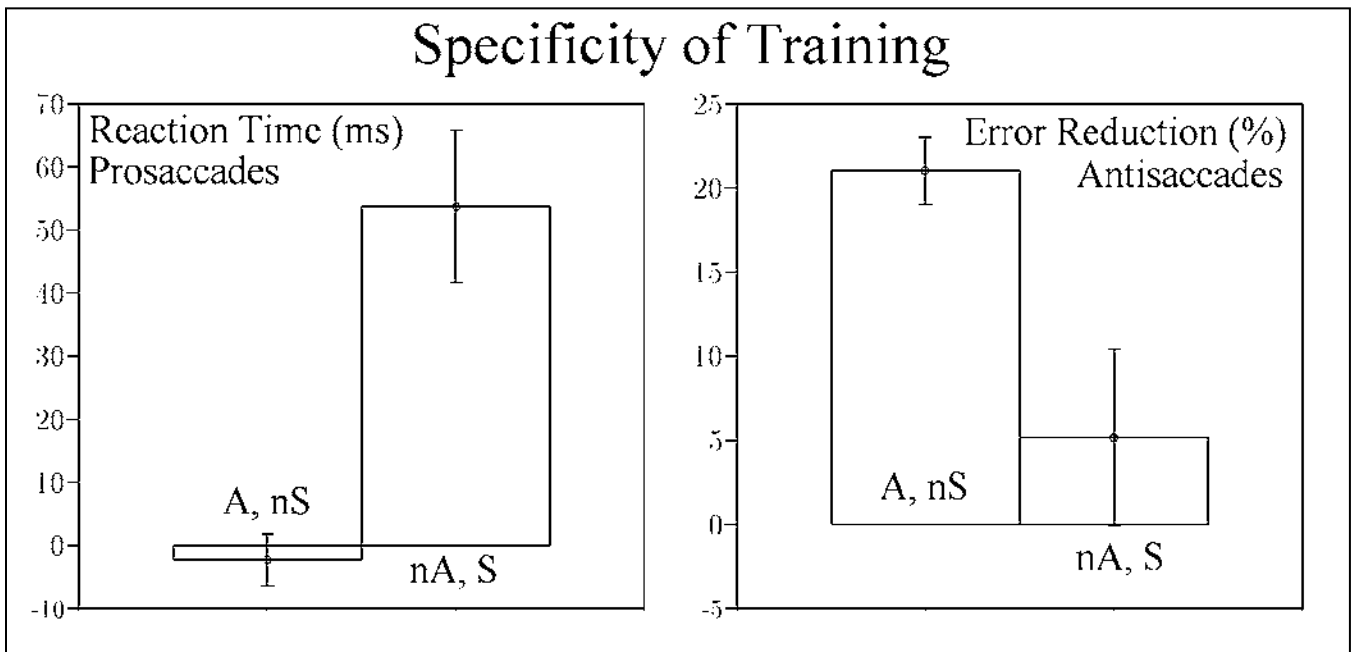

Figure 7   *The diagrams illustrate the effects of the training to be different depending on which task was part of the training of the subjects. The letter A indicates that the antitask was part of the training, nA means that the antitask was not part of the training. Similarly, S and nS means that the saccade task was or was not part of the training, respectively. For details see text. The columns indicate the difference in reaction time of prosaccades obtained in the overlap prosaccade task (left panel) and difference in error rate obtained in the gap antisaccade task (right panel).*

The right diagram of Figure 7 depicts the reduction of the errors, which occurred in the antisaccade task with gap conditions. The group who trained the antitask, but not the saccade task (A, nS) reduced the number of errors by about 20% on average, but the group, who did not train antisaccades but trained saccades (nA, S) did not change the percent number of errors.

This kind of specificity supports the hypothesis of independence of the components of saccade control. It shows also, that the effect of the training is not accompanied by placebo effects, because all

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circumstances of the training were the same for both groups. This aspect of training is important when looking at the transfer of the training on reading competence.

Transfer of the training to reading: To see effects of the training on reading a group of 21 dyslexic children was divided into an experimental and a waiting group (see Methods). The number of reading errors was determined before the training, right after the training, and after an additional period of reading lessons given to the whole recombined group.

Reading errors were significantly reduced by almost 45% in the experimental group (white column of Figure 8) and by about 20% in the waiting group. This difference was highly significant (t-test, p=. 01). Figure 8 shows this result graphically by the left most pair of white and black columns. An ANOVA with age as covariate revealed a significant interaction term. Therefore, the data were analysed in relation to age. You can note that the other pairs of columns in Figure 8 show the percentage of error reduction when the younger participants were excluded from the analysis. One sees an increase of error reduction in the experimental group (white columns) and a decrease in the waiting group (black columns). This shows that age had an opposite influence in the two groups: Older subjects had a greater profit from the training as compared to younger subjects.

Discussion

The studies presented in this article have shown, that deficits in voluntary saccade control can be found in up to 70% of the dyslexic children in the age range of 7 to 17 years by using standard eye movement recording, with pro- and antisaccade tasks, and the analysis of several variables. While the variables of the prosaccade task did not reveal large differences between the experimental and control groups, the error and correction rates derived from the antisaccade tasks revealed highly significant differences. The components of saccade control diagnosed as "impaired" could be improved by daily practice at home in a systematic way. The improvements in saccade and/or fixation control transferred to reading skills. This last observation indicates that deficits in saccade control can be considered as causal factors creating problems in reading.

Of course, deficits in saccade control are not the only factors that may contribute to the symptoms of dyslexia.

Single dyslexic subjects could also fail to reach the values of the age-matched control group with respect to other eye movement variables. For example, subjects may generate high numbers of express saccades in the prosaccade task with overlap conditions. A preponderance of express saccades indicates a weakness of the fixation system not being able to suppress visually guided saccades.[26] In addition to the high number of express saccades these subjects had difficulties preventing prosaccades in the antisaccade task, but they corrected almost all of these errors within short correction times. These subjects were given a long lasting (3 to 5 weeks) training of the fixation task and - after this period - a one-week training of the antitask. Most subjects succeeded in reducing the number of express saccades and to reduce their error rate in the antisaccade task.

Another deficit was observed with respect to simple or binocular fixation stability. Either there were too many involuntary saccades during the first period of the prosaccade task or there were slow drifts of one or both eyes with different velocities. In these cases, a monocular training of the fixation task was given. In accordance with earlier findings, covering one eye during reading resulted in not only a better binocular stability but also the subjects' reading skills
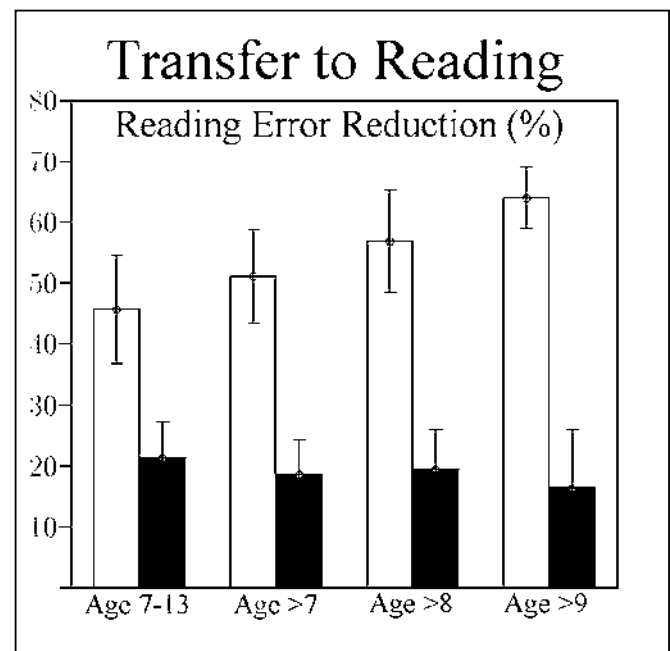

Figure 8 *The figure shows the effect of the training on the reduction of reading errors expressed as percent difference of errors before and after the training. White columns are obtained from the experimental group, black columns from the control group. The left pair of columns depicts the total mean values over the experimental and control group, respectively, irrespective of age. The pairs to the right are obtained, when children with increasing age were excluded from the analysis. For details see text.*

improved.[27] The number of involuntary saccades, however, remained the same.

Other deficits occurring in dyslexics are subitizing and visual number counting[28] and deficits in low level auditory differentiation.[29] Specific trainings of the corresponding visual[30] and auditory tasks were successful in 40 to 80% of the cases depending on the specific visual and/or auditory domains. The visual training transferred to basic arithmetic skills, while the auditory training transferred to spelling.[31]

Together, the recent literature on children with problems in reading and/or spelling at school suggests, that relatively basic (low level) neural processing in the visual, optomotor, and auditory domain may constitute causal factors for these problems. It is unknown, to which extend these problems did not exist in the past or remained undetected because of a lack of diagnostic and therapeutic methods.

Successful diagnosis and training of any of these functions do not imply that other causal factors do not exist. One important domain to consider has to do with language processing, which remained untouched in the studies described here and mentioned above. For example, those dyslexic children, who did not show any deficit with respect to saccade control, vision or audition, must have deficits of different nature. Furthermore, dyslexic children, who showed perceptual deficits and who successfully improved these deficits by training, may still exhibit difficulties in spelling and reading which indicates that other domains may play an important role as well. Therefore, it is important to use a multidisciplinary approach when trying to help children with dyslexia.

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