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DYSLEXIA AS A LEARNED TRAIT.

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ABSTRACT

By a test (FRF) for letter and letter-string recognition in the peripheral visual field, English-native severe dyslexics differ from ordinary readers in the right field, Hebrew-native severe dyslexics in the left. FRF measures lateral masking not acuity. The results suggested that lateral masking is a task-depended modifiable perceptual strategy rather than a fixed property of the peripheral visual field. A hand-eye practise regimen was designed for four severe dyslexics. Their reading skill improved sharply within a few months and their FRF profile reverted to that of the ordinary reader. We conclude that dyslexia is a learned trait.

1. INTRODUCTION

Dyslexia, not associated with other brain or eye disease, is presently unaccountable and is classified by default as a disorder of some higher function. Among the possible mechanisms is a physiological variant of Geschwind's Disconnection Syndrome [7]. That is, the necessary information for reading is functionally suppressed but the pathway to convey it is intact. At first this sounds like a distinction without a difference. But we propose to show that such suppression can be measured, that the measure is diagnostic, and that the suppression can be relieved.

This suppression is a variant of a well-known but ill-understood visual process, lateral masking, which was first discovered in the peripheral visual field (refs) and is still thought to be confined there [2,13,16,17]. Since it has been assigned no role in the central visual field it occupies only a small niche in the clinical literature on vision. The phenomenon is demonstrated in figure 9.

We were led by accident to the work reported here. In our research on lateral masking, done for other reasons [4], 5 of the 44 subjects were so different from the others and so similar to each other as to form a separate group. The difference lay in their unusually good recognition of letter strings at 8° eccentricity in the peripheral field. On interviewing them we found a common factor -- all had been diagnosed at one time or another in their lives as dyslexic. We then searched out other dyslexics to study the observed difference and to check its reliability. First results were reported as a clinical observation [5].

The new tests were confined to the distribution of single letter recognition and of lateral masking along the horizontal axis of the visual field from 2.5 degrees to 12.5 degrees away from the center of gaze given a letter at the center. The results told dyslexics from ordinary readers with high reliability. It remained to show that the tests tell something about the underlying process in dyslexia. This study developes that relation.

2. METHODS

Apparatus and Stimuli: A three way tachistoscope was constructed. It was comprised of three slide projectors that were focussed from behind on a framed translucent diffusing screen. Each projector was set to give a uniform illumination across the screen at 180 cd/m^2 as measured at the front of the screen. This enabler screen was 35 cm. long and 23 cm. high. The larger screen was 48 cm. wide and 35 cm. high. Observed from 100 cm. distance the visual angle of the smaller screen is 20° wide and 13° high. At 69 cm. distance the larger screen is 39° wide and 28° high.

One projector used a blank white slide with only a small black dot on it to give a fixation point on the screen. The second projected the stimulus slides. The third projected the "eraser" slide, which in this case was completely blank. (A structured eraser would have prejudiced recognition of stimuli in favor of ordinary readers; dyslexics are confused by it.) Each projector was occluded with an electrically driven shutter that opened or closed within 5.5 ms. The opening and closing of the shutters were electronically timed by the sequence shown in figure 1 to give least change in background luminance during transition between sequential slide permutations (phases). The effective stimulus phase duration could be set as short as 2 ms. On each stimulus slide there were two letters, one at the fixation point and another eccentric to the left or right along the horizontal axis. In an alternative experiment the eccentric letter was replaced by a string of three letters. For either experiment several eccentricities were used, with twenty stimulus slides at each eccentricity. The basic experiment in this paper is the first type and the following description applies to it. When we use the alternative, the emendation is given in the text.

No two letters on any slide were the same, and no two slides were the same. In order to reduce bias in letter recognition (some letters are easier to recognize than others), each letter was presented with the same frequency at all eccentricities as well as in the center. The letters were taken from a group of ten Helvitica-Medium capital letters. We chose the letters from three groups, N, W, Y; O, C, S; E, T, H; and, in a class by itself, I. The letters displayed by each stimulus slide were never from the same group (to prevent partial eccentric enhancement or demasking [4]. The angular height of the letters subtended 35 min. of visual arc and their contrast was 90%. All

eccentricities are given in terms of visual angle away from the fixation point.

Procedure: The subjects were seated in a dimly lit room in front of the screen. The slide with the fixation point was projected on the screen and testing begun (figure 1). After verbal warning ("ready?") by the experimenter the stimulus phase occurred and was immediately followed by the eraser phase which endured for 2.5 sec. before the fixation point was again projected. In this sequence, wherein the average background luminance does not vary significantly, the effective stimulus duration (from onset of the stimulus until the onset of the eraser) was adjusted for each subject in such a way that the best score of identification - at whatever eccentricity of the peripheral letter gave best recognition - lay just below 100%. This normalization for best form resolution allows comparison of form identification across the visual field without tying it to contrast or lightness. The stimulus duration did not exceed 7 ms. (In another study we measured correct identification when stimuli exposure durations were equal for all subjects. The results were similar to the ones obtained with this normalization, but were less distinct.)

In the initial study the stimulus exposure duration was set for each subject prior to the test itself by a pilot run with different exposure durations. Once the best test duration was determined for a subject it was fixed for that subject throughout that test at all eccentricities. After each stimulus presentation, the subjects reported verbally what letters they had seen, which letter was at the fixation point, and which in the periphery. The report was recorded and the next stimulus was given. When twenty such exposures of different letter pairs were delivered at one eccentricity, the eccentricity was changed and a new series of twenty was presented. Once all slides for all eccentricities had been presented, the percentage of correctly identified letters at each eccentricity was determined.

The centering of the subject's gaze on the fixation point was visually monitored by the experimenter. This crude monitoring was sufficient, as later use of an eye tracker has shown. Its sufficiency could also be seen in the results of additional experiments (reported in the results section) where the letters in the periphery had the same probability of appearing on the left or on the right of the fixation point.

Subjects: The subjects were English-native speakers, all of them above 18 years of age. All but two of them were unaware of the purpose the tests until the testing was finished. Twenty persons were tested. The ten ordinary readers (3 females and 7 males) were clustered between 18 and 25 years of age with one person at the age of 35. The ten severe dyslexics (2 females and 8 males) were distributed between 20 and 58 years of age. The ordinary readers came from the general university-level student population. The severe dyslexics wandered into our laboratory on hearing of our interest. They belonged to no specially defined or targeted group. They were all previously diagnosed as dyslexics by neurologists, psychologists and teachers and had no special tutoring within the last 3 years prior to testing. None of the dyslexics had any additional known neurological findings nor any uncorrected refractive errors. The severe dyslexics had a normal level of comprehension of heard texts, but all had serious difficulties in reading. Their reading scores were much lower than two grades below their age level.

In one experiment we used another five adult ordinary readers (20-31 years old) and another five adult severe dyslexics (17-28 years old). All of them were Hebrew-native speakers who were exposed primarily to Hebrew through their first ten years of life and who had been taught to read only Hebrew for the first 3 school years. These subjects came from a similar background as the English-native speakers. The severe dyslexics were diagnosed by their respective neurologists and psychologists as with the other group of severe dyslexics. Their reading scores were also lower than two grades below their age level. All the Hebrew-native subjects learned to speak English beginning at their 4th year in school and had had training in reading it.

3. EXPERIMENTS AND RESULTS

a. The Form-Resolving Field (FRF) : In a test flash (as described in the methods) the displayed letters are presented at some fixed angular size and contrast against a background of fixed luminance. Once the flash duration is chosen for a subject it is held constant for the run of measurements. The displayed letters are changed with every flash, and their angular distance from the gaze axis can be varied. Two letters are exposed in each flash, one at the fixation point (the center of gaze) the other at some angular distance in the peripheral field. The two letters are never the same. Both are

to be verbally identified by the subject immediately after the presentation. After the tests at all eccentricities are finished we plot the percentage of correct identification of the peripheral letters as a function of eccentricity. This plot is the FRF operationally defined. It is not a measure of acuity, as will be evident later. What is at issue is the recognition of form rather than the resolving power. In figure 2a we plot the averages of the FRFs for English-native ordinary readers and severe dyslexics.

In general, letter recognition falls off with eccentricity from the center of gaze. However, there are obvious differences in the shape and the grading of the fall-off depending on the type of subject.

Average scores of letter recognition in the right side of the visual field are plotted to the right of the mid-line (0°) in Figure 2a. At all the eccentricities on the right, except at 5°, we recorded two significantly different populations: those of ordinary readers and those of severe dyslexics [at 2.5° $F(1,18) = 11.18$, $p < 0.01$; at 5° $F(1,18) = 1.92$, $p < 0.2$; at 7.5° $F(1,18) = 7.13$, $p < 0.02$; at 10° $F(1,18) = 102.42$, $p < 0.001$; at 12.5° $F(1,18) = 20.02$, $p < 0.001$]. These two populations differ significantly in the overall shapes of the FRF on the right [5].

Ordinary readers recognize letters best when they are presented nearest to the center. The FRF falls off sharply with growing eccentricities, in accordance with the Aubert-Foerster law [1]. In contrast, severe dyslexics, on the average, recognize letters best at 5° eccentricity. Recognition falls off towards the center (at 2.5°) and further in the periphery. At 2.5° eccentricity the recognition score of severe dyslexics is significantly lower than that of ordinary readers. At 7.5° eccentricity and farther in the periphery, letter recognition for severe dyslexics is significantly superior to that of ordinary readers for all measured points. The dip in the dyslexic FRF near the center is where the two letters of the display are closest together. At that angular distance, the letters mutually mask each other for severe dyslexics because single letter recognition in and near the center is much the same for ordinary readers and severe dyslexics.

It is important to note that what the FRF measures is certainly not what is ordinarily meant by "acuity". We do not hold that there is a difference in peripheral acuity between ordinary readers and dyslexics. Instead the difference lies in the perception of forms and not in the resolving power. The difference also lies in the perception of two-letter configurations. For severe dyslexics the letters mask each other when the eccentric one is brought near the center. This does not occur for ordinary readers.

All the above refers to the right visual hemifield. In the left visual hemifield (the left side in figure 2a letter recognition for ordinary readers and severe dyslexics is not significantly different at any eccentricity. Hence, the shapes of the FRFs on the left side are similar for both groups, and are much like a mirror image of the right hand side of the FRF for ordinary readers.

b. The FRF measured with random left-right display: For technical reasons (the size of the screen) we have measured each side of the visual field separately, at first all the eccentricities on one side and then all the eccentricities on the other side. This procedure could have introduced some bias of expectation of letter appearances, as well as an offset of the fixation. To deal with this possibility of bias we performed an additional set of tests. In these experiments we repeated the test described above with a new group of 7 ordinary readers, presenting the stimuli first to all the eccentricities on one side and then to the other. Then we subjected the same group to a similar test, where all conditions were identical except that the letters were randomly displayed to the left or to the right side of the visual field at each eccentricity. This was made possible after we enlarged the screen and seated the subjects at 69 cm. distance from the screen. In this way the laterality for expectation of letters lost its bias. Also, systematic fixation offset would have been detected by the scoring. The results of these tests showed similar letter recognition scores for both conditions. (Only at 10° eccentricity to the left was recognition significantly better when letters were displayed randomly to the right or to the left.) In addition we tested 6 other dyslexics with random left-right display. Their FRFs were similar to those of the dyslexics tested by the earlier method. We conclude that bias of letter expectation and fixation offset do not significantly affect our original observations.

c. Asymmetry reversal of the FRF. As mentioned before, the FRF of severe English-native dyslexics is significantly asymmetric [6]; it is wide and not monotonic in fall-off on the right side but narrow and monotonic in fall-off on the left. The FRF of ordinary

readers is almost symmetric, narrow and monotonic in fall-off to both sides. This asymmetry cannot be attributed to the dyslexics being predominantly left-handed, because when we measured the FRFs of right-handed and of left-handed ordinary readers separately (together with Franco Fabbro (not yet published)) we found that the forms of the FRFs were almost identical. There was a small shift to the right for the FRF of the left-handed. This shift is small and does not resemble the FRF of dyslexics.

All the subjects who participated in this test were English-native speakers. We suspected that the asymmetry in the dyslexic FRF was related to the direction of reading. Therefore we compared the FRFs of severe dyslexic Hebrew-native speakers with the FRFs of severe dyslexic English-native speakers (Hebrew is read from right to left). We asked ten adult Hebrew-native speakers to participate in the testing. Five of them were ordinary readers and five were severe dyslexics. We measured their FRFs in the same way we measured it for the English-native speakers. (In this test we used the random presentation of letters to the left and right.) The only difference was that the letters in the new test were Hebrew rather than Latin. We matched the font, size and type of the Hebrew letters to be similar to the Helvetica-medium letters which were used with the English-native speakers.

The resulting FRFs of the Hebrew native speakers are shown in figure 2b. On the left side two distinctly different forms of the FRFs appear. A narrow one is found for ordinary readers and a wide one for severe dyslexics [at -7.5° $F(8,1) = 10.03$, $p < 0.02$; at -10° $F(8,1) = 4.83$, $p < 0.05$; at -12.5° $F(8,1) = 10.01$, $p < 0.02$]. On the right side the FRFs of the two groups are similar except for two points; at 2.5° letter recognition is significantly lower for severe dyslexics [$F(8,1) = 14.29$, $p < 0.01$] and it is higher (but not significantly) than that of ordinary readers at 12.5° {$F(8,1) = 4.4$, $p < 0.2$].

The FRFs of ordinary readers who are either English or Hebrew native speakers are similar except for a slightly wider right side (not significant) for Hebrew readers. However, the FRFs of severe dyslexics are markedly aberrant in the direction of reading. The FRF is wide to the right for English-native speakers and wide to the left for the Hebrew ones. We conclude therefore, that the direction of reading is strongly correlated with the asymmetry of the FRFs of severe dyslexics. However, this reversal is not complete. The dip at 2.5° remained on the right side for all the severe dyslexics, English-native and Hebrew-native.

d. Lateral masking between letters in a string. We have mentioned that the lateral masking at the center of gaze, such as occurs in dyslexics, looks similar to the lateral masking in the peripheral field had by ordinary readers. It remains to show how ordinary readers and dyslexics differ in the measure of lateral masking within letter strings.

The apparatus and methods were the same as for the FRF test. The differences lay in the nature of the stimuli and the duration of the stimulus-exposures. In this test four letters were presented in each stimulus (instead of two as in the previous test). One letter was at the fixation point and a string of three letters was in the periphery. The strings were displayed at four different eccentricities and there were twenty displays at each eccentricity. The distance between the letters in each string remained constant for all displays and was 35 min. of visual arc. All letters in each stimulus display were unlike each other and as in the previous experiments no two slides were alike. The duration of the stimulus exposure was 61 ms. for all subjects. In this experiment, as in the previous ones, letter recognition was measured as a function of eccentricity.

The left side of figure 3 shows the average scores of correct letter recognition of five ordinary readers. At each eccentricity of the string we give the average identification scores for each locus along the string (first, middle and terminal letters). On the right side of figure 3 the average score of nine severe dyslexics is depicted. All the subjects who participated in this experiment had been tested for the FRF.

Some general properties of lateral masking are seen in the plots for ordinary readers: masking increases with eccentricity for all positions in the string. It is least effective for the terminal letter of the 3-letter strings and strongest for the middle letter. These properties are generally preserved for the severe dyslexics. However, there are some differences: a. Near the center the masking of the middle and last letters are about the same for severe dyslexics and for ordinary readers, but the first letter is overmasked for dyslexics due presumable to influence of the letter at the fixation point. At 10° eccentricity the middle letter is significantly less masked for severe dyslexics

than for ordinary readers; b. Near the center, average lateral masking for the string is about the same for the two groups; however, at 10° eccentricity, the string is less masked for severe dyslexics.

e. Learning visual strategies. In this part we will describe how a new visual performance was acquired by severe dyslexics. At first we will describe in detail one case and then we will deal with a set of four to show some generality in the approach.

The subject was a 25 year old male who is an English-native speaker with normal vision. He is also ambidextrous. He was diagnosed as dyslexic by a neurologist and a few psychologists. When he was in high school in his teens he received remedial help for reading. When he appeared in our laboratory his reading level was comparable to that of a 3rd grade pupil.

At first we tested him for the FRF in the way described. The results are plotted in figure 4 (in dotted line). This FRF is an extreme version of the FRFs of other severe dyslexics. There is strong masking near the center of gaze and a very wide letter recognition in the periphery.

The second test was the direct measurement of lateral masking in a string of letters, as a function of eccentricity (similar to the test described in paragraph 3d. The results are shown in the left side of figure 5. At 2.5° eccentricity his score for all the letters in the string was almost zero. At the same time his score for the fixation letter also went to zero, as if the mutual lateral masking was extremely intense in the region around the center of gaze. With respect to this test he acts as if he had little or no vision for aggregates of letters close to the fovea. However, at 7.5° and 10° he performed as if there were little lateral masking and little loss of letter recognition (as evident also from the initial FRF in figure 4). In this respect he was much superior to readers in his peripheral vision. Such a case might raise the suspicion of some organic deficit in retinal function at the fovea were it not for the fact that so long as the background was blank up to 5° away from the center of gaze, he had normal vision for single letters presented at the axis of gaze.

This was the first case where we asked if it were possible for this man to learn a new visual strategy that would permit him to read. Whatever distribution of masking he possessed excluded reading at and around the center of gaze. i.e., no use of his central field could teach him to read by central vision because no reinforcement could be made under the severe masking. Since his FRF as well as his performance with the tests on lateral masking showed that his near peripheral vision had acuity adequate to reading, we decided to probe whether he could learn to read through use of the peripheral field. If he could, and our tests measured something that correlated with reading strategy, then a retest after training would show the change. Our hopes were supported by the well-known phenomenon of speed-reading which implied that peripheral vision might be adequate to the task.

We emphasize here that we were not and are not proposing a therapy. We are only testing the hypothesis that a new visual strategy can be learned if it does not compete in the domain of other firmly set and competing strategies. I.e. it would not be advisable to train for foveal reading if lateral masking is strong in the fovea.

The practise consisted of two complementary parts. In the first part we advised him to devote two hours every day to the performance of novel, direct, small-scale, hand-eye coordination tasks such as drawing, painting, clay-molding, model-building, etc. The rationale for this practise comes from experiments performed by Held and Gottlieb [8], Held and Hein [9], and remarked by Helmholtz [10] on how a person shifts spatial localization after viewing his hand through a prism. The general idea was to provide visual perception with a new space of operation as defined by the new tasks.

The second part was to try reading through a window in the peripheral field. A sheet lay over the text to be read. It could be transparent and colored, or translucent, or opaque. Its only purpose was to pre-define a background by a definite quality. On it lay a fixation point or mark. At the right of that mark a window was cut to a size somewhat larger than the length and height of a long word in the text. The distance from the fixation point to the center of the window was set by using the eccentricity of the peak of the FRF and the eccentricity at which lateral masking masked least the middle letter in a string. In his case, it was 7.5° left of the window (or about 3.5 cm. from the window when reading distance is kept to 25-30 cm.).

When he intended to read he had to lay the window over the desired word or words in the text while gazing at the fixation point and try to read what appeared in the window. Keeping gaze on the fixation point he then shifted the sheet so that the window lay over the next word, and so on. In this way the words in the window might be seen as form rather than texture, without interference from the ambience.

He did the practise alone, reporting to us by occasional phone call. Three weeks after the start of this program, he called to tell us, "at last I see the forms of the words". Altogether he responded to the procedure remarkably, and, within four months went from a third grade reading level to the tenth grade level. In practical terms he was able to take a job in which he had to read memos, bills of lading, and the like. When tested at the end of four months he showed the change in FRF given by the solid line in figure 4 and the change in lateral masking shown in the right side of figure 5. He was now able to make out letters in strings presented at 2.5° eccentricity. His performance at that eccentricity is not as good as that of an ordinary reader or residual dyslexic, but is far better than in the initial test. Curiously, in reporting the letters at that eccentricity, he stuttered [5].

As the result of this case, we asked another three severe dyslexics from the group of 10 to participate in a program aimed at their learning a new strategy. At first we characterized each of the additional 3 subjects with the two tests. Then we asked them to follow the same practise pattern as the one described above for the single case.

After 12-20 weeks with this combined practise during which time we didn't see the subjects, we again measured the FRF curves for each of the three. We also inquired about, but did not measure, their reading skills. Figure 6 shows the averaged FRF for the four subjects (including the single case from above) before and after the practise term. For comparison, the curve for ordinary readers (from figure 2a) is also displayed.

We should remark that the four subjects were not chosen by us. They were the only candidates among the 10 original subjects who could afford the time to practise daily. We did not instruct or guide the subjects more then by occasional telephone conversation after laying out the schedule of practise.

As seen in figure 6 there is a significant shift of the FRF from before the regimen to after. The shift is toward the FRF of ordinary readers. Ordinary readers do not vary significantly in FRF over time although we measured some over periods of 2 years and longer.

The reading performance of all the four improved much. The reading score of one went from 3rd grade before practice to 10th grade after practice. Another subject went from hardly reading at all (about 2nd grade) to reading fluently for half an hour at a time (difficult to estimate grade level). Another went from spells of slow reading for five minutes at a time to spells of reading fluently for hours at a time (so he reported). The fourth, before he began the regimen, could only skim fast (like speed reading) with many errors. He had no ability to read slowly and with care. After the regimen he was able to read "word by word" as well as by skimming.

Three of the four stopped practising after they had achieved some skill, and quickly regressed in their ability to read. This change was also reflected in their FRFs. An account of the regression appears in the discussion.

f. "Unusual" Cases: As a final note we want to describe two unusual cases, the first in some detail. A male, 30 years of age, has the peculiar complaint that while he can read facilely when he is "alert", he is unable to read or reads with great difficulty when he is "tired". When he is extremely "tired" he is able to "speed read" or skim a newspaper with good comprehension of the text, but he is unable to read in the "usual" way.

We interviewed him and tested him in two of his phases, the "alert" one (mostly occurring in the mornings) and the "tired" one (in the same afternoons). We did not test him in the "extremely tired " phase.

When he was in the "tired" phase he appeared to be markedly dyslexic. He had high level of comprehension and intelligence. He seemed generally alert in his tired phase and without optical defects, but could hardly read. In the "alert" phase his reading was good for long spells of time (over an hour), with the usual speed of reading and with only an occasional stumble now and then over an unfamiliar long word.

The measures of his FRF in these two phases are shown in figure 7. On the right side of the figure, one of the plots matches nicely the FRF of ordinary readers. These data were taken when he was in the "alert" phase. The other plot was taken when he was in his "tired" phase. It falls off shallowly with eccentricity and so extends further into the peripheral field. It resembles that of the dyslexics. On the left side of figure 7 the differences in the plots are small although a slight extension of the FRF into the periphery is evident for the "tired" phase.

Figure 7 shows a clear relation between measures of the FRF and task-competence reported by the subject. In the light of his subjectively distinct states we can suppose him to be a conditional dyslexic whose states can be told by objective testing. He switches between these states for some not very obvious reason. In the "tired" state he is not fatigued -- he used the term "tired" only to describe his inability to read; otherwise he is alert and competent. That this is not a problem of acuity is driven home by the fact that these states are in the same individual. If his acuity is improved for peripheral vision, can the same change in optics worsen his foveal acuity, if one supposes that his physical optics have somehow altered? Alternatively, can one suppose that his retina has changed its connectivity somehow? Has he changed his linguistic ability? If so, what tests could be used to distinguish his clearly reported states? Has he altered the anatomical connections in his brain?

After we had made our measurements on this subject and explained to him our notion of task-determined strategies, he succeeded in teaching himself to use the wide field (dyslexic) strategy when he was "alert" (in the morning). He did this because he knew that creative art work was easier for him when he was "tired". When he needed to do creative work while he was "alert" he now could switch voluntarily to the "tired" mode. The reverse shift, from in the "tired" mode (wide FRF) to "alert" mode (narrow FRF), he still is unable to do voluntarily. Since his ordinary work pre-empts the practise we imposed on the severe dyslexics, we could not devise an alternate avenue to open him up, so to speak, in his central vision.

The second similar case is a child, 11 years old. He had normal vision but has had treatment for strabismus when he was 7. He also was advised at that time to read with one eye closed. He came to our laboratory with the complaint that he can read only for a short time (20 min.) and then he cannot read any more and occasionally gets a headache. We started testing his FRF. By the time we finished half of the test (half of the slides at each eccentricity) we made an interim average. The score was much like the scores of ordinary readers. However, when we tested the second half (the remaining slides in all the eccentricities) and averaged it separately from the first half, we saw an FRF which was much wider than the first half. (This difference of the two halves is uncommon, in fact we had not encountered such a major difference before). Accordingly he was able to read well before the beginning of the test and was reading with great difficulty after it.

4. DISCUSSION

a. The thrust of the experimental results.

Ordinary readers and dyslexics differ by their form-resolving-field (FRF). As a measure, the FRF of an adult is rugged and reliable. Over a 4 year period it shows little if any variation. The adult dyslexic maintains the same FRF over time except if taught as described earlier.

FRF is well-correlated with the ability or the inability to read in the ordinary way. The FRFs of ordinary readers are of one shape, and those of severe [6] and reading dyslexics are of another [5]. The FRFs of ordinary readers are narrow, whether they are English or Hebrew native speakers, and reflect that lateral masking increases rapidly with eccentricity. This shape of the FRF and the complementary distribution of lateral masking provides a central cone of distinct vision most suitable for progression from one word or word group to the next. It is what makes usual reading possible (we do not include speed reading). On the other hand, severe dyslexics have an FRF which is wide in the direction of reading (wide to the right for English-native speaker and wide to the left for Hebrew-native speaker),masking for aggregates of letters at and near the center, and best vision for aggregates in the near periphery. In addition, lateral masking is much reduced in the direction of reading. When severe dyslexics gaze directly at an

aggregate of letters it is indistinct because of lateral masking. (The use of "lateral" does not refer to the peripheral field. It refers to an interaction between a visual form and its neighbors on both sides. Thus lateral masking can occur in the center of the field of vision.) At the same time their form vision for symbol aggregates is better further out in the direction of reading. They can't see words where they gaze , as do ordinary readers.

Of the dyslexics we saw, 9 came from a college specialized for people with learning problems. They had learned to read, though not with high efficiency. Their FRFs were similar to those of the adult severe dyslexics in spite of their intensive training [5]. This indicates that what they had learned was confined by their visual strategy.

The functional implications for ordinary readers are straight forward: they can attend best at the center of gaze without being distracted by text in the periphery. The implication for the severe dyslexics is almost counter-intuitive: they laterally mask (for aggregates) at the center of gaze where the daylight visual acuity is best. They spell out letter strings best in the near periphery (5° - 7.5°) but, at the same time they perceive much of the text near the word they are about to read (they "see all at once", as they say) due to the wide FRF in the direction of reading. As a result they have great difficulties in learning what the forms of words are and they have great difficulties in sequencing what they see.

The striking difference between ordinary readers and severe dyslexics is also the masking at and near the center of gaze. Previously Bouma and Legein [3] observed that, in and near the fovea, ordinary reading children recognize a string of letters better than dyslexic children, while single letter recognition was similar for both groups. Another observation made by Thorn [15] demonstrated "crowding" in the direction of gaze for all children 5-7 years old which was relieved for most children after they became 9 years old.

When dyslexics and ordinary readers are confronted with two letters, one at the point of fixation, one in the periphery, but in steady view as a figure, there is not much difference between them for eccentricities up to about 10°. Letter identification is saturated with the angular size of the letters about that in fig. 9. By bringing the process down to a threshold operation we can find differences. It was only due to the normalization procedure, done separately for each subject, as described earlier, that distinctions began to appear.

For example the measurements near the center of gaze would not have showed the masking between central and eccentric letters characteristic of dyslexics unless we could display the operating range below saturation. With a string of letters, differences between the groups mounted so steeply as a function of string length that we could use strings under steady view, with gaze directed at the fixation point to demonstate lateral masking as in figs. 9 and 10. But any isolated single letter in the periphery (from the letters we chose) except for I, is also made of parts, except that the number is far less than in the string and the parts are connected. The relation between the FRF and the equivalent measure for strings led us to suppose that complex letters (more than one part) are self-masked, but so weakly that the process doesn't show except as conditions are reduced to threshold. That is, self-masking is a limit form of lateral masking, but involves the same underlying process.

Therefore, the differences between severe dyslexics and ordinary readers in the shapes of the FRFs and in the direct measures of lateral masking can be considered as differences in the distribution of lateral masking over the visual field. Moreover, as this distribution of lateral masking is so nicely correlated with the skill of reading we suggest that the active masking in the periphery is what makes usual reading possible. In a previous study we suggested that lateral masking is a contingent process which still allows retrieval of masked information by demasking [4]. We also mentioned that lateral masking is not intrinsic to the visual system but is learned.

The asymmetry reversal of the FRF for Hebrew and English native speakers and its dependence on the convention (direction) of reading is a support for the notion that the FRF and the associated lateral masking are learned. We suggest therefore, that it is a visual strategy which is learned by practise in order to accomplish the task of reading.

Figure 8 compares the average FRF's of 19 English-native dyslexics with 29 ordinary readers for the right visual field. There is little difference between the two groups in the left field. The case is reversed for Hebrew-native dyslexics against

Hebrew-native ordinary readers as in Fig. 2b. We suspect that the picture is slightly compromised by the fact that all members of the group learned English early as a second language. This qualitative mirror-image between the aberrant plots for the two languages suggests two hypotheses: a) Either dyslexia is learned as a function of direction of reading, or b) there is a pre-existing asymmetry between the two halves of the field, and those unfortunate enough to have the right hand version become dyslexic for European printed language while those who have the left hand version become dyslexic for Hebrew or Arabic. In one case of a Hebrew-native adult severe dyslexic who was taught to read Hebrew and English at the same time (at age 6) we found two asymmetries. The one for Hebrew letters was similar to that of Hebrew-native dyslexics, and the one for Latin letters was similar to that of English-native dyslexics. Therefore we tend to hold the first hypothesis.

It is important to note that at 2.5° eccentricity the severe dyslexic has a lower score than at 5°. Since the FRF is measured with one letter at the fixation point, the other in the periphery, the dip at 2.5 degrees reflects lateral masking between the letters. (One type of childhood remediation that emphasizes and extends this dip on later measure is that in which the child is taught to read letter by letter using a pointer or a finger to indicate the letter.) This dip characterizes all adult English-native dyslexics.

With the 4 adult severe dyslexics subjected to the training described in the text, the average FRF shifted as shown in Fig. 6, from that of the severe dyslexic to that of the ordinary reader. For the 9 young adult reading dyslexics who had been trained, moderately successfully, in a remedial college, the FRF was that of the other adult dyslexics [5]. This does not mean that the reading improvement of our 4 was better than that of the 9, although our impression was that it occurred more rapidly.

The aim in the self-training of the 4 was to see how well they could be brought to read through the use of peripheral vision. But the improvement over a few months was accompanied by a shift to the FRF of the ordinary readers. This surprised us. We reported the first case in the initial publication that set forth the FRF as a test for dyslexia [5]. That subsequently the other 3 responded in the same way was initially heartening. But over the months after the post-training test it became obvious that there was a price on the improvement that 3 of the 4, (who did not know one another) were individually unwilling to pay. It involves a variant of the answer to the famous question of Dr. Molyneux in the 17th century, so well expounded by von Senden in his book, *Space and Sight [14]*. His question was, how well would a person, blind at birth, see if vision were given at adulthood, say the age of 20? The answer is that they can't use that vision well at all, and become depressed by their new-found and swamping incapability of handling an embarrassment of information, meaningless to them.

The problem can be exemplified by the first case, which in a general way reflects what happened to the other two. He spontaneously explained why he wanted to stop practising the training and doing his daily reading. He had been the sort of person who could attend several things at once: follow a conversation while working at some manual job, while listening to the news on the radio, while instructing a novice co-worker, etc. This kind of multi-media living was his natural state. But as his reading improved and the FRF shifted he found himself impaired -- he could only attend one thing at a time. This impoverished experience repelled him, and although he had taken on a position that called for dealing with paper work and was doing what he initially professed as his goal, he felt the price of reading was too high. Within a month after his second test showing the changed FRF, he abandoned his job, stopped practising his reading, and a few months later, when tested, showed almost the same FRF of the severe dyslexic as before training started. However, he was happier for the renewed welter of on-going experience.

One way or another the same kind of discomfort with the new state afflicted the others quite separately. They hadn't met each other and so the phenomenon was not communicated. The exception, the only hold-out, was a college student who desperately wanted to keep up with the classes. This must be contrasted with the 9 dyslexics who had survived about 3 years of conventional training at a college that specialized in disorders of reading and learning. There was no shift in visual strategy in their FRF's which stayed that of the dyslexic, and they were quite pleased with their modest ability which simply added to the armamentarium without changing the persona. However, we don't know if a phenomenon like that among our 4 trained dyslexics also occurs in their school.

That is why we emphasize that the mode of training we constructed may not be proper for young adults but only for children in their early school years when they are acquiring reading ability. In fact, the training we gave was fairly equivalent to the old Palmer method of handwriting exercise used in grammar schools half a century ago, and was consciously patterned after it, using hand-eye coordination in new practise to set a strategy of seeing.

The shift in FRF in this group of 4 to that of ordinary reader was unexpected. But it showed what we wanted, that visual strategy was task-determined and could be learned [6]. In a sense that is what is implied by the work of Held [8,9], Kohler [11], and others: the shift in handling a new mode of visual information depends on the proprioceptive input from the active use of a novel mechanical task-performance for which a new visual mode is necessary to the task. Visual cognition alone is not enough. Our results demonstrated that the reading strategy of the ordinary reader could be learned by an adult dyslexic. Therefore, at least in these cases, the dyslexia is expressed in a visual strategy that, by its nature, prevents the flow of the necessary information from the central field to the higher order processes. Whatever the nominal cause of dyslexia it is a physiological form of Geschwind's disconnection syndrome [7], with lateral masking as the "disconnection" agent. Analogous processes occur in the other sensory modalities.

This brings up an issue to be covered more extensively in a later paper. The dyslexic FRF was found on dyslexics. Could it be seen in others not classified as dyslexics? We found some scholars whose mastery of the literature in their fields was extensive. They enjoyed reading but showed the dyslexic FRF. These subjects gave histories of having been classified as reading problems by 3rd grade. Somewhere around the age of 10 to 12 they independently and spontaneously discovered speed-reading by themselves, not through instruction, and thereafter were able to handle their school books. Yet their FRF's remained that of the dyslexic. And in the general populace there are some who have learned speed-reading autonomously in grammar school, after being remarked as a reading problem, but who did not go on to advanced education. We have no notion about how wide spread such histories are in the population, but we suspect, purely on the basis of information conversations, that it is not a negligible number.

Our impression from the tests is that once visual strategies for reading are learned for use before a critical point, somewhere about 8 - 10 years of age, improvements in reading are not thereafter reflected in the shape of the FRF. This is supported by comparing the average FRF's of English-native children, 7 - 8 years old, who are ordinary readers for their expected level, with the average of adult ordinary readers. The two plots are almost the same, those of the children being slightly narrower in the left peripheral field (unpublished results).

Finally we must reaffirm that the FRF only tests the visual strategy used in dealing with text. We believe that other visual strategies are used by the same subjects for other tasks. The learned strategies are discrete -- they don't shade into each other, and are not modifiable after they are learned. Instead one has a lexicon of learned strategies and switches between them as is appropriate to the learned tasks. That does not contradict the statement that a new strategy can be learned by practise and added to the lexicon. But in the adult it must be learned by new task-performance in a manner where existing strategies are not challenged directly. The training of the 4 dyslexics shows this to be possible. What is most interesting about the result is that the strategy they learned fitted so closely that used by ordinary readers; it was not some compromise or modification.

b. The process of lateral masking.

The phenomenon of lateral masking has not been sufficiently explained. It was first found in the peripheral visual field and is commonly thought to be confined there. While it extends globally over the whole peripheral field there are some differences between its effects along the vertical versus horizontal axis of the field [4]. That will not concern us here. We will deal only with strings of letters or symbols along the horizontal axis of the visual field.

The effect is in daily experience, and an example is given by figure 9.

At reading distance the size of the letters in Fig. 9 is well above the lower limit set by acuity. The isolated N on the left is easily identified while gaze is fixed on the x. But the N, as an arrangement of parts, masks itself somewhat and so is less distinct

than expected from the acuity measure. Self-masking increases as parts increase.

To the right of the fixation x in fig. 9, the N, which is at the same distance from the x, but imbedded in a word, can't be made out at all by the great majority of readers. That the effect does not depend on handedness to the ordinary reader is made obvious by turning the figure upside down.

The word is not blurred, as by defocussing, although that is how it may be reported. The average of contrast and gross appearance seem much the same as under direct gaze, and the string is clearly comprised of parts. But somehow, while the parts seem to have sequence and shape, these extensional properties are ambiguous, and except for the initial and terminal letters, the word, eccentrically viewed, can't be spelled.

The effect increases as letters are condensed, or as the string is presented more eccentrically [2]. The middle letters are most masked, the extreme letters least [16]. Some letters, or symbols, such as O, are most resistant to masking [4]. But that is second order to the unreadability.

That the effect is not tied to language is shown in fig. 10. On the left the circular arrangement of circles can be told while gaze is fixed on the x. On the right the small circles are visible as circles but their arrangement in circular array is not, showing that acuity is not compromised. The word in fig. 9, and the circular disposition of small circles inside the large one in fig. 10 have lost the form due to their arrangement and the parts, while visible, provide only a texture.

Since acuity is not at issue, this blunted legibility must be accounted otherwise than by appeal to optical or retinal resolution. On the other hand it can't be informational swamping of cognition since the same letter string can be recognized on direct gaze and the individual letters recognized eccentrically.

To the observer, gazing at the fixation x, it is as if the parts mutually interfered with one another in perception -- each part exerting its influence on all sides of it. The "lateral" in lateral masking refers to that spread of influence away from a part -- not to the fact that it affects vision in the peripheral field.

Both ordinary readers and dyslexics recognize the isolated letter in Fig. 9 whether looking at it directly or seeing it eccentrically. But, for the string of letters the dyslexic complains of "crowding" when looking at it directly. It is a very good expression of how the string appears to readers when it is seen eccentrically. Without overly stressing the point since the evidence has not been systematically assembled, we find that English-native dyslexics can often spell out the letter string on the right while their gaze is fixed on the x. They do worse if the letter string is on the left. Ordinary readers, gazing at the fixation x, can't give the full sequence whether the string is on left or right.

From these plain examples the nature and function of lateral masking is not easily explained, and it is not obvious what more careful testing would contribute except tables of data and measures of contingency. The universality of the process does not allow it to be dismissed as a phenomenon of secondary importance.

Is lateral masking a fixed property of perception in that part of the visual field? Or is it a conditional loss, as if some kind of masking process could be switched in or out? So far there are two ways of demasking. If only the middle thoroughly masked letter of the eccentrically seen word is slightly but suddenly displaced normal to the string it becomes for the moment sharply distinct and can be read before it lapses quickly back to texture. This does not happen if the whole word is suddenly slightly displaced as a single object. A second way was reported by us before we began the study of dyslexia. In tachistoscopic presentation of an eccentric string of 3 letters the middle one is more profoundly masked than the end letters. But, for any of the letters, if the same letter in the same font, contrast and orientation is flashed at the fixation point at the same time that an eccentric string is presented, it is demasked in the string. The effect is not cognitive since upper case letters are not demasked by their lower case equivalents. These two instances only make the point that lateral masking is not like optical blurring or a general depression of visual resolution.

Another question is whether lateral masking ever occurs in the fovea of readers, i.e. around the center of gaze. It does, and is currently called "foveal suppression", but is a matter of some dispute. During a large saccade, the ability to read words in large

bold upper case such as a newpaper headline, is much compromised [12]. The experiment was done in a dark room with the newspaper illuminated by a bright flash, a few microseconds in duration. There were two programs for flashing. One was at random intervals and the other only in the middle of a large saccade that carried the axis of gaze across the headline. While the headline is quickly read within a few flashes in the first case it could not be read over very many flashes in the second case. There are entoptic ways of showing the same saccade-gated "suppression". It has a quality like that of lateral masking. Such observations, however crude and qualitative, are enough to suggest that lateral masking is labile, can be established or relieved.

The responses of severe dyslexics to the letter strings around the center of gaze and the spontaneous descriptions of what they see are markedly similar to how ordinary readers respond to the same strings at ~8° eccentricity and how they describe what they see. In both instances the common language is not sufficient---it has no words for varieties of confusion. That severe dyslexics do better on letter strings at that eccentricity than ordinary readers provides a crucial point. There need be no disorder of cognition in the dyslexic but only one of acquiring the information regionally from the central visual field.

It is commonly supposed that what the sense-data-driven perception reports is directly available for interpretation and judgment by the apperceptive or higher order processes. But there is a modifying operation, attention, which partitions the scene into a foreground of distinct forms against a background in the awareness. The notion is that some influence, like form-resolving power, becomes concentrated in what is clearly seen, but at the expense of that influence in the rest of the field. The spot-light of attention illuminates what matters at the moment while the background recedes to the shadow of simple awareness. In this metaphor attention is regional and local and that which is attended is grouped in that narrow solid angle. However, there are other forms of attention, well-experienced but poorly tested, such as that which allows successful negotiation of a scrimmage in football, the eluding of an adversary in rapid pursuit, the hunting of prey, or fast driving in dense traffic. In these cases the attention is not only on objects but on their probable expected trajectories and over a wide angle in the field. A good way of appreciating this point is to compare what you see at a football game or hockey game with the running commentary of an experienced reporter, often a former player.

The nature of attention as a process is under renewed study now. To take attention as cognitively driven raises a primitive point. Do we see the whole visual field as clearly and distinctly as the physiology can allow and cognition can parse, so as to determine what not to see clearly? In short do we see distinctly what is not interesting so as to decide to ignore it? Or do we see the whole field clearly but not distinctly and somehow bring to the foreground of distinction what is interesting? Put this baldly neither operation seems appealing, the former because of the glut of unnecessary process, the latter because of the emergent property of distinction. There is an additional factor. An ordinary reader, gazing at the fixation point can intend most strongly to bring an eccentric string of letters to legibility but without much success. The severe dyslexic can do the same for the string at the fixation point equally fruitlessly. That the eccentric string is in fact parsible visually is shown by the dyslexic. Yet the reader, without switching the eyes, can't switch the spotlight of his attention to the eccentric string, bringing it to legibility; nor can the dyslexic work the other way round. It is borne on us that except under unusual circumstances (e.g., as in observing entoptic phenomena) attention may not be driven by will alone but instead be associated with intended action in expert task-performance (including eye movement), and so be a product of practise.

The underlying physiology of lateral masking is mysterious and, in this way, resembles all the rest of the processes in vision. The curious shift from form to texture can be regarded as a way of markedly reducing the general load on cognitive processes during task performance when speed of prediction becomes essential. Masking as a regionally controlled filter for the content of perception, passing enough content to establish texture, but not enough to provide local form distinction, is hard to imagine in terms of physiology as currently sketched, or in terms of circuitry for an adaptive model.

However, one approach to a mechanism of masking is given by some empirics had from physiology. We know that there is a point-to-point mapping between the retinal surface and the primary visual cortex. But at every point in the cortical map the information is in terms of extensional information within a receptive field, an angular

area of visual field around the corresponding point on retinal surface. The information refers to the sharpness and contrast across boundaries and the preferred orientation of a boundary moved into the receptive field. The overlap of receptive fields in the cortical map is fairly large in the peripheral visual field and the receptive fields grow in size with eccentricity.

Processed from this discrete manifold of receptive fields is the global continuous visual field of our cognition to provide a representation of distinct objects disposed in definite arrangement in continuous space. Whatever is the process sequence mediating that higher representation, it is not simple. But we can say this: any local extensional feature in the image on the retina has a distributed representation over many adjacent receptive fields in the cortex, and in each of these receptive fields the representation is different. But in that distribution the extensional properties such as sharpness and shape of a boundary are already encoded. Not necessarily encoded are the spatial relations between the extensional features. To retrieve those spatial relations calls for something like a spatial differencing operation (analogous to a Laplacian) applied to the distributed representations of local extensional features. When such a sharpening operation is not applied, only representation of texture is available; when it is applied, representations of forms and arrangements issue. We propose that this sharpening operation can be switched in or out regionally in the visual field, and that it intervenes between the sense-data-based perceptual and the cognitive processes.

Scribes and scholars use the central field of vision in their expertise; hunters, ballerinas, and hockey players use the peripheral field. In the peripheral field, whatever moves differently from what is about it breaks lateral masking and takes the foreground of distinction; vanishes into background when it stops. In the central field whatever is at rest has form, whatever moves is less distinct unless the eye moves to follow it.

There are two sorts of visual tasks that we perform, local and global. In local tasks our movements are directed at changing the local scene, e.g. reading a page, doing a jigsaw puzzle, moving through a room to pick up a specific object, etc.

In global tasks the scene is active and our movements are responsive to the actions, e.g. during sports, chasing a person or an animal, driving a car through traffic, etc.

In both cases the task-performance, from moving only the eyes to moving the whole body about, is based on predicting the content of the next state of perception and having a model of the world somehow represented in us. Expert task-performance is had by practising those actions by which an intended next state of perception is achieved efficiently by correcting the error between it and the state predicted under current conditions. This is not only the way we work but also, in analogy, those machines that we make to track objects.

In the prediction necessary to perform tasks expertly it is important to single out the relevant from the irrelevant in the welter of information given. What is relevant to the task emerges from practise. If, having identified the relevant, we can relegate all the rest to background by a single general operations, our ability to perform increases. Rather than blank everything else away we simply lessen the cognitive load by draining it of specifics but keep it in awareness.

Once prediction is involved, the external arm of the loop that couples instructed action to perception in global tasks requires a detailed internal world model and an efficient sub-programming of bodily action to work in fast responsive matched time with relatively accurate step-to-step prediction. The cognitive load of this expert action is much reduced by having a stripped down model of that part of the world in which expert performance occurs. With this performance it is not the whole change of the world that is intended but a specific distribution of some of its parts. After all, the world is large and variegated but we each possess only one body. And so we propose that learning expert bodily performance in global action involves a double deed -- one is the design of the best strategy for attaining the desired perception, and the other is the reduction in unnecessary detail of what doesn't matter to the task -- a reduction of the <u>ceteris paribus</u> to a background of texture. The major reduction for global activity responsive tasks would be in the detailed account that is usually rendered by central vision for a passive scene. And so we expect to be true that which athletes and hunters and ballerinas tell us, that the center of vision is used simply to establish a reference, an epicenter, in the visual field around which the world of interesting events goes its course. The foveal region is masked. That is also the case with dyslexics who often

excel in the arts and active pursuits and, for some reason, have trouble in reading.

Consider instead the scholars whose prey is pursued through paper. Theirs is not a world of changing targets but of words fixed in print. A different strategy is required for motoric negotiation of that world -- a flick of the eye to a footnote or to an earlier paragraph, an unhasty turn of the page, the lifting of an alternate volume. Negotating the texts and writing notes are different kinds of perceptual trajectories from those used in adversarial sports, yet they equally invoke predictions to speed the action. But there is no independent movement of the text as there is of the objects in the hunter's or team-player's world, and no masking of central field except perhaps in the fly-back of the eyes to the beginning of the next line. And again learning the optimum strategy to read is a double deed -- a proper eye movement attended by appropriate masking in the periphery.

At this point we propose that lateral masking is an operation that takes place early in the chain of process just after perception which is entirely sense-driven. Its function is to reduce the informational content communicated by perception. To be specific, a distribution of masking in the visual field is developed together with motor skill in the performance of a task, and the distributions are determined by the nature of the tasks. Accordingly, we suppose lateral masking to be task-associated or task-determined. The strategy calling for good peripheral vision invokes masking in the central field, and vice versa. Most people possess at least two masking strategies, one for reading, one for negotiating an active world, and can switch between them as needed. On a gross level this is apparent in driving a car. But if a strategy has somehow been improperly learned in early task-performance, it becomes difficult to modify, since masking excludes the reinforcement needed to establish an alternative.

It is true that the tests we have devised show in ordinary readers only the presence or absence of the FRF for the masking strategy associated with ordinary reading. The existence of masking strategies associated with global expert performance has been inferred from experience. That strategies of lateral masking can differ is established by the tests. That a strategy can be locked against specific tasks is exemplified by dyslexia. That the lock can be opened even in adult dyslexics is clear from the training of the four severe dyslexics by a regimen that did not challenge the lock. The "diurnal" dyslexic shows how a lock on a strategy can be established by training. We have no doubt that there are other visual strategies that are switched as states, and that locking can occur in them. However, our efforts have been directed to show at least two strategies of masking which we believe are basic, learned early in life, and ordinarily easily switched as required by the task. But the switching can get sticky, as shown by the diurnal dyslexic, and by three of the four trained dyslexics who acquired the lateral masking strategy appropriate to reading and became uncomfortably locked in it.

5. CONCLUSIONS

1. The (normalized) FRF as defined in the text and used in the tests, measures two varieties of lateral masking as a function of eccentricity of the letter in the peripheral field: a) between the parts of a letter in the peripheral field, b) that between the letter in the peripheral field and another in the central field.

2. The FRF of an ordinary reader, English-native or Hebrew-native, falls off steeply and monotonically to both sides away from the center of the visual field and is fairly symmetric.

3. For English-native dyslexics the FRF in the right visual hemifield has its maximum at about 5° eccentricity. It falls off much less steeply with increasing eccentricity than that of the reader. It also falls off from 5° with decreasing eccentricity. In the left hemifield the FRF is about the same as for a reader.

4. In Hebrew-native dyslexics the FRF on the left falls off less steeply with eccentricity than for the Hebrew-native reader. Thus the asymmetry follows the direction of reading in English-native and Hebrew-native dyslexics. Both English-native and Hebrew-native dyslexics have the same dip in the FRF toward the center in the right hemifield. Both show lateral masking in the central visual field. That is their complaint.

5. For adult ordinary readers the FRF does not change with time. FRF characteristic of the adult dyslexic remains the same after standard procedures for remediation in reading.

6. In 4 English-native adult severe dyslexics we altered the FRF by a hand-eye coordination augmented mode of training with rapid acquisition of reading ability. In them the FRF shifted to that of the ordinary reader. In one dyslexic with a diurnal cycle he learned to shift his FRF from that of reader to that of dyslexic. (He was a graphic artist and preferred the latter state).

7. Of the 4 adult severe dyslexics so trained, 3 decided to abandon practise and soon reverted back to the dyslexic state deliberately. With the reading came the curious limitation that they "could do only one thing at a time." This was much at variance with their usual state of attending several tasks at once, and they decided that reading was not worth the change in personal habits and competences.

8. The evidence implies strongly that dyslexia is a learned visual strategy of lateral masking in the central visual field, and is acquired in early life before the age of 8 years (between second and third grade in grammar school). It persists because it prevents reinforcement of an alternate visual strategy in the central field. The visual strategy of the ordinary reader can be learned by the adult dyslexic under conditions that do not challenge or accomodate the lateral masking in the central field. This alternate strategy is developed from a regimen that uses unfamiliar hand-eye coordination practise to provide the avenue for learning in the central field. We believe this method can serve as basis for treating children at risk.

9. The dyslexic visual strategy, as a trait, may even have a predisposing factor. But, like many other traits, its expression is contingent. Expression of the trait as simply inability to read is not a necessary consequence of possessing the trait.

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FIGURE LEGENDS

Figure 1. A schematic drawing of the sequence of events for a single stimulus. Top part of the figure shows the events on the screen. Reading from left to right, at first a fixation point is presented (by projector I). Except during a test this slide is constantly on. In a test the shutter in front of projector I shuts as that in front of projector II opens for short interval, T_1, to present the stimulus image. T_1 is followed by a second interval, T_2 , when no projection plays on the screen. The effective stimulus duration is counted as the sum of T_1 and T_2. Following the interval T_2 the eraser goes on (projector III) for 2.5 seconds. The eraser consists of a blank lit screen. Following the eraser a new cycle starts after the subject reports.

Figure 2. Displays the Form-Resolving Fields (FRF) averaged separately for adult ordinary readers (dashed lines) and adult severe dyslexics (dotted line). The measures are of % correct identifications of letters at different eccentricities in the periphery. Vertical bars show the standard deviations. The scores for the letters presented at the same time at the fixation point are constant for all eccentricities (95%±4%) and are not given here. a. English-natives (10 ordinary readers and 10 severe dyslexics) and b. Hebrew-natives (5 ordinary readers and 5 severe dyslexics).

Figure 3. Lateral masking in a string of letters measured as a function of eccentricity. Ordinary readers are compared with dyslexics for correct identification of each letter in 3-letter strings that are presented at various eccentricities. The % of correct identification at each locus along the string is given separately. The vertical bars (given only for the middle letter) denote the standard deviation. The correct identification of the letter at the center of gaze was above 95% for ordinary readers at all eccentricities and above 80% for severe dyslexics.

Figure 4. Plots of the FRF of a severe dyslexic. One FRF was taken upon on arrival (dotted line), the other plot was taken four months later after he practised as described in the text (solid line).

Figure 5. Lateral masking in a string against string eccentricity (measured as in figure 3). The initial performance (left plots) of the same severe dyslexic as in figure 4. On the right the performance of the same subject to the same test, four months later

after the practise described in the text.

Figure 6. The effect of learning and practising a new strategy. The FRF are of the right visual hemifield averaged for 10 ordinary readers (solid line, taken from figure 2a). The dashed line is for four severe dyslexics prior to the practise described in the text and the dotted line is for the same four severe dyslexics after that practise. The cars measure standard deviation. The FRF of the left visual hemifield remained unchanged during this period.

Figure 7. Two strategies in one subject are measured within a few hours interval. The dashed line is the plot of the FRF which was taken when the subject was in the 'alert' phase. The other was taken 6 hours later when he was in a 'tired' phase (solid line).

Figure 8. The FRF of the right visual hemifield of English-native speakers. The dashed line is the average FRF of 29 ordinary readers, the dotted line is the average of 19 dyslexics (reading dyslexics, dyslexics and severe dyslexics together).

Figure 9. A demonstration of lateral masking. Fix your gaze on the x. Without shift of your gaze, the N on the left will appear clear and distinct whereas the N on the right will not be legible, though segmented lines will be clear. This holds for ordinary readers only.

Figure 10. Another demonstration of lateral masking. Gaze fixedly at the x. Note that there is a ring arrangment of small circles apparent on the left. But on the right, while the small circles are still identifiable as such, their ring arrangement is lost.

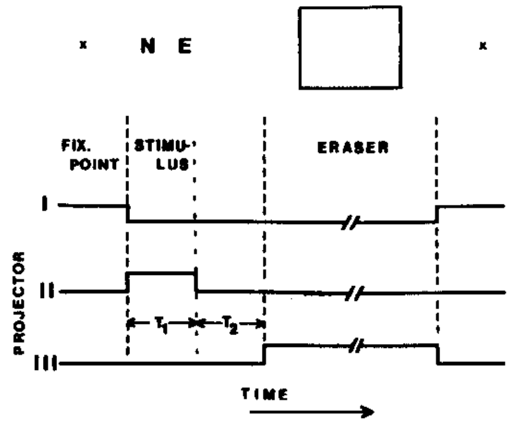

Fig. 1

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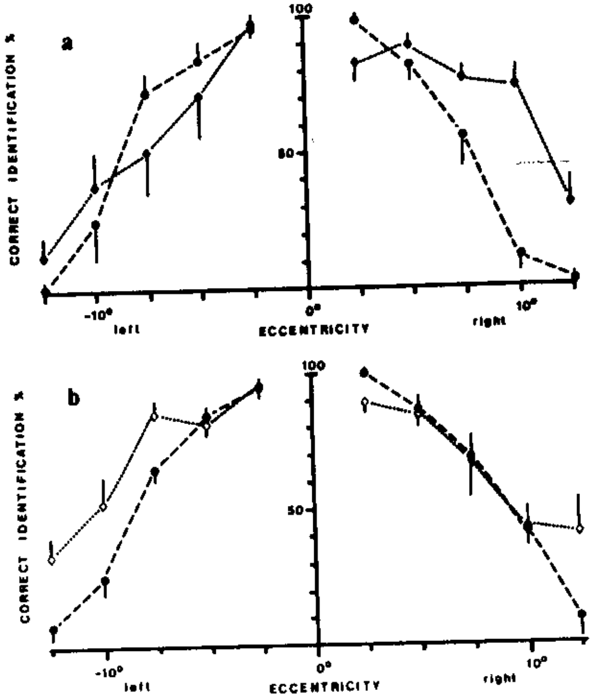

Fig. 2

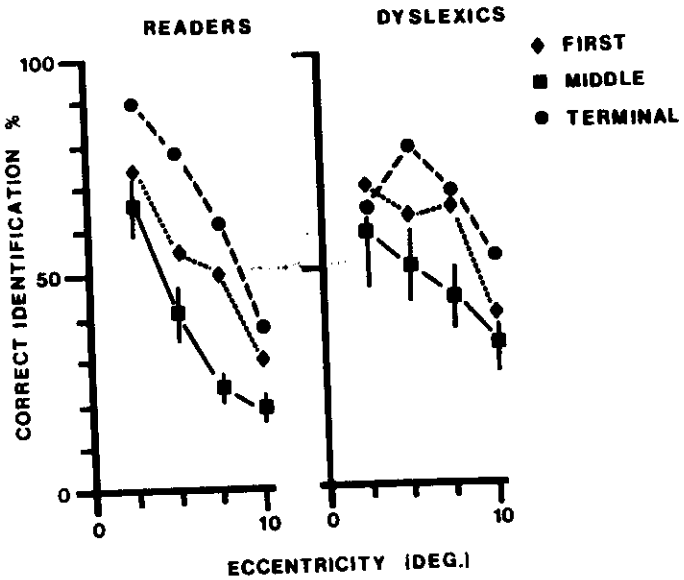

Fig. 3

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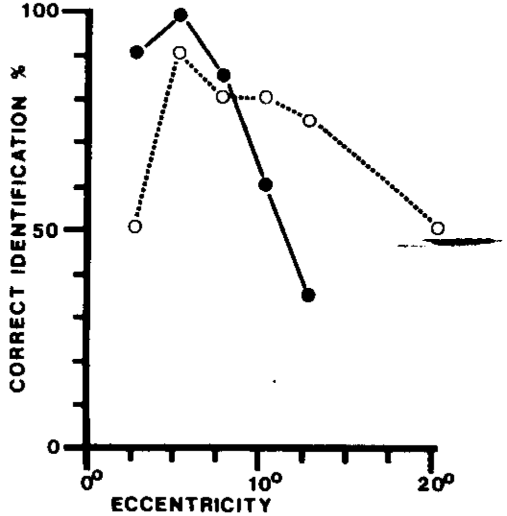
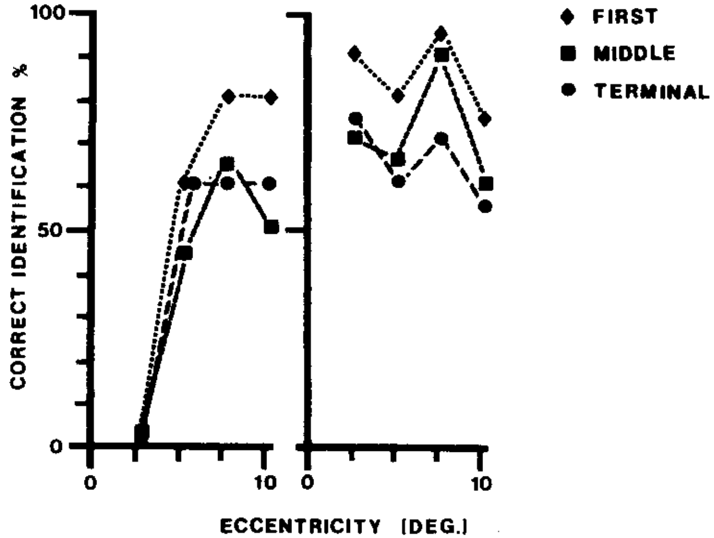


100
50
0
CORRECT IDENTIFICATION %
0°
10°
20°
ECCENTRICITY

Fig. 4



FIRST
MIDDLE
TERMINAL
100
50
0
CORRECT IDENTIFICATION %
0
10
0
10
ECCENTRICITY (DEG.)

Fig. 5

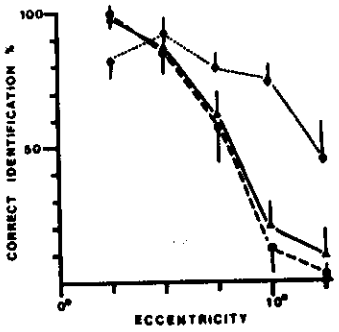


Fig. 6

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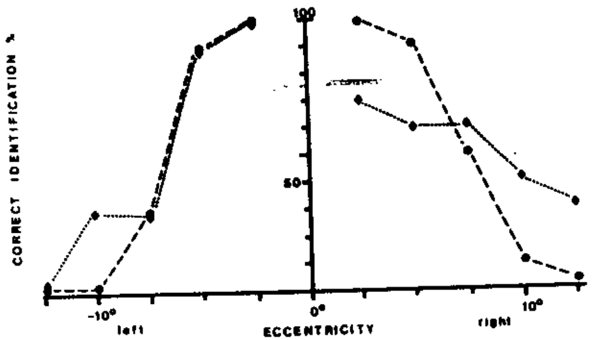

Fig. 7

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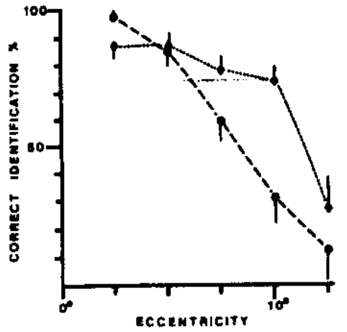

Fig. 8

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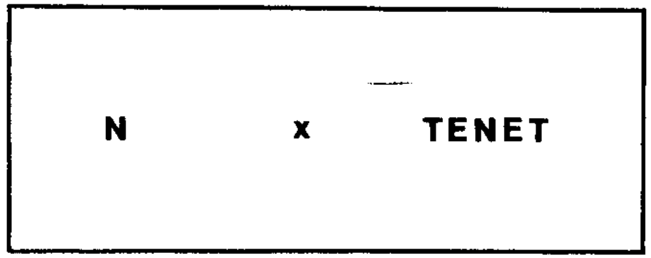

Fig. 9

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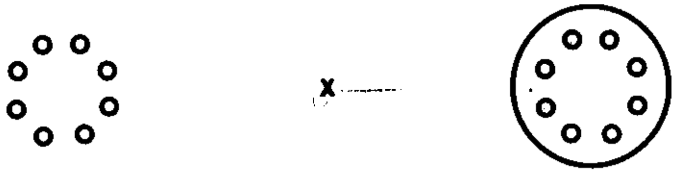

Fig. 10

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