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Task-determined strategies of visual process

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Lateral masking in the peripheral field of vision obscures letter recognition and is not accounted for by diminished acuity. In measuring lateral masking between letters in the peripheral visual field we accidentally discovered that ordinary readers and severe dyslexics differ markedly in tachistoscopic letter recognition tasks. Tests were devised to measure the differences accurately. Ordinary readers recognize letters best in and near the center of gaze. Recognition falls off rapidly with angular distance in the peripheral field. Severe dyslexics recognize letters farther in the periphery in the direction of reading (English-natives to the right, Hebrew-natives to the left). They have marked lateral masking in and near the center of the field when letters are presented in aggregates. With dyslexia as an example, we proposed that the distribution of lateral masking is a task-dependent strategy in visual perception. To test this notion we designed an active practise regimen for 4 severe adult dyslexics, who within a few months improved sharply in reading. At the same time their test results changed to those of ordinary readers. We conclude that there are switchable task-determined pre-cognitive strategies of vision that can be learned and that the distribution of lateral masking may be part of what is learned.

INTRODUCTION

Lateral masking has been studied mainly in the peripheral visual field[2,14,18,19]. Since it is an ill-understood process and has been assigned little importance in the foveal and parafoveal visual field it occupies but a moderate niche in the literature on vision. The phenomenon is demonstrated in Figs. 1 and 2. Acuity is good enough to resolve the elements of an arrangement – as for example, the little circles in the ensemble on Fig. 2. Yet the circular array of these circles – the spatial arrangement of elements – is much compromised by the circumscribed circle.

Two kinds of questions arise from the demonstration in Fig. 1. Is lateral masking a fixed property of the visual process? What role does it play in compromising form perception well beyond the level expected from loss in acuity?

When Aubert and Foerster[1] set down the law that linearly relates the angular size of a just recognizable letter to its angular distance from the gaze axis, they used readers as the obvious subjects and exposed them tachistoscopically to many letters of same size presented at the same time over the whole visual field. But, if lateral masking is involved, as it must be if the conditions of their experiment are reviewed, any attribution of that law to the decay of visual acuity in the peripheral field is premature.

We were led by accident to an interesting apparent departure from the Aubert-Foerster law[1]. In our research on lateral masking and demasking[6], 5 of the 44 subjects were so different from the others and 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[7].

Dyslexia, not associated with other neurological or visual deficit, is presently unaccountable and is classified, more by default than by demonstration, as a disorder of some neurological function. But among the possibilities is a physiological explanation. That is, the necessary information for reading may be blunted be-

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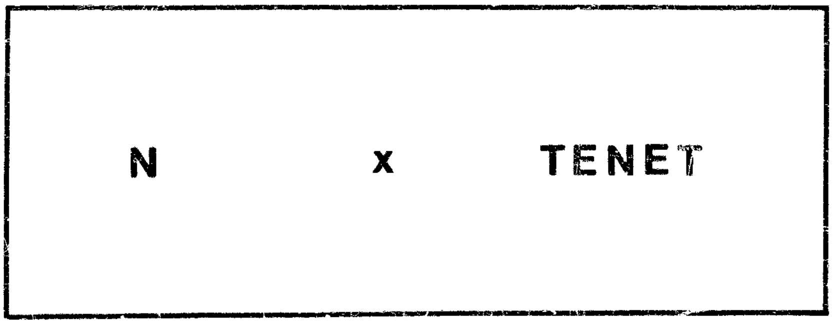

Fig. 1. A demonstration of lateral masking. Fix your gaze on the x. Without shifting your gaze, the N on the left will appear clear and distinct whereas the N on the right will not be legible though segmented lines will be clear. This holds for ordinary readers only.

fore cognition by misuse of a normal process but the pathway to convey the information is intact as is the higher function itself. At first this sounds like a distinction without a difference and, further, makes visual process arbitrary. But we propose to show that such blunting can be measured, that the measure is diagnostic, and that the blunting can be relieved by suitably designed practice.

Dyslexia thus provides a tool for the study of lateral masking and the differences in visual strategies. At the same time, the process of lateral masking, if it can be found in the central visual field[3], provides part of the psycho-physiological basis for the disorder. Lateral masking, insofar as it compromises the spatial relations between seen elements, but not the acuity by which these elements are seen, would account for the 'crowding' or 'confusion' that occurs without blurring under lateral masking. To this end we devised a new set of visual tests.

These new tests were confined to the distribution of letter pair recognition and of lateral masking along the horizontal axis of the visual field from 2.5° to 12.5° away from the center of gaze given a letter at the center. The results distinguished dyslexics from ordinary readers with high reliability. It remained to show that the tests indicate something about underlying processes in vision. The discussion develops that point and suggests an unusual but hitherto unstudied process-gating. Supplementing the tests, but not used to modify or extend the results are observations on some singular cases. These are to be considered anecdotal only, but are included to show a few empirics that guide our hypothesis.

MATERIALS AND METHODS

Apparatus and stimuli

A 3-way tachistoscope was constructed. It was comprised of 3 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 resulting at a luminance of 180 cd/m^2 as measured at the front of the screen. This first and smaller screen used was 35 cm long and 23 cm high. The second and larger screen used later 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. The question can be raised, why we did not use a video screen? In preliminary design we found marked differences between ordinary CRT displays and projection displays with respect to central vs. peripheral vision and chose that which gave highest discrimination and reliability in the results.

One projector used [illegible] slide [illegible] 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. (We found initially that a structured eraser prejudices recognition of stimuli in favor of ordinary readers; dyslexics were confused by it. See also ref. 4). 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 Fig. 3 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,

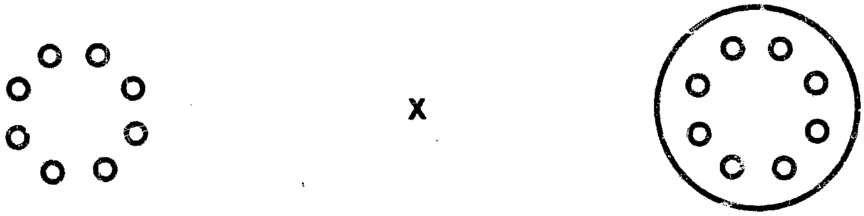

Fig. 2. Another demonstration of lateral masking. Gaze fixedly at the x. Note that there is a ring arrangement of small circles apparent on the left. But on the right, while, the small circles are still identifiable as such, their ring arrangement is lost.

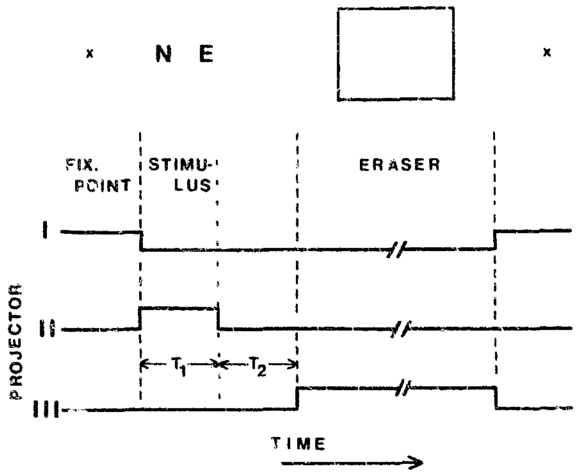

Fig. 3. A schematic drawing of the sequence of events for a single stimulus. Top part of the figure shows the events on the screen. Reading from left to right, at first a fixation point is presented (by projector I). Except during a test this slide is constantly on. In a test the shutter in front of projector I shuts while that in front of projector II opens for short interval, T_1, to present the stimulus image. Interval T_1 is followed by a second interval, T_2 (to account for the delay and opening duration of the shutter in front of projector III). Following the interval T_2 the eraser goes on (projector III) for 2.5 s. The eraser consists of a blank lit screen. The effective stimulus duration is counted as the duration from the 'off' of the fixation to the beginning of the onset of the eraser. Following the eraser a new cycle starts after the subject reports.

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 3 letters. For either experiment several eccentricities were used, with 20 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 10 Helvetica-Medium capital letters. We chose the letters from 3 sub-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[6]). The angular height of the letters subtended 35′ of visual arc and their contrast was 90% for both screens. 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 (Fig. 3). After verbal warning ('ready?') by the experimenter, the stimulus phase occurred and was followed after an interval of T_2 (so adjusted as to account for the delay and duration of opening of the shutter in order to keep constant the level of luminance) by the eraser phase which endured for 2.5 s before the fixation point was again projected. In this sequence, wherein the average background luminance does not vary significantly, the effective stimulus duration (from the cessation of the fixation slide 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 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[16], but were less useful because of lack of normalization between subjects.)

First, the stimulus exposure duration was set for each subject prior to the test itself by a pilot run with different exposure durations. Once the exposure 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 on which side the letter in the periphery was. The report was recorded and the next stimulus was given. When 20 such exposures of different letter pairs were delivered at one eccentricity, the eccentricity was changed and a new series of 20 was presented. Once all slides for all eccentricities had been presented (200 slides in 5 eccentricities on the right and 5 on the left), 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 Results, 'The FRF measured with random left-right display') 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 in our initial group were English-native speakers, all of them above 18 years of age. All but 2 of them were unaware of the purpose of the tests until the testing was finished. Twenty persons were tested. The 10 ordinary readers (3 females and 7 males) were clustered between 18 and 25 years of age with one person at the age of 45. The 10 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 volunteered on hearing of our interest. They belonged to no specially defined or targeted group. They had all been diagnosed as dyslexics by their neurologists, psychologists and teachers and had received no special tutoring within the last 3 years prior to testing. We emphasize that they had been previously diagnosed and tested by competent practitioners. Our interest was in the symptom of inability to read in the absence of other impairment of performance or understanding, and it was the mechanism of the symptom rather than the cause that concerned us. None of the dyslexics had any additional known neurological impediments nor any uncorrected refractive errors. The severe dyslexics had a normal level of comprehension of heard texts, but all had profound impairment of reading. The clinical correlative features such as handedness, specific classification of dyslexia and the like are not germane to this study which is concerned only with the visual process.

In a later testing, we used another 5 adult ordinary readers (20–31 years old) and another 5 adult severe dyslexics (17–28 years old). All of them were Hebrew-native speakers who were exposed primarily to Hebrew through their first 10 years of life and who had been taught to read only Hebrew for the first 3 school years. These subjects came from a background similar to that of 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 was also profoundly impaired. All the Hebrew-native subjects had learned to speak English beginning at their 4th year in school and had had training in reading it.

RESULTS

The form-resolving field (FRF)

In a test flash (as described in Materials and Methods) two letters are exposed, one at the fixation point (the center of gaze) the other at some angular distance in the peripheral field. Both are to be verbally identified by the subject immediately after the presentation. After the tests at all eccentricities are finished we score correct identification of both central and peripheral letters and plot the percentage of correct identification of the peripheral letters as a function of eccentricity. Taking empirically that under the normalized conditions, recognition of the eccentric letter alters with angular distance from the reference letter at the fixation point, we suppose there to be a recognition field around the letter at the fixation point that can be measured as a distribution of probability of recognition which we name the form-resolving field, (FRF). We have sampled this field along the vertical (unpublished results) and horizontal axes, but for this study we consider only the field along the horizontal axis. What is at issue is the recognition of form rather than the resolving power. In Fig. 4a we plot the averages of the FRFs for English-native ordinary readers and severe dyslexics, which were measured with the smaller screen.

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 Fig. 4a. At all the eccentricities on the right, except at 5°, we recorded two significantly different plots: 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° $F_{1,18} = 20.02$, $P < 0.001$ and overall group × position $F_{5,94} = 2.31$, $P < 0.05$). These two populations differ significantly in the overall shapes of the FRF on the right[7]. Similar results were obtained by Perry et al.[16].

Ordinary readers recognize letters best when they are presented nearest to the center. The FRF falls off sharply with growing eccentricities, in accordance with

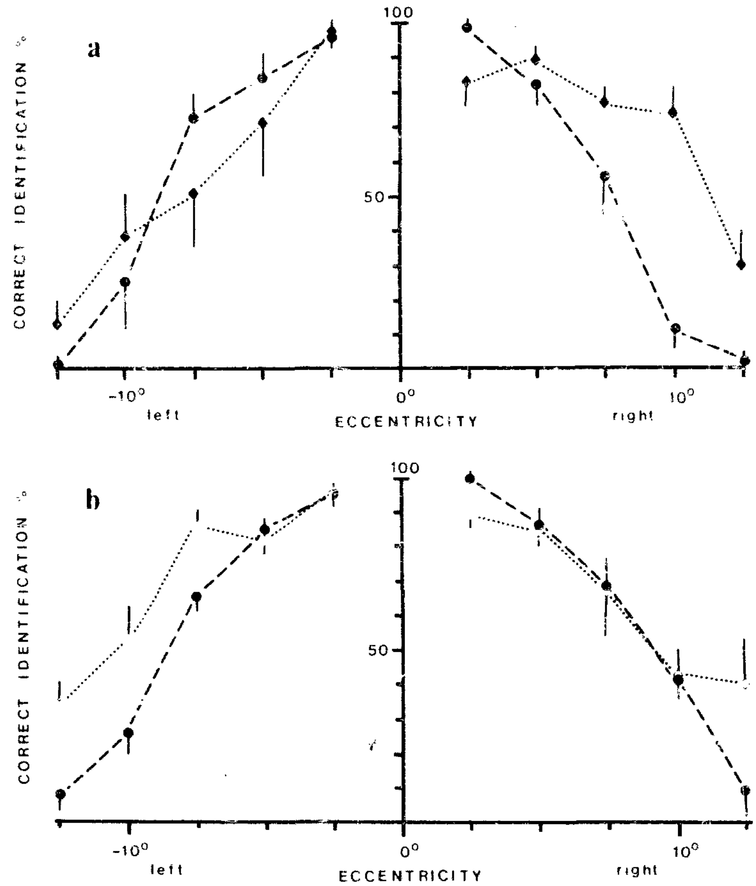

Fig. 4. Display of the form-resolving field (FRF) averaged separately for adult ordinary readers (dashed lines) and adult severe dyslexics (dotted lines). The measures are of % correct identifications of letters at different eccentricities in the periphery. Vertical bars show the standard deviations. 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; b: Hebrew-natives: 5 ordinary readers and 5 severe dyslexics.

the Aubert-Foerster law[1]. In contrast, in the right half of the field, severe dyslexics recognize letters best at 5° eccentricity and recognition falls off significantly towards the center (at 2.5°) and towards the periphery. At 2.5° eccentricity, where the two letters of the display are closest together in these tests, the recognition score of severe dyslexics is also 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.

It is important to note that what the FRF measures is not what is ordinarily meant by 'acuity'. We do not hold that there is a difference in visual acuity between ordinary readers and dyslexics. Instead, the difference lies in the perception of arrangements 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. However, single letter recognition in and near the center is much the same for ordinary readers and severe dyslexics.

In the left visual hemifield (the left side in Fig. 4a) 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.

The FRF measured with random left-right display

For technical reasons (the size of the screen) we have measured on the small screen 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 on the larger screen. 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 distance from the center. This was made possible by using the large 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 8 other dyslexics with random left-right display on the large screen. Their FRFs were similar to those of the dyslexics tested by the earlier method. We concluded that bias of letter expectation and fixation offset do not significantly affect our original observations.

Asymmetry reversal of the FRF

The FRF of severe English-native dyslexics is significantly asymmetric[8]: 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 compared the FRFs of right-handed and of left-handed ordinary readers separately (together with F. Fabbro (not yet published)) we found that the forms of the FRFs were almost identical.

All the subjects who participated in this test were English-native speakers. We suspected that the asymmetry in the FRF of dyslexics was related to the direction of reading[15]. 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 10 adult Hebrew-native speakers to participate in the testing. Five of them were ordinary readers and 5 were severe dyslexics. We measured their FRFs with the large screen in the same way we measured it for the English-native speakers except with Hebrew letters. (In this test we used the random presentation of letters to the left and right.) 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 Fig. 4b. 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 $-7.5°$ $F_{1,8} = 10.03$, $P < 0.02$; at $-10°$ $F_{1,8} = 4.83$, $P < 0.05$; at $-12.5°$ $F_{1,8} = 10.01$, $P < 0.02$). 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 ($F_{1,8} = 14.29$, $P < 0.01$) and it is higher (but not significantly) than that of ordinary readers at 12.5° ($F_{1,8} = 4.4$, $P < 0.2$).

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.

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 by ordinary readers. It remains to be shown 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 using the small screen. The differences lay in the nature of the stimuli and the duration of the stimulus exposures. In this test 4 letters were presented in each stimulus (instead of 2 as in the previous test). One letter was at the fixation point and a string of 3 letters was in the periphery. The strings were displayed at 4 different eccentricities to the right and there were 20 displays at each eccentricity. The distance between the letters in each string remained constant for all displays and was 40′ 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 (and their correct position in the string) was measured as a function of eccentricity.

The left side of Fig. 5 shows the average scores of correct letter recognition in the right half-field for 5 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 Fig. 5 the average score of 9 severe dyslexics is depicted. All the subjects who participated in this experiment were adult English-natives and were tested for the FRF in the previous experiment.

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 terminal letters are about the same for severe dyslexics and for ordinary readers, but the first letter is overmasked for dyslexics due presumably to influence of the letter at

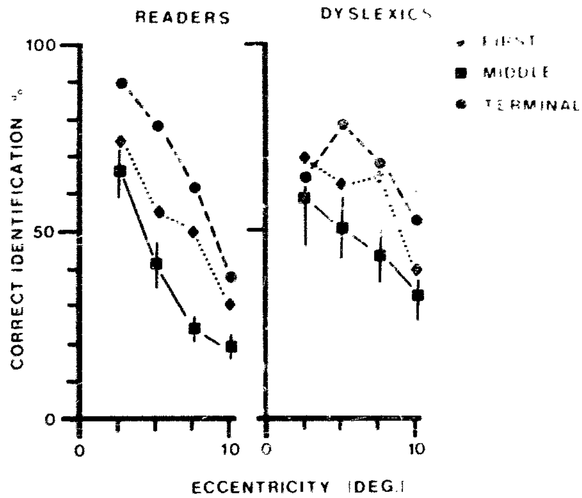

Fig. 5. Lateral masking in a string of letters measured as a function of eccentricity. Ordinary readers are compared with dyslexics for correct identification of each letter in 3-letter strings that are presented at various eccentricities. The plot of the % correct identification at each locus along the string (first, middle and terminal letters) 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 90% for severe dyslexics. At 2.5° it was 80% for severe dyslexics.

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.

Testing for the learning of 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 4 to show some generality in the approach.

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

At first we tested him for the FRF with the small screen in the way described. The results are plotted in Fig. 6 (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.

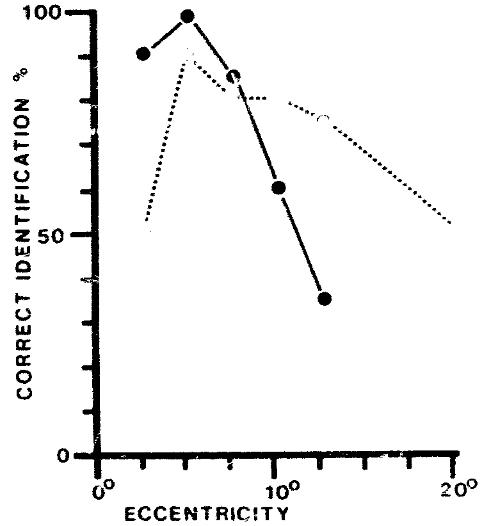

Fig. 6. Plots of the FRF of a severe dyslexic. One FRF was taken upon arrival (dotted line), the other plot was taken 4 months later after he practised as described in the text (solid line).

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 'Lateral masking between letters in a string' above). The results are shown in the left side of Fig. 7. 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 acted 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 Fig. 6). 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 was possible for this man to learn a new visual strategy that would permit him to read. Whatever distribution of lateral 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 strings of letters 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 (unpublished results).

We emphasize here that we 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 practice 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 practice comes from experiments performed by Held and Gottlieb[10], Held and Hein[11], and remarked by Helmholtz[12] on how a person shifts spatial localization after viewing the scene through a prism. The general idea was to provide visual perception with a new space of operation as defined by the new tasks.

Separate from the two-hour first part, 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. 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

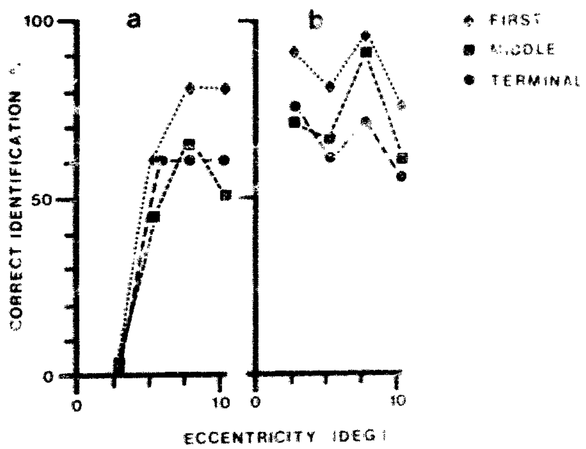

Fig. 7. Lateral masking in a string against string eccentricity (measured as in Fig. 5). On the left, the initial performance of the same severe dyslexic as in Fig. 6. On the right, the performance of the same subject to the same test 4 months later after the practice described in the text.

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 he 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 have been seen as distinct forms rather than texture, without interference from the ambience which was covered by the blank sheet.

He did the practice 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 4 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 4 months he showed the change in FRF given by the solid line in Fig. 6 and the change in lateral masking shown in the right side of Fig. 7. He was now able to make out letters in strings presented at 2.5° eccentricity. His performance at that eccentricity was not as good as that of an ordinary reader but was far better than in the initial test. Curiously, in reporting the letters at that eccentricity, he stuttered[7].

Encouraged by these results, we found 3 more severe dyslexics from the group of 10 who were willing to devote the time for 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 practice pattern as the one described above.

After 12–20 weeks with this combined practice during which time we did not see the subjects, we again measured the FRF curves for each of the 3. We also inquired about, but did not measure, their reading skills. Fig. 8 shows the averaged FRF for the 4 subjects (including the single case from above) before and after the practice term. For comparison, the curve for ordinary readers (from Fig. 4a) is also displayed.

We should remark that the 4 subjects were not chosen by us. They were the only candidates among the 10 original severe dyslexic subjects who could afford the time to practise daily. We did not instruct or guide the subjects more than by occasional telephone conversation after laying out the schedule of practice.

As seen in Fig. 8 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

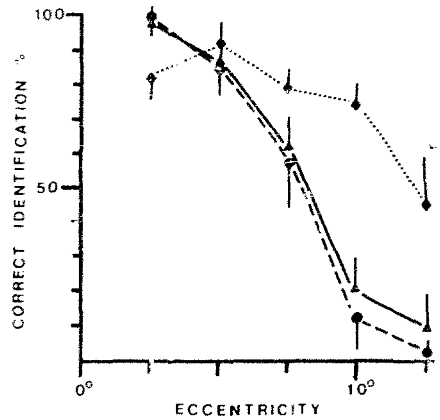

Fig. 8. The effect of learning and practising a new strategy. The dashed line FRF is of the right visual hemifield averaged for 10 ordinary readers (taken from Fig. 4a). The dotted line is for 4 severe dyslexics prior to the practice described in the text. The solid line is for the same 4 severe dyslexics after that practice. The bars measure standard deviation. The FRF of the left visual hemifield remained unchanged during this period.

do not vary significantly in FRF over time although we measured some over periods of 4 years and longer. Similarly, the FRFs of 3 of these 4 severe dyslexics were measured twice in intervals of 2–3 months prior to initiation of the regimen and they did not vary over this period.

The reading performance of all the 4 improved markedly. The reading score of one went from what will be comparable to 3rd grade before practise to 10th grade after practise. 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 5 min 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) but 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. There was a marked improvement in all 4 in comprehension, word recognition, speed of reading and ability to write.

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 that regression appears in the discussion.

'Unusual' cases

As a final note we want to describe two unusual cases, the first in some detail. A male commercial art student, 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 large screen measures of his FRF in these two phases are shown in Fig. 9. 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 Fig. 9 the differences in the plots are small although a slight extension of the FRF into the periphery is evident for the 'tired' phase.

Fig. 9 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 the 'tired' mode (wide FRF) to 'alert' mode (narrow FRF), he is still unable to do voluntarily. Since his ordinary work pre-empts the practice 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 mild strabismus when he was 7. He was also 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

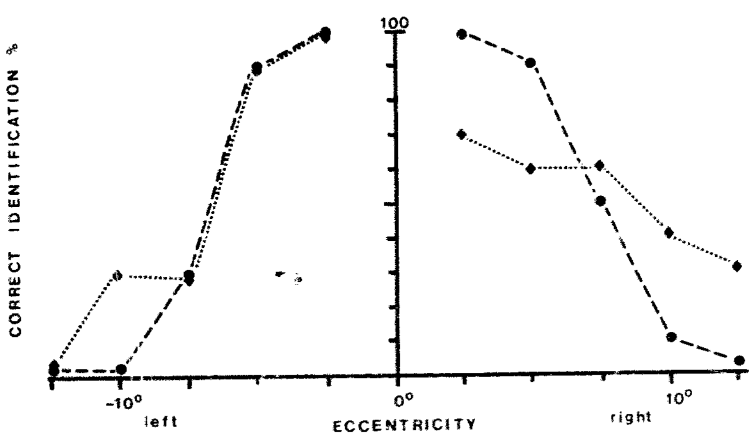

Fig. 9. Two strategies in one subject are measured within a few hours interval. The dashed line is the plot of the FRF which was taken when the subject was in the 'alert' phase. The other was taken 6 h later when he was in a 'tired' phase (dotted line). See text for further explanation.

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.

DISCUSSION

The process of lateral masking

Lateral masking is the reduction in recognizability of a form when it is flanked or surrounded by other visible things; the 'lateral' refers to the flanking, not to the position relative to the center of gaze. While it occurs anywhere in the visual field there are some differences between its effects along the vertical vs. horizontal axis of the field[6]. That will not concern us here.

The effect is in daily experience, and an example is given by Fig. 1. At reading distance the size of the letters in Fig. 1 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. To the right of the fixation x in Fig. 1, the N, which is at the same distance front the x, but imbedded in a word, cannot 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. The average of contrast and gross appearance seem much the same as under direct gaze, and the string clearly has parts. But somehow, the parts are confused, and except for the initial and terminal letters, the word, eccentrically viewed, cannot be made out. 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[18]. Some letters, or symbols, such as O, are more resistant to masking[6].

That the effect is not tied to letters is shown in Fig. 2. 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 but spatial relations are uncertain. Since the small circles are all at the same distance from the enveloping circle we might expect the impression of circularity in the group to be enhanced by the envelope. That it is not, suggests that the concept of 'distance between' as a metric in vision is not appropriate. The word in Fig. 1, and the circular disposition of small circles inside the large one in Fig. 2 have lost form; 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 and is thus considered of higher order[5]. On the other hand it cannot 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 of the figure and the parts of the parts mutually interfered with one another in perception – each part exerting its influence on all sides of it and the interaction giving an impression of a lack of a specific order. Small figures such as stars, triangles, etc. can be substituted for letters without much changing the effects.

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 express the confusion in what they see. In both instances the common language is not sufficient – it has no good words for varieties of confusion.

Lateral masking, as an interaction between perceived figures is as if each figure and segment of it had a masking field around it, falling off with distance. Is the strength of the masking field a fixed function of angular eccentricity front the center of gaze or can it be controlled by other factors?

In tachistoscopic presentation of eccentric strings of 3 letters at 8° away from fixation the middle letter is more profoundly masked than the end ones. 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 the eccentric string is presented, it is demasked in the string[6]. The effect is not cognitive, and occurs with a set of arbitrary figures, e.g. stars, triangles and the like[6]. The point is that lateral masking does not signify an irretrievable loss of information from a region in the visual field – it can be varied in the strength of its effect.

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 derived 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. That 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. In each element of that manifold the extensional properties such as sharpness, orientation and shape of a boundary are already encoded in and distributed among neighboring elements. Not necessarily encoded are the spatial relations between boundaries. To retrieve those spatial relations calls for a separate operation applied to the distributed representations of boundaries. When such a localizing or local distancing operation is not applied, only representation of texture is available. The boundaries are identifiable but not ordered. When the operation is applied, representations of forms and arrangements issue. Change of this kind of local distance ordering could also occur by functionally changing the surround size for receptive fields at that level. We propose that this higher order operation can be switched in or out regionally in the representation of the visual field, and that it intervenes, from the psychological view, between the sense-data-based perception and the cognitive processes.

Visually guided task performance, 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 acquired by practising those actions by which an intended next state of perception under the conditions of the task is achieved efficiently by correcting the error between it and the state predicted from 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 practice. If, knowing the region of the relevant, we can relegate all the rest of the field to background by a single general operation, our ability to perform increases. Rather than blank everything else away we simply lessen the cognitive load by draining it of specifics (i.e. reducing it to texture) 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 only a specific redistribution 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 does not matter to the task.

At this point we propose that lateral masking is an operation that takes place after perception which is entirely sense-driven and before cognition which is apperceptive and arbitrary. 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.

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 4 severe dyslexics by a regimen that did not challenge the lock. The 'conditional' 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 become problematic, as shown by the conditional dyslexic, and by 3 of the 4 trained dyslexics who acquired the lateral masking strategy appropriate to reading and became uncomfortably locked in it.

Measures of visual strategies and the results

From our observation on the malleable differences between dyslexics and ordinary readers, our basic thesis is that genetic or pathologic causes need not be determinative of their expression – a well-known principle in biology. Whatever the cause, and presumably there are at least as many causes as schools of thought on the subject, dyslexia can he regarded as a contingent expression, not a necessary one, and therefore modifiable once intelligible principles of the active system can be proposed. For that reason we have not addressed causes of dyslexia but only treat it as an expression.

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 a new practice as described earlier.

The FRF is well-correlated with the ability or the inability to read in the ordinary way. FRFs of ordinary readers are of one shape, and those of severe[8] and reading dyslexics are of another[7]. FRFs of ordinary readers are narrow, whether they are English- or Hebrew-native speakers, and reflect that lateral masking increases rapidly with eccentricity. 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, masking for aggregates of letters at and near the center, and showing 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 the individual letters are indistinct because of 'crowding' which we interpret as lateral masking in the central field. At the same time their form vision for aggregates is better further out in the direction of reading. But they perceive much of the text near the word they are about to read (they 'see all at once', as they say). 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. They cannot see words where they gaze, as do ordinary readers.

Previously Bouma and Legein[3] observed that ordinary reading children recognize a string of letters in and near the fovea better than dyslexic children, while single letter recognition was similar for both groups. Another observation made by Thorn[17] demonstrated crowding around the axis of gaze for all children 5–7 years old which disappeared for most children after they became 9 years old. Both observations support the differences in central masking between ordinary readers and severe dyslexics as we have reported.

It was only due to the normalization of the exposure duration procedure, done separately for each subject, as described earlier, that distinctions began to appear in the measurements near the center of gaze. They would not have showed the masking between central and eccentric letters characteristic of dyslexics unless we could display the operating range below saturation. With strings of letters, lateral masking displays similar properties when presented for steady viewing (in Fig. 1) or in a flash (as performed with a string of letters, see Results, 'Lateral masking between letters in a string'). Any isolated singly bounded letter in the periphery (from the letters we chose) except for I, is also made of parts, but 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 does not show except as conditions are reduced to threshold. That is, self-masking of a complexly shaped symbol is a limited form of lateral masking, but involves the same underlying process. The notion that only 'complex' letters and not single bars are demasked[6] is a support for the concept of self-masking.

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 in ordinary readers is so nicely correlated with the skill of reading we suggest that the active masking in the periphery is what makes usual reading possible and is learned. That these differences are not due to a different distribution of cones in the retina[9] or other 'hard-wired' differences is demonstrated by the conditional dyslexics and by the dyslexics who have learned a new strategy.

The asymmetry reversal of the FRF for Hebrew-and English-native dyslexics and its dependence on the convention (direction) of reading is a support for the notion that dyslexia, as an expression, is learned, and that the FRF measures the related distribution of lateral masking. We suggest that the visual strategy reflected in the FRF is learned by practice in order to accomplish the task of reading. What is learned is where to relegate the background to texture by lateral masking.

With the 4 adult severe dyslexics subjected to the training described in the text, the average FRF shifted as shown in Fig. 8, from that of the severe dyslexic to that of the ordinary reader. On the other hand, 9 young adult reading dyslexics who had been trained, moderately successfully, in a remedial college with conventional reading training, the FRF was that of the other adult dyslexics[7]. This does not mean that the reading improvement of our 4 was better than that of the 9, although our strong impression was that it occurred more rapidly. But, it does show that a new strategy is learned by using new kinds of challenges rather than by attempting to modify distribution of an existing strategy.

The aim in the self-training of the 4 was to see how well they could be brought to learn a new strategy and 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[7]. That the other 3 subsequently responded in the same way was initially heartening. But over the months after the posttraining 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.

The problem of price can be illustrated by the first case, which in a general way reflects what happened to the other two who decided that improved reading was not worth the change in other habits. 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 multimedia 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 that showed 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 experience. One way or another the same kind of discomfort with the new state afflicted the others quite separately. They had not met each other and so the phenomenon was not communicated. The exception to reversion was a college student who desperately wanted to keep up with class work.

In this group of 4 the shift in FRF to that of ordinary readers showed what we wanted, that visual strategy was task-determined and could be learned[8]. In a sense that is what is implied by the work of Held and Gottlieb[10], Held and Hein[11], Kohler[13] and others: the change of visual state in handling the visual information that guides new task performance depends on the proprioceptive information about the adequacy of action in performing the task. That is, the structure of space as induced from local spatial relations is not intrinsic to the modality of vision. It arises from other senses that provide the necessary information about a space containing tangible bodies, remoteness and nearness in that space, and movability. The teaching method we used was to provide a novel and detailed hand-eye coordination task, not involving reading but calling for use of central vision, and separately to provide for presentation of single words in the peripheral region where reading was possible for them. In short we wanted both practice in foveation and, independently, practice in word recognition, in the hope that the subjects would put the two together. Our results demonstrated that the reading strategy of the ordinary reader as measured by the FRF, could be learned by an adult dyslexic.

Finally we must reaffirm that in this study, 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 as described in a forthcoming paper[20]. The learned strategies are discrete – they do not shade into each other, and do not seem 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 practice 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 resembled so closely that used by ordinary readers: it was not some compromise or modification. That was unexpected.

CONCLUSIONS

1. Evidence shows the existence of at least two different task-determined visual strategies, characterized by different distributions of lateral masking under the same visual test, one in ordinary readers, the other in dyslexics.

2. Plots of the FRF measure the distributions of lateral masking along the horizontal axis of the visual field.

3. Lateral masking is a locally gradable precognitive process that corrupts the spatial ordering [illegible]nctly shaped forms into a less determinate ag[illegible]n of less qualifiable forms, i.e. a texture. It is a process that reduces information in what is irrelevant to a task and can be differently distributed depending on the task.

4. When severe dyslexics are taught to read by a regimen of practice that does not challenge their existing visual strategies, their acquired ability to read is accompanied by a shift of visual strategy to that of the ordinary reader. This suggests that visual strategies can be learned, and that the distribution of lateral masking found in the ordinary reader is what makes ordinary reading possible.

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REFERENCES

1 Aubert, H. and Foerster, Beitraege zur Kenntniss des indirecten Sehens, *Graefes Archiv Ophthalmol.*, 3 (1857) 1–47.

2 Bouma, H., Interaction effects in parafoveal letter recognition, *Nature*, 226 (1970) 177–178.

3 Bouma, H. and Legein, Ch.P., Foveal and parafoveal recognition of letters and words by dyslexics and by average readers, *Neuropsychologia*, 15 (1977) 69–80.

4 Di Lollo, V., Hanson, D. and McIntyre, J.S., Initial stages of visual information processing in dyslexia. *J. Exp. Psychol. Hum. Percept. Perform.*, 9 (1983) 923–935.

5 Flom, M.C., Heath, G.G. and Takahashi, E., Contour interaction and visual resolution: contralateral effects, *Science*, 142 (1963) 979–980.

6 Geiger, G. and Lettvin, J.Y., Enhancing the perception of form in peripheral vision, *Perception*, 15 (1986) 119–130.

7 Geiger, G. and Lettvin, J.Y., Peripheral vision in persons with dyslexia, *N. Engl. J. Med.*, 316 (1987) 1238–1243.

8 Geiger, G. and Lettvin, J.Y., Dyslexia and reading as examples of alternative visual strategies. In C. von Euler, I. Lundberg and G. Lennerstrand (Eds.), *Brain and Reading*, Macmillan, London, 1989, pp. 331–343.

9 Grosser, G.S. and Spafford, C.S., Perceptual evidence for an anomalous distribution of rods and cones in the retinas of dyslexics: a new hypothesis, *Percept. Mot. Skills*, 68 (1989) 683–698.

10 Held, R. and Gottlieb, N., Technique for studying adaptation of disarranged hand-eye coordination, *Percept. Mot. Skills*, 8 (1958) 83–86.

11 Held, R. and Hein, A.V., Adaptation of disarranged hand-eye coordination contingent upon re-afferent stimulation, *Percept. Mot. Skills*, 8 (1958) 87–90.

12 Helmholtz, H.V., *Handbuch der Physiologischen Optik, Vol. III*, L. Voss, Leipzig, 1867.

13 Kohler, I., Experiments with goggles, *Sci. Am.*, 206 (1962) 62–72.

14 Mackworth, N.H., Visual noise causes tunnel vision, *Psychon. Sci.*, 3 (1965) 67–68.

15 Orbach, J., Differential recognition of Hebrew and English words in right and left visual fields as a function of cerebral dominance and reading habits, *Neuropsychologia*, 5 (1967) 127–134.

16 Perry, A.R., Dember, W.N., Warm, J.S. and Sacks, J.G., Letter identification in normal and dyslexic readers: a verification, *Bull. Psychon. Soc.*, 27 (1989) 445–448.

17 Thorn, F., Letter crowding disrupts letter identification by young children, *Invest. Ophthalmol. Vis. Sci.*, 28 (1987) 216.

18 Townsend, J.T., Taylor, S.G. and Brown, D.R., Lateral masking for letters with unlimited viewing time, *Percep. Psychophys.*, 10 (1971) 375–378.

19 Wolford, G. and Chambers, L., Lateral masking as a function of spacing, *Percep. Psychophys.*, 33 (1983) 129–138.

20 Zegarra-Moran, O. and Geiger, G., Visual recognition in the peripheral field: letters vs. symbols and adults vs. children, *Perception*, in press.