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"Visual recognition in the peripheral field: letters versus symbols and adults versus children"

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Visual recognition in the peripheral field: letters versus symbols and adults versus children

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Abstract. The plot of the form-resolving field (FRF) was obtained by tachistoscopically presenting two figures in each stimulus, one in the center of gaze and the other in the peripheral field. The figures in the periphery were placed at various eccentricities in different presentations. The ensuing plot of average letter recognition as a function of eccentricity is the FRF. Only the horizontal components of the FRFs were used in the comparisons.

Three sets of figures were used as stimuli: regular-size letters, large-size letters, and symbols. Three groups of subjects were compared: adult ordinary readers, reading children, and pre-reading-age children. The last were tested with symbols only.

In letter recognition, the FRFs for young and adult ordinary readers are similar and fall off monotonically and symmetrically with eccentricity, hence conforming with the first Aubert-Foerster law (1857). However, the FRFs tested with symbols are narrower than those tested with letters of the same sizes and stroke widths, which is not in accordance with the first Aubert-Foerster law. In addition, the FRFs of symbols are different for each subject group. It is suggested that recognition in the peripheral field is not determined by visual acuity alone; rather, it is further confined or determined by the visual strategy employed to accomplish the task, and its associated distribution of lateral masking.

1 Introduction

Aubert and Foerster (1857) studied how visual performance changes with angular distance away from the visual axis of gaze. They first measured recognition of letters and numerals (figures) in the peripheral field as related to actual size, angular size, and the distances from which these figures were observed. Next, they measured visual acuity as a function of eccentricity by using detection of separation between two dots. In this way they distinguished form resolution from visual acuity. They tested form resolution tachistoscopically (using the discharge of a Reiss bottle, equivalent to a Leyden jar). The flash illuminated a vertically oriented sheet which had many different figures painted on it. There were several such sheets. On each sheet the figures were of fixed size and separated from each other by fixed distance. They viewed each sheet monocularly through a short black cylinder which was pointed at the center of the supporting board. The cylinder shielded the eye from the glare of the spark and gave a fixed wide angle of view. Aubert and Foerster varied the viewing distance by moving the cylinder normal to the board. The position of the figures was changed by rolling a sheet upward or downward on shafts which were attached to the upper and lower ends of the supporting board. There were some sheets in which the sizes of the figures as well as the spacing between them were different. After each flash Aubert and Foerster recorded the figures which were recognized, and then changed the position of the figure and the distance of observation. They repeated this procedure about 500 times with themselves as subjects. They used the terms 'figure-angle' (Zahlwinkel) for the angular diameter of the figures and 'space-angle' (Raumwinkel) for the angular range (area) within which the figures

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could be recognized. They came to the following conclusions concerning form recognition:

> "1. *The farther a figure is away from the axis of gaze, the larger it has to be, in order to be recognized clearly* ... .
> 2. While determining whether *the ratios of the sizes of the figures to the spaces in which they are recognized, are either increasing or decreasing*, a peculiar contradiction appears in the observations which we have to leave unsolved. In comparing the figure-angle and space-angle *of the figures on the same sheet* [the same actual figure size and the same spacing between figures (GG)], one observes that at almost every distance from the sheet it is the same ratio between the two as given in the tables. One finds accordingly not a progressive [nonlinear (GG)] but a *proportional* reduction of the figure-angle and space-angle. Only from the zone of the blind spot onwards does the reduction of the space-angle with relation to the figure-angle become *progressive* ... ."

This portion of their conclusions is usually refered to as the first Aubert-Foerster law. Their conclusions continue:

> "(2) ... On the other hand, when comparing, for the same distance of observation, the ratios of the figure-angle to their space-angle, *a strong progressive reduction* of the space-angle is seen... . For *the same figure-angle* (with different figure sizes observed from different distances), *smaller figures which are at shorter distances from the eye, would be recognized farther away from the axis of gaze than larger figures which are observed from larger distances*; or: for the same figure-angle, the space-angle of larger more distant figures, is smaller than that for smaller and nearer figures ... ."

This part of the conclusions is referred to in the literature as the second Aubert-Foerster law. They continue:

> "3. *The ability for recognition (Wahrnehmen) for forms does not decrease in a circular concentric fashion; instead, it decreases faster upwards and downwards and slower outwards and inwards* ... ." [translated by GG].

The second part of their study is concerned with the perception of the separation of two dots at different eccentricities, which was measured in non-tachistoscopic presentations (Aubert and Foerster 1857). We dwell on this wording by Aubert and Foerster because recently there has been some confusion in the literature with respect to their methods, observations, and conclusions.

A modern correlate of their form recognition test is the form-resolving field (FRF) test, which was suggested by Geiger and Lettvin (1987, 1989). In this test each stimulus is comprised of a pair of letters which are tachistoscopically projected on a screen by optical means. One letter lies in the center of gaze and the other in the peripheral field. Many such pairs are sequentially presented, in which the peripheral letters are at different eccentricities. Recognition of both letters is recorded. The plot of average peripheral letter recognition as a function of eccentricity is the FRF. In this test, as in the test by Aubert and Foerster, more than one figure is presented in each flash and the score of all the letters is recorded. However, in the FRF tests the size of the letters and the distance of observation remain constant. What is plotted in the FRF test is the probability of letter recognition against eccentricity. A steep fall-off of recognition with eccentricity of a 'just recognizable' letter is implied by the Aubert-Foerster law.

The study by Aubert and Foerster, their method, observations, and conclusions are admirable and valid to this day. However, it is reasonable to assume that the subjects in their study, namely Aubert and Foerster themselves, were ordinary readers, or, rather, excellent readers. As was demonstrated by Geiger and Lettvin (1987, 1989) the FRF of adult ordinary readers was in accordance with this law, but recognition of letters in the peripheral visual field was significantly different for adult dyslexics

(Geiger and Lettvin 1987) and adult severe dyslexics (Geiger and Lettvin 1989) and did not follow the Aubert–Foerster law. This observation was verified by Perry et al (1989) for dyslexics. An attempt to repeat these findings by using computer-driven stimuli on a CRT with only the peripheral letter in each stimulus did not reveal the significant difference between dyslexics and ordinary readers (Klein et al 1990). This cannot be attributed to presenting single letters as stimuli, as Perry et al (1989) have also observed the differences between ordinary readers and dyslexics in spite of using single peripheral letters as stimuli. The differences between the results which were observed with optical projection displays and a CRT display could be attributed to the narrowing of the letters with eccentricity owing to the curvature of the standard CRT tube, which in turn results in higher contrast farther in the periphery. Also, there is a difference in the sensitivities of the peripheral field and the center field to the diagonal lines which are jagged in the CRT (Geiger and Lettvin 1986), and there is a central–peripheral field difference in sensitivity to the flicker in a CRT (Geiger et al, unpublished results). The differences also reflect the second Aubert–Foerster law, as the screen of the CRT is much closer to the subject than the projection screen, although viewing from near distance is more similar to ordinary reading conditions. The conditions mentioned above make the CRT less suitable for investigations of central–peripheral field relations and for the evaluation of the differences between ordinary readers and dyslexics, as dyslexics respond differently from ordinary readers to these conditions.

In a later study it was observed that the deviation from the Aubert–Foerster law in adult dyslexics was only in the direction of reading (to the right for Latin-native and to the left for Hebrew-native dyslexics) while the other side conformed with that law (Geiger et al 1992).

The differences in the FRF between adult ordinary readers and adult dyslexics were attributed by Geiger and Lettvin to different learned task-determined visual strategies. Moreover, they have demonstrated that adult dyslexics could learn a new visual strategy by practice. The new strategy enabled the dyslexics to read with greater competence, and was also reflected in a change in the FRF toward resembling the FRF of adult ordinary readers (Geiger and Lettvin 1987, 1989) and in accordance with the Aubert–Foerster law. Accordingly, the differences between the visual strategies of ordinary readers and dyslexics were attributed to different distributions of lateral masking over the visual field (for reviews on lateral masking see Bouma 1970; Mackworth 1965; Townsend et al 1971; Wolford and Chambers 1983). Lateral masking in ordinary readers is least effective at and near the center of gaze, and increases with growing eccentricities. This implies best recognition of forms in the center. Dyslexics, on the other hand, laterally mask in and near the center of gaze, when presented with an aggregate of letters, whereas in the peripheral field, in the direction of reading, lateral masking is much reduced. This distribution of lateral masking implies a wider extent of letter recognition in the direction of reading and difficulty in recognition of aggregates in and near the center. When dyslexics learned a new visual strategy, the distribution of lateral masking changed to that of ordinary readers (Geiger and Lettvin 1987, 1989; Geiger et al 1992). The notion that lateral masking is learned was suggested earlier by a study on what was termed 'demasking' (Geiger and Lettvin 1986).

The studies we mentioned above were conducted with adult subjects only and with letters and numerals as the only stimuli. They suggested a particular distribution of letter recognition in the peripheral field (Aubert and Foerster 1857) for ordinary readers and a different one for dyslexics (Geiger and Lettvin 1987; Perry et al 1989). In this context we asked two questions regarding the FRF and its associated distribution of lateral masking: (i) Does the FRF change for different types of figures which are commonly viewed differently, and if so how does it change? (ii) How does the FRF change with age and the learning of new visual strategies during development? Alternatively, does the Aubert–Foerster law hold for figures other than letters or numerals and is it also applicable to younger subjects?

When designing the test for comparing the FRF at different ages, including pre-reading-age children, a difficulty arose: Pre-reading-age children are not familiar with letters, but reading children and adult ordinary readers are. For that reason we had to design a new set of stimuli which were familiar to all ages. These were a set of line drawings of figures from everyday life which are shown in figure 1. We named these figures 'symbols', as contrasted with letters.

The first experiment in this study is a comparison of the FRF of reading children with that of adult ordinary readers. The reading children have just learned to read and have mastered the skill to a level appropriate to their age. The second experiment is a comparison of the FRF for letters and symbols tested with adult ordinary readers. The third experiment is the same test as the second, conducted with reading children. The last experiment is a comparison of the FRF of pre-reading-age children with the FRF of reading children, tested with symbols as stimuli.

2 Methods

2.1 *Apparatus and stimuli*

Three slide projectors with electric shutters in front of their lenses, casting on a diffusing screen from behind, served as a home-made inexpensive wide-screen tachistoscope. The projectors were all aimed at the same image position and were equipped with flat-field lenses, which resulted in a uniform luminance of 360 cd m^{-2} across the whole screen.

One projector carried a central fixation point. Another projector carried the stimulus slides and the third carried an 'eraser' slide which was blank. The order of presentation on the screen and the duration of the stimuli were controlled by an adjustable electronic timer. Stimulus presentation durations were adjustable from 1.6 ms to 150 ms. The screen was 48 cm wide and 32 cm high, corresponding to 39 deg arc wide and 26 deg arc high, when observed from a distance of 69 cm.

Each stimulus slide had two elements on it, one in the center at the location of the fixation point and the second in the periphery. The stimuli were divided into five (or six) groups. In each group the elements in the periphery were at a fixed distance from the center, at 2.5 deg, 5 deg, 7.5 deg, 10 deg, or 12.5 deg (or 15 deg). Each group contained forty slides of which half were presented to the left of the fixation point and the other half to the right in a random order (ie there were twenty slides at each eccentricity). This procedure helped to maintain the fixation by the observer at the center and reduced the bias of expectation of appearance (Geiger and Lettvin 1989; Geiger et al 1992). The two elements on each stimulus slide were not alike, and were chosen from a fixed set of ten elements. Each element appeared equally frequently at each eccentricity (direction and distance from the fixation point).

There were three sets of stimuli: 'regular-size' letters, 'large-size' letters, and 'symbols'. The first two were all uppercase Helvetica-medium letters which were chosen from ten letters (I, S, C, O, V, M, N, E, T, H) which are in common use in the Italian language. The symbols were from a set of ten designs shown in figure 1. The height of the regular-size letters subtended 35 min arc, the height of the large-size letters and symbols was 86 min arc, and the width of their strokes were equal. The large-size letters and regular-size letters were accurately scaled in all respects. The contrast for all stimuli was 90%.

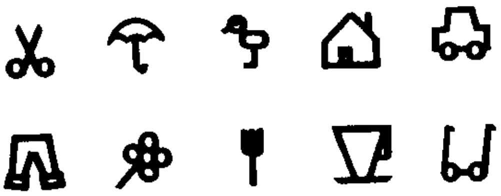

Figure 1. The ten figures used as 'symbol' stimuli.

2.2 *Subjects*
All the persons tested were volunteers, There were three groups of subjects: (i) adult ordinary readers who came from a university background and were 20-50 years old, (ii) reading children who came from the second and third grade of elementary school in Trieste and were 7-9 years old, and (iii) pre-reading-age children from the kindergarten level and the beginning of the first-grade of elementary school, who were 4.5-6 years old. All the readers had reading levels appropriate to their ages. None of the participants of these groups had any evident problems in reading or learning. All the participants had normal vision or trivially corrected vision.

2.3 *Procedure*
The subject sat in front of the screen and was asked to maintain gaze with both eyes on the fixation point. Shortly after a verbal warning the fixation point vanished and was replaced by a brief display of the stimulus which was then followed by a blank eraser slide for 2.5 s duration. [A structured eraser for ordinary readers had only prolonged the stimulus exposure durations without changing the shape of the plots (unpublished results). On the other hand, tests with dyslexics have shown that they have greater difficulties in telling apart a structured eraser from the stimulus (unpublished results; see also Di Lollo et al 1983). We were uncertain whether the pre-reading-age children would be affected by the structured eraser in a manner similar to the dyslexics so that the results would be biased.] Then the subject was asked to name verbally the displayed elements and tell which was at the center and which peripheral and to which side. Similar cycles of presentation were given for all stimulus slides. The average correct identification of elements at each eccentricity is the plot of the FRF. The average correct identification of the element at the fixation point stays high and is stated in each figure.

Prior to the test the appropriate stimulus exposure duration had to be determined. For this purpose different durations were tried until the best score of element identification at whatever eccentricity (which in this study was at 2.5 deg) reached near 100%. This was considered to be the appropriate stimulus duration for this subject. Once that duration was determined it was held constant for that subject through the tests. This procedure enabled measurement of relative form recognition at different eccentricities, uncontaminated by sensitivity to contrast or lightness. It also made it possible to compare 'slow' and 'fast' performers with the full range of sensitivity.

3 Results

3.1 *The FRFs of ordinary readers: adults versus children*
The average FRF of ten adult ordinary readers was compared with that of ten reading children from the second and third grade of elementary school. The stimuli in this test were regular-size letters. In these measurements and in the following experiments we measured only the horizontal axis of the FRF, mainly for practical reasons (prolonged measurement sessions were difficult with children). The vertical components which were measured with another group of adult ordinary readers were asymmetric with fall-off of recognition being nearer upwards and farther downwards (unpublished results; see also Aubert and Foerster 1857).

Two plots of the FRFs are shown in figure 2, one FRF for adult ordinary readers and the other for reading children. The plots are nearly identical in the right visual hemifield and are similar in the left one except for one eccentricity at −10 deg where they are significantly different.

The FRFs are symmetric to the left and right with respect to the direction of gaze, with best identification at and near the center and a rapid fall-off of correct identification farther in the periphery, which is in accordance with the Aubert-Foerster law.

Owing to the normalization procedure, the duration of the stimulus presentation was different for different subjects. Calculations of the mean stimulus duration for each group separately show significantly longer exposure durations (12.7 ms ± 4.5 ms) for reading children than those for adults (5.4 ms ± 2.7 ms). This may indicate that adults are faster and more experienced in recognizing letters, but the distributions of relative recognition were similar for reading children and adults.

Once the similarity was established we asked whether adults recognize symbols in the same manner as that in which they recognize letters.

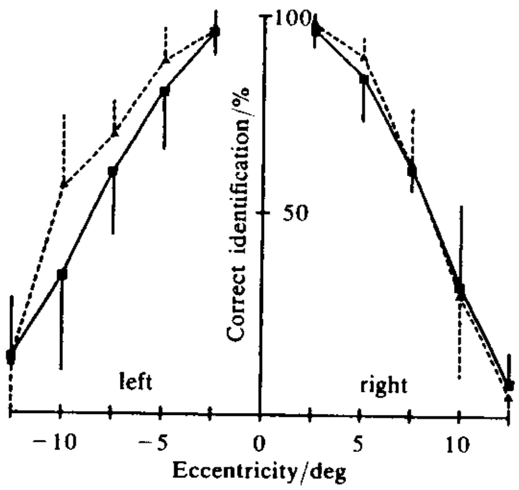

Figure 2. The average FRF of ten adult ordinary readers (triangles) compared with the average FRF of ten reading children (squares). Both FRFs were tested with regular-size letters. The FRFs of both groups are similar except at −10 deg eccentricity where recognition for adults was significantly higher than that of children ($F_{1,18} = 4.64$, $p < 0.05$). Identification of the letters at the fixation point was 97.1% ± 4.5% for adults at all eccentricities of the peripheral letter, and 98.2% ± 4.0% for the children. The fixation point is in the direction of 0 deg. The vertical bars denote the standard deviations.

3.2 *Three different stimulus types tested on adults*

For practical reasons the size of the symbols could not be reduced to the size of the regular-size letters. Therefore we made the symbols larger and made an additional set of letters in the same size: the large-size letters. We tested six adults (from the group in the first test) with the three different stimuli: regular-size letters, symbols, and large-size letters.

First they were tested with regular-size letters. The stimulus duration for each subject was determined with regular-size letters and was used throughout the three tests. The second test was with symbols and the last test was with large-size letters. Before testing with the symbols, the subjects were given time to make themselves familiar with the symbols and establish an agreed naming. The testing was made on consecutive days, one test in each day.

Figure 3 shows separately the average FRFs obtained for each stimulus type. The narrow plot (marked with diamond shapes) is the correct identification of the peripheral regular-size letters at different eccentricities. This plot is similar to the one in the previous experiment. The widest plot (marked with squares) is the average FRF of the same group of subjects as were tested with the large-size letters. On the right, recognition is 100% until 7.5 deg and then falls off rapidly in parallel with the first plot. The angular distance at which the fall-off begins for the large-size letters is three times the distance for the regular-size letters. Similarly, the angular size of the letters was in about that ratio (2.5), as prescribed by the Aubert - Foerster law.

The intermediate third plot (marked with triangles) is the FRF tested with symbols. The fall-off of recognition on the right side begins at 2.5 deg at a certain rate until 7.5 deg and only then the fall-off rate becomes parallel to the other plots. Altogether the plot of the FRF as tested with symbols is significantly different from the FRF tested with the large-size letters although both sets of stimuli were of the same angular (and actual) size. This is a clear deviation from the Aubert - Foerster law, ie letters and symbols of the same angular (and actual) size were not recognized to within the same angular distances from the direction of gaze. This cannot be attributed to visual acuity as the elements were of the same size and had strokes of the same thickness. It also cannot be attributed to difficulty in recognizing the symbols per se, as they have been recognized clearly at and near the center. We shall discuss the differences later, but first let us see how reading children fare with the same test.

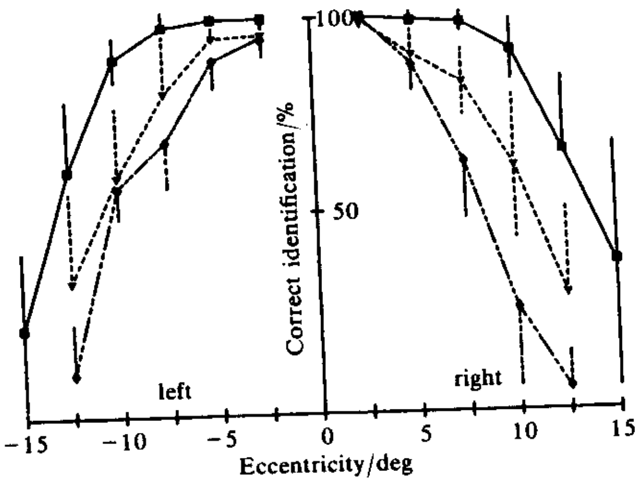

Figure 3. The average FRFs of six adult ordinary readers tested with three different stimulus types: regular-size letters (diamond shapes), symbols (triangles), and large-size letters (squares). The FRF tested with large-size letters is different from that of symbols of the same size. The difference is significant at the following eccentricities: −10 deg ($F_{1,10} = 13.1$, $p < 0.05$); −7.5 deg ($F_{1,10} = 6.3$, $p < 0.05$); −5 deg ($F_{1,10} = 15.0$, $p < 0.05$); 5 deg ($F_{1,10} = 9.3$, $p < 0.05$); 7.5 deg ($F_{1,10} = 15.9$, $p < 0.05$); 10 deg ($F_{1,10} = 11.5$, $p < 0.05$); 12.5 deg ($F_{1,10} = 7.7$, $p < 0.05$). On the right side the FRF of symbols is also significantly different from the FRF tested with regular-size letters at the following eccentricities: 7.5 deg ($F_{1,10} = 8.3$, $p < 0.05$); 10 deg ($F_{1,10} = 9.2$, $p < 0.05$); 12.5 deg ($F_{1,10} = 5.0$, $p < 0.05$). Correct identifications at the fixation point were 96.9% ± 5.2%, 99.3% ± 2.0%, and 100% for regular-size letters, symbols, and large-size letters respectively. The vertical bars denote the standard deviations.

3.3 *Three different stimulus types tested on reading children*

Five reading children (not all of them from the previous group), 7 - 9 years old from the second and third grades of elementary school, were tested with the three stimulus sets which were used in the previous experiment. The tests were performed in the same order. The first test was with regular-size letters for which the stimulus exposure duration was determined before the start of the test. The second test was with symbols and the last with large-size letters.

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The plots in figure 4 show the average FRFs for each stimulus type separately. The FRF which was tested with regular-size letters is almost identical to that of reading children in the first experiment and is similar to that of adults. The FRF which was tested with the large-size letters is wider than the one tested with regular-size letters and resembles that of adults but is slightly wider than the latter.

The FRF measured with symbols is similar to that measured with regular-size letters on the right side although the symbols were 2.5 times larger than the regular-size letters. In the left visual field, the FRF which was tested with symbols is wider than in the right, so that the overall shape of the FRF is asymmetric with respect to the center. As with adults, the recognition of the symbols which were of the same size as the large-size letters did not extend to the same eccentricities as the recognition of letters did. The difference in the extent of recognition for the same figure size, and the asymmetric shape of recognition do not follow the Aubert – Foerster law.

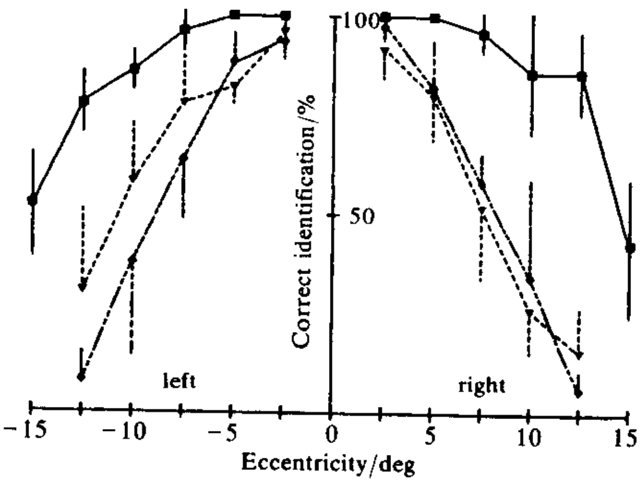

Figure 4. The average FRFs of five reading children tested with the three stimuli: regular-size letters (diamond shapes), symbols (triangles), and large-size letters (squares). The FRF tested with symbols is significantly narrower than that tested with large-size letters (−12.5 deg, $F_{1,8} = 18.6$, $p < 0.05$; −10 deg, $F_{1,8} = 13.1$, $p < 0.05$; −7.5 deg, $F_{1,8} = 8.1$, $p < 0.05$; −5 deg, $F_{1,8} = 81.0$, $p < 0.05$; 5 deg, $F_{1,8} = 13.3$, $p < 0.05$; 7.5 deg, $F_{1,8} = 21.5$, $p < 0.05$; 10 deg, $F_{1,8} = 43.9$, $p < 0.05$; 12.5 deg, $F_{1,8} = 94.2$, $p < 0.05$) and is similar to the FRF tested with regular-size letters. The correct identifications at the fixation point were: 97.8% ± 4.0%, 93.6% ± 8.7%, and 99.4% ± 2.4% for regular-size letters, symbols, and large-size letters respectively.

3.4 *Comparing pre-reading-age children and reading children*

We compare here the FRF of ten pre-reading-age children with the FRF of the five reading children from the previous experiment, measured with symbols. The ten pre-reading-age children were 4.5–6 years old, could write their names but were unable to read except for three subjects who could read a few easy words. (We took more pre-reading-age children for the test, to be sure that if a 'might be dyslexic' were among them, his or her results would have little effect on the average.) Before the test began the stimulus exposure duration was determined for each subject with symbols, by the same procedure as it was determined for the older subjects with regular-size letters. The stimulus durations for the reading children were the same as in the previous experiment. As it turned out, the same durations were also the appropriate durations for testing with symbols.

The average FRFs of pre-reading-age children and reading children, tested with symbols, are shown in separate plots for each group of subjects in figure 5. The FRF of pre-reading-age children is symmetric to the left and right and that of reading

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children is asymmetric. The FRFs of reading children and pre-reading-age children are similar on the right side but, that of pre-reading-age children is narrower than that of reading children on the left side. In addition, the average stimulus duration of pre-reading-age children (42.5 ± 31.7 ms) was significantly longer than that of reading children (12.7 ± 4.5 ms).

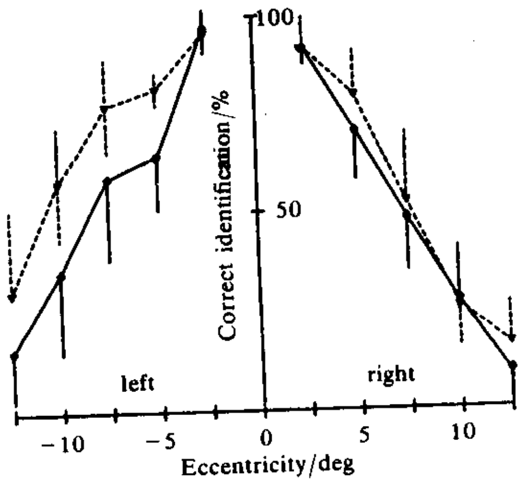

Figure 5. A comparison of the average FRF of ten pre-reading-age children with the average FRF of five reading children (from experiment 3.3). Both groups were tested with symbols. The FRF of the reading children (triangles) is wider on the left side than that of the pre-reading-age children but it is not significantly different at any eccentricity. Correct identification at the fixation point for pre-reading-age children was 97.1% ± 4.5%.

4 Discussion

The observation by Aubert and Foerster (1857) that "the farther away a figure is from the axis of gaze, the larger it has to be in order to be recognized clearly" holds in general and in all the instances we have demonstrated here. It is the quantitative aspects of their first law which we shall discuss here in detail.

The differences in form recognition across the visual field, for a variety of figures and tasks, imply that the limiting factors of recognition in the peripheral field are not solely dependent on visual acuity, as has also been suggested previously (Levi et al 1985; Smith and Cass 1989; Westheimer 1982). We would like to discuss how factors other than visual acuity determine form recognition in the peripheral field.

We started with the testing of the FRF of adult ordinary readers and compared it with that of reading children. The FRFs, as tested in this study, were obtained by briefly presenting two forms in each stimulus, one form at the center of gaze and the other in the periphery [in essence resembling the measurements of Aubert and Foerster (1857) on form recognition]. Testing FRF in this way resulted in a measure of the angular extent or area of form recognition and the probabilities of recognition in this area, rather than measuring only the distance away from the direction of gaze at which a single form was recognized. In addition, as a pair of forms were displayed in each stimulus, the perceptual interactions between the forms were part of the results. Therefore, the two-dimensional plot of the FRF depicts the probabilities of forms being recognized within certain angular extents and their corresponding areas, and at the same time it includes the perceptual center–peripheral field interactions between the forms. That is, the FRF is a complex description of areas with recognition probabilities assigned to each area. As mentioned before, we are concerned here only with the horizontal component of this measure.

By adjusting the stimulus duration individually to result in 100% correct identification at the eccentricity of the peripheral form at which recognition was best, we made the measurement more sensitive and we were able to normalize the recognition relative to the eccentricity of best recognition across subjects. With this procedure the FRF measures only relative form recognition across the visual field. That is, it maps the areas of relative form saliencies for each subject and for the average between subjects.

Measured with regular-size letters the FRF of adult ordinary readers is similar in shape to that of reading children (figure 2), although the reading performances of the two groups were different. The FRFs of both subject groups are narrow, symmetric to left and right, and letter recognition falls off rapidly with eccentricity from the eccentricity at which recognition is 100%. However, the mean stimulus exposure durations were different for each group. Children and adults differ mainly in the speed of reading and in the ability to decipher long and unknown words. These differences could be accounted for in terms of experience. The adults, who had longer periods of practice in reading, are more experienced in reading than the children, who have only recently learned to read. This is analogous to the improvement in vernier acuity with practice described by McKee and Westheimer (1978), and to improvement with practice in other perceptual tasks (Fiorentini and Berardi 1980; Gibson 1969; Ramachandran and Braddick 1973). The lesser expertise of children was—we suggest—reflected in longer stimulus exposure durations which were needed for them to recognize the letters (see also Fisher and Lefton 1976). Yet, the FRFs were similar in shape for both groups, ie the relative saliency of letters across the visual field is similar for both groups.

Consequently, the FRFs measured with large-size letters were also similar for both groups (figure 6) (although, the FRF of the children is slightly but not significantly wider than that of adults). As expected from the Aubert-Foerster law the FRFs which were measured with large-size letters are wider than those which were measured with regular-size letters.

An earlier study of the perceptual span with the subjects reading with sliding electronic windows of different sizes and measurements being made of the corresponding reading speeds have shown an increase of span size with age and reading skills, as well as a left-right asymmetry of the span (Rayner 1986). This method is different from tachistoscopic presentations and therefore addresses different aspects

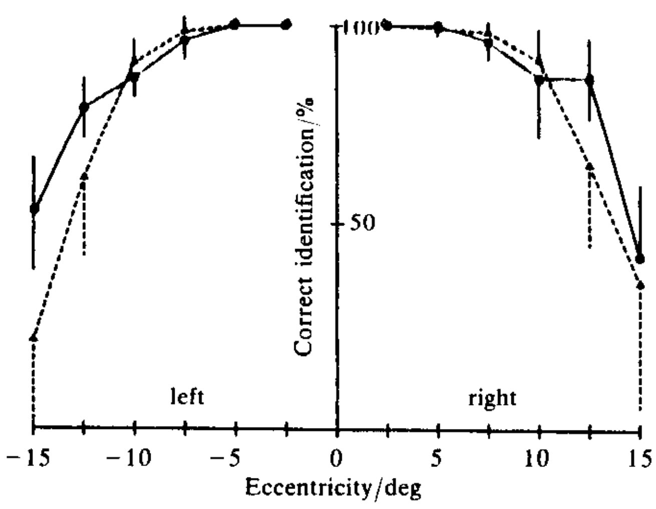

Figure 6. The average FRFs tested with large-size letters: a comparison of the FRF of five reading children from experiment 3.3 (circles) with the average FRF of six adults (triangles) from experiment 3.2. The FRF of reading children is significantly wider than that of the adults only on the far left side (-15 deg, $F_{1,10} = 7.3$, $p < 0.05$).

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of the processing during reading [as was also suggested by Rayner (1986)]. Other measurements, by Bouma and Legein (1977) who used tachistocopic presentations, have shown a left-right symmetry in recognition of single letters in the parafoveal field but an asymmetry in recognition of words and strings of letters. In these experiments no figure was presented in the center together with the peripheral stimuli. We suggest that the absence of the center figure and additional features relating to word recognition are the cause of the asymmetry in word recognition, as had also been suggested by Orbach (1967).

A marked difference is evident when the FRFs measured with letters are compared with those measured with symbols on the same subjects. Letters of a fixed size were recognized farther in the periphery than were symbols of the same size and same stroke width for all the subjects tested (figures 3 and 4). If the Aubert-Foerster law had applied to forms in general, the results for letters and symbols should have been fitted by the same FRF.

Adult ordinary readers have a wide FRF for large-size letters and a significantly narrower one for symbols of the same size; both have left-right symmetry (figure 3). Similarly, reading children have an average FRF at least as wide as that of adults for large-size letters, but a narrow FRF for symbols of the same size, and this FRF for symbols is significantly narrower than that of adults. In addition it has a left-right asymmetry. Why then are letters recognized farther in the periphery than symbols of the same size and stroke width? And why are the FRFs measured with symbols different for reading children and adults while the FRFs of letters are similar for both groups?

One obvious difference between the symbols and letters is that most symbols which were used here are comprised of a larger number of parts than are letters. We suggest therefore that the larger number of parts comprising each symbol may increase the internal lateral masking of a form on itself by mutual lateral masking of the parts (Geiger et al 1992). The internal lateral masking between the parts is apparently dependent on the number of the parts and the similarity between the parts from which the form is comprised (unpublished results). The increase of internal lateral masking will narrow the FRF as lateral masking augments with eccentricity (Bouma 1970).

However, the analysis of recognition of individual letters has shown that at given eccentricities recognition of some letters is more probable than that of other letters (see also Meinecke 1989), this being not strictly dependent on the number of their internal parts: some letters with a large number of parts were recognized more easily than letters with a smaller number of parts at a given eccentricity. Similar observations were made with the individual symbols. Therefore the additional internal lateral masking caused by a larger number of parts may narrow the average FRF measured with symbols. But it can not explain why the FRF measured with symbols in reading children is narrower than that of adults and why it is asymmetric.

This asymmetry of the FRF in reading children and the asymmetry found previously with adult dyslexics (measured with letters) which reverted, in some dyslexics, after practice (Geiger and Lettvin 1989; Geiger et al 1992) suggests that the FRF tested with symbols is not narrower because of undersampling, blur (Smith and Cass 1989), or magnification factors (Cowey and Rolls 1974; Daniel and Whitteridge 1961; Levi et al 1985) but because of perceptual considerations.

In contrast, the FRF of pre-reading-age children measured with symbols is narrower than that of reading children, but it is symmetric (figure 5).

The FRF measured with symbols changes with age from being symmetric and narrow for pre-reading-age children to being asymmetric and wider for reading children. The FRF becomes again symmetric and even wider for adults. An even wider and symmetric FRF was found with letters (of the same size as the symbols) for all ordinary readers: children and adults. All these observations indicate complex perceptual processing. We suggest that the differences between the FRFs of letters and symbols could be explained by the different visual strategies employed for the accomplishment of the various tasks together with the internal lateral masking due to the overall disparity in the number of internal parts. We shall discuss the notion of visual strategies next.

We accept the commonsensical notion that, for the accomplishment of a visually guided task, certain parts of the visual scene should be more salient than others. That is, the accomplishment of a task calls for a particular distribution of saliences across the visual field, hence for the accomplishment of different tasks there will be different saliency distributions. Accordingly, the FRF is the measure of what is most relevant for the task, as it is a measure of the distribution of form saliency.

Previously the task of reading on one hand, and dyslexia (a great difficulty in reading) on the other were correlated with two distinctly different FRFs: a narrow and symmetric FRF for ordinary readers and an asymmetric and wide (in the direction of reading) FRF with masking near center right for dyslexics (Geiger and Lettvin 1987, 1989; Geiger et al 1992; Perry et al 1989). The causal relation between the shape of the FRF and the task of reading was demonstrated by dyslexics who had initially a wide and asymmetric FRF, and after learning by practice a new visual strategy, had FRF which resembled that of ordinary readers. This change was accompanied by marked improvement in their reading skills (Geiger and Lettvin 1987, 1989; Geiger et al 1992). In other tests, the FRF (measured with letters) of English-native 'speed' readers have been found to be different from that of ordinary readers (Geiger and Lettvin 1991). These examples demonstrate the sensitivity of the shape of the FRF to the different visual strategies employed for the accomplishment of a task.

In the present study, the FRFs which were measured with letters on adult and reading children are similar to those of ordinary readers in the studies mentioned above. We therefore consider the particular symmetric shape of the FRF to be correlated with the visual strategy of ordinary reading. The asymmetric perceptual span which has been found for readers (eg Orbach 1967; Rayner 1986) was, as mentioned before, measured differently. It involved longer inspection durations and larger stimuli, therefore additional processing (for reading) was involved on top of the processing of letter recognition in the FRF measurement.

Letters and what we here call symbols (which are line drawings of objects) are commonly viewed in different ways. Letters are usually viewed in strings and are perceived in the context of words, or as parts of a whole word. This extends perception to the left and right of the center of gaze considerably. The symbols, on the other hand, are usually viewed in isolation and perceived as isolated or distinct forms.They might have a contextual relation to the environment but are still commonly viewed as single forms. These forms do not usually extend as far from the center of gaze as do words for equivalent angular sizes of the forms.

Practise for the accomplishment of a task results in improved performance and, as mentioned before, improved perception. However, Nazir and O'Reagan (1990) claimed that the visual system is not generally translation-invariant with respect to pattern recognition, ie novel and previously unseen patterns which are learned to be recognized in only one part of the visual field will not necessarily be recognized in other parts when they are first introduced. Hence practice, and the particular way a form or an object is usually viewed to accomplish a task, will establish visual areas at which this form will be recognized better. For other forms another way of viewing and practise (strategy) will establish a different area at which these forms will be most salient.

Considering the measurements in this study, young and adult ordinary readers have similar FRFs for letters, which indicates that both groups have learned a similar visual strategy for reading, irrespective of how experienced they were in the performance of the task. Once the visual strategy was learned and practised, the FRF associated with that visual strategy remained constant, independent of the level of expertise. [During testing we found that the FRF of a subject, measured with letters, remained constant over time and did not change for the same stimuli over periods of five years and longer unless the subject had learned a new strategy for reading (unpublished results)]. The FRFs measured with symbols are narrower than those measured with letters of the same size for all readers. We suggest that this difference is due to the different visual strategies used to view letters (in words) and symbols and the different practice used for each strategy. In addition, we regard the differences of the FRFs measured with symbols between adults, reading children, and pre-reading-age children to be due to the still-developing strategy for viewing single objects (or their symbolic representation in line drawings): a symmetric FRF, with narrow central scrutiny for pre-reading-age children, a somewhat wider and asymmetric FRF allowing detailed scrutiny with regard of some contextual aspects for reading children, and a wider one for adults. The differences in the way scenes are viewed by children and adults have been previously demonstrated by Mackworth and Bruner (1970).

We suggest that a visual strategy is composed of the distribution of lateral masking caused by the forms and their parts, together with the way the viewing of the form is practised.

5 Conclusions

Letters are perceived farther in the periphery than symbols of the same size and stroke width for all reading subjects. Hence the Aubert-Foerster first law was confirmed for ordinary readers tested with letters. It does not apply to other kinds of figures.

The limiting factor for how far figures will be recognized in the periphery is not visual acuity alone. It is the specific task-determined visual strategy employed which shapes the detailed map of recognition. A visual strategy is composed of the way viewing the forms is done for the accomplishment of the task and its associated distribution of lateral masking.

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