

Deficit of Visual Contour Integration in Dyslexia

Anita J. Simmers and Peter J. Bex

PURPOSE. The visual processing of text occurs spontaneously in most readers. Dyslexic persons, however, often report both somatic symptoms and perceptual distortions when trying to read. It is possible that the perceptual distortions experienced by those with dyslexia reflect a disturbance in the basic mechanisms supporting perceptual organization at the early stages of visual processing. Integration of information over extended areas of visual space can be measured psychophysically in a task that requires the detection of a path defined by aligned, spatially narrow-band elements on a dense field of otherwise similar elements that are randomly oriented and positioned. In the present study a contour integration task was used to investigate such perceptual organization in dyslexia.

METHODS. The detection of contours or paths composed of Gabor micropatterns was performed within a field of randomly oriented distracter elements in a 2-alternate forced choice (AFC) task. The stimuli were manipulated by randomly varying both the density of the background noise elements and the number of elements that defined a path of constant length.

RESULTS. In all observers, sensitivity to the paths increased with the number of target elements comprising the path, and subjects in both groups exhibited similar trends in relative density of the stimuli. However, in all conditions, dyslexic observers were two to three times less sensitive to path stimuli than the control group.

CONCLUSIONS. In the present study the authors have described a visual deficit in a global integration task in dyslexia. The pattern of deficits reported suggest that abnormal cooperative associations may be present in dyslexia that are indicative of poor perceptual integration. (*Invest Ophthalmol Vis Sci*. 2001; 42:2737-2742)

The specific reading difficulty of dyslexia affects 3% to 10% of the population.^{1,2} There are many theories concerning the origin of dyslexia, and it is likely that the condition is itself heterogeneous. Although most of the literature supports an underlying deficit in phonologic processing,³⁻⁴ it is now widely accepted that low-level visual processing abnormalities are also present,⁵⁻⁶ showing a selective loss in sensitivity at low spatial and high temporal frequencies in anatomic,⁷ psychophysical,^{5,8} electrophysiological,⁷ and brain-imaging studies.⁹

Dyslexic persons often report both somatic symptoms (asthenopia, headaches) and perceptual distortions (small letters and words appear distorted, move, and are blurred) when trying to read.^{6,10} Recent evidence suggests that the global

characteristics of text can produce such symptoms and subsequent difficulties in reading.^{11,12} Reading can be described as a hierarchical object process, in that letters are grouped into words and words into lines. The interference of the global percept of a page may cause disruption to the more salient local analysis at a word-line level in dyslexia.

It has been well established through physiological¹³ and behavioral¹⁴ studies that the receptive fields of early visual detection mechanisms are small and highly selective for a limited range of stimulus attributes, such as spatial frequency and orientation. This means that information about the fine spatial structure of letters and words and thereafter the global organization of text may be based on the combined integrative responses of a number of independent, local inputs across the visual field. It is possible that the perceptual distortions experienced by dyslexic persons reflect a disturbance in the basic mechanisms supporting such perceptual organization at the early stages of visual processing.

Increasing evidence in cortical neurobiology further suggests that neurons with disparate receptive fields in primate primary visual cortex (V1) are linked by long-range connections, depending on the orientation preferences of cells,¹⁵⁻¹⁹ that may serve to integrate distributed neuronal activity. The efficiency of such visual connections that integrate local feature codes into global object properties across visual space can be measured psychophysically in a task that requires the detection of a path defined by narrow-band elements aligned spatially on a dense field of otherwise similar elements that are randomly oriented and positioned.²⁰ The process of this integration has been extensively explored in recent years through psychophysical studies^{15,16,20,21} that have revealed that the detection of such stimuli is supported by well-defined interconnections among neighboring detectors, along the orientation axes of nonoverlapping filters (Fig. 1).

In general, sensitivity to contours increases with the length and straightness of the path,²⁰⁻²³ although closure of highly curved paths can increase sensitivity through the circular structure of such stimuli.²⁴ Sensitivity also increases with exposure duration²⁵ and with the similarity in the phase²⁶⁻²⁸ or spatial frequency of the elements defining the path.^{16,26} Contours can also be integrated within and across depth with similar factors determining sensitivity.^{29,30} Recent studies have also demonstrated that such perceptual organization is not fully developed in young children.²¹ This late maturation process has consequently been shown to be susceptible to the effects of abnormal visual development in the form of amblyopia.^{31,32}

In the present investigation, to assess perceptual organization in dyslexia, we compared the ability to integrate spatial information across the visual field in the form of a contour or path detection paradigm.

MATERIALS AND METHODS

Subjects

Ten subjects (mean \pm SD age, 22.3 ± 5.5 years) were recruited for the study who reported a prior diagnosis of dyslexia by either a psychologist or neurologist. These subjects had a reading age (variables considered were speed and accuracy) more than one SD behind that

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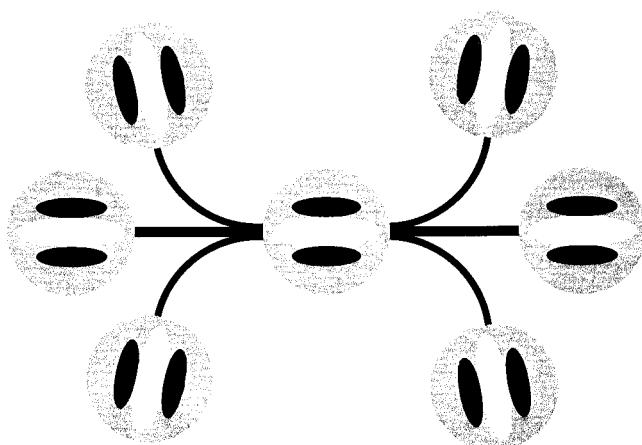


FIGURE 1. Schematic illustrations of the association field model. The connecting lines show facilitatory connections among neighboring receptive fields, narrowly selective for orientation and spatial frequency, that support contour integration. Adapted, with permission from Elsevier Science, from Field DJ, Hayes A, Hess RF. Contour integration by the human visual system: evidence for a local "association field." *Vision Res.* 1993;33:173-193.

expected from their performance intelligence quotient (IQ). No subjects reported an attention disorder.

A carefully age- and sex-matched control group (mean age, 24.8 ± 8.5 years) of volunteers were selected who had no reported history of reading difficulty, visual stress, or any difficulties with near vision. Both groups had normal visual acuity and binocular vision and were practiced in contour detection tasks before formal data collection.

All experimental procedures followed the tenets of the Declaration of Helsinki, and informed consent was obtained after the nature and possible consequences of the experiment had been explained.

Apparatus

Stimuli were generated on computer (Macintosh G4; Apple Computer, Cupertino, CA) by software adapted from the VideoToolbox routines³³ (provided in the public domain by New York University and available at <http://www.vision.nyu.edu>) and were displayed on a monitor (PS400, Sony, Tokyo, Japan) in gray scale at a frame rate of 75 Hz and a mean luminance of 50 candelas (cd/m^2) with a contrast of 95%. The contrast of each image was ramped on and off with a raised-cosine temporal envelope lasting 160 msec. The luminance of the display was linearized with pseudo 12-bit resolution³⁴ in monochrome and calibrated with a photometer (Minolta, Osaka, Japan). Images were presented in gray scale by amplifying and sending the same 12-bit monochrome signal to all red-green-blue (RGB) guns of the display. The display measured 34 cm horizontally (1024 pixels) and 26 cm vertically (768 pixels) and was placed 115 cm from the observer in a dark room.

Stimuli and Procedure

Stimuli were composed of multiple Gabor elements pseudorandomly positioned in a $6.6^\circ \times 6.6^\circ$ region. The display was divided into either an 8×8 (64 Gabor elements), 10×10 (100 Gabor elements), or 14×14 grids (196 Gabor elements) of equal-sized cells (Fig. 2). Each cell

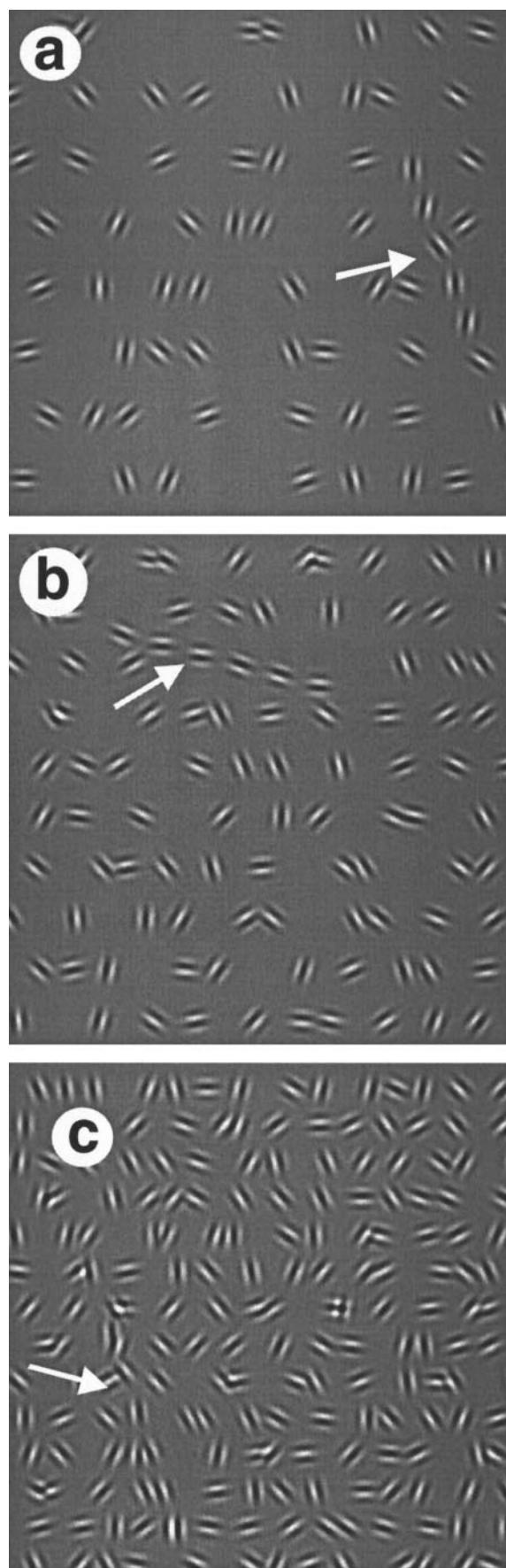


FIGURE 2. Path detection stimuli. A white arrow helps the reader locate the path, but was not presented in experimental trials. The subject's task was to detect the path within an element density containing (a) 64, (b) 100, or (c) 196 Gabor elements. An effective change occurred in signal-to-noise ratio with changing grid density.

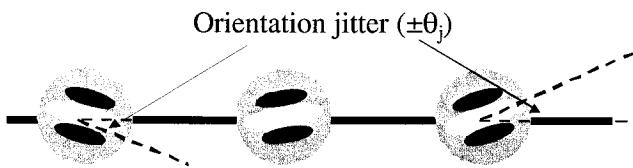


FIGURE 3. The orientation jitter (θ_j) controlled the orientation of the element with respect to the contour, where $\theta_j = 0^\circ$ was in perfect alignment. For any path element, θ_j was randomly selected from a uniform distribution from $-\theta_j$ to $+\theta_j$, the range of which was determined by a staircase under computer control.

contained a Gabor element that was the product of a circular gaussian envelope and an oriented sinusoid:

$$G(x, y) = e^{-(x^2+y^2)/2\sigma^2} * \cos [2\pi * (\cos \theta * x + \sin \theta * y)/p + \phi]$$

where θ controls orientation and ϕ the phase of the sinusoid. The spatial frequency of the elements was 6 cyc/deg and the SD of the gaussian envelope was 0.1°.

Each trial consisted of a 1-second interval, in which two images with the same element density (Fig. 2) were presented simultaneously at either side of a central fixation cross. One image contained a path, the other only randomly oriented elements. The observers' task was to identify which of the images contained the path. Auditory feedback was provided after incorrect responses.

The path was a set of either four, five, or six oriented Gabor elements aligned along a contour that was embedded in a background of similar but randomly oriented Gabor elements. The elements defining the path were separated by either an 0.83° (four-element path), a 0.66° (five-element path), or a 0.54° (six-element path) gap. The starting phase of the first element was randomly selected (between 0° and 360°). The phase of successive elements along the path were then kept in phase with the first element.

The complete contour or path was randomly positioned in the display. The remaining cells (number of elements in the background minus the number of elements comprising the path) were then occupied by distracter elements of random orientation and with random starting phase. The mean separation of the random background elements, including diagonals was an 0.83° (64-element density), a 0.66° (100-element density), or a 0.54° (196-element density) gap, plus a randomization of ±10% to eliminate periodic cues to the presence of the path. The distracter elements were randomly positioned within these unoccupied cells, with the constraint that each cell contained the center of only one Gabor, to eliminate clumping of elements. Overlapping elements summed. In the random pattern, all cells contained a randomly positioned element of random orientation and with random starting phase.

The stimuli were manipulated by randomly varying both the density of the background noise elements (64, 100, or 196 Gabor elements) and the number of elements (four, five, or six Gabor elements) that defined a path of a constant length of 3.3° of visual angle.

A psychophysical procedure²⁷ was adapted to measure sensitivity to different paths. Sensitivity to a path is greatest when the elements are aligned to the contour, and it decreases as the orientation between adjacent path elements increases.²¹ Sensitivity was therefore measured as the amount of local orientation jitter that produced 75% correct performance in the detection task. Each path element was aligned to the contour plus a random orientation jitter selected from a uniform distribution, the range of which was under the control of a QUEST (quality, utilization, effectiveness, statistically tabulated) staircase procedure³⁵ from $-\theta_j$ to $+\theta_j$ (Fig. 3). The staircase increased the range when observers correctly identified the interval containing the path, and decreased the range when observers were unable to identify the interval containing the path.

Consequently, the ability to perform this task demonstrated that observers could spatially integrate information about image structure across extended areas of visual space. The stimuli used make it unlikely that, the path may be segregated by filtering along any one dimension because of the following: (1) These were band-pass stimuli and did not contain any low spatial frequency structure; (2) the path had a constant visual angle of 3.3°, and successive elements were spaced up to a distance of 0.85° (These are distances that are much greater than physiological estimates of the receptive field size of neurons selective for a 6-cyc/deg grating patch in primary visual cortex [V1]); and (3) the metric of sensitivity to the paths involved manipulating the local orientations of the elements defining the path. This orientation randomization has the same effect as alternating the spatial phase of path elements.

It is important to note, however, that in conditions in which the spacing of elements in the path is less than the spacing of the background elements, it is possible to identify the path simply on the basis of the relative density of elements around the path,^{20–21} a first-order texture density cue.

RESULTS

The results are shown in Figure 4. In all conditions, dyslexic observers were two to three times less sensitive to path stimuli than the control group. For all observers, sensitivity to the paths increased with the number of target elements comprising the path, (i.e., as the separation between adjacent elements decreased). This suggests that the long-range associations that support contour integration increase with the spatial proximity of the analyzers that detect the local components of the path. This is further supported by recent research, which has demonstrated through computational modeling^{36–37} that interelement separation and the angle of deviation from collinearity are not independent variables in these psychophysical paradigms, which suggests that there is no separability between position and orientation in cortical connectivity. Rather, these results demonstrate that the connectivity function or association field²⁰ is tapered, with successive elements being afforded a lesser degree of deviation from collinearity (orientation jitter) the farther apart such elements lie.

In agreement with previous studies,^{21,32} a decrease in the signal-to-noise ratio (i.e., as the background element density increased) was found to reduce sensitivity to the paths. When the spacing between target elements in the path is less than that of the noise elements, it may be possible to detect the path by means of element density information. However, when the path elements are presented on a dense noise field, detection of the path is only permitted by means of long-range interactions, as has been conclusively documented in the literature. The proof that there is no density cue is that a contour stimulus composed of isotropic elements is undetectable.

Subjects in both groups exhibited similar trends with respect to the relative signal-to-noise ratio of the stimuli and the number of target elements constituting the path. However, a group analysis of variance revealed dyslexic performance consistently worse than that of the control group across all stimulus parameters. A two-factor ANOVA for the factors of subject group (control versus dyslexic) and number of target elements defining the path revealed, for the following background element densities: Figure 4a, a significant effect of subject group ($F_{1,132} = 29.3, P = 0.0001$) and target elements ($F_{2,132} = 58.4, P = 0.0001$) and no significant interaction ($F_{2,132} = 1.2, P = 0.3$); Figure 4b, a significant effect of subject group ($F_{1,132} = 29.8, P = 0.0001$) and target elements ($F_{2,132} = 90.8, P = 0.0001$) and no significant interaction ($F_{2,132} = 1.5, P = 0.2$); Figure 4c, a significant effect of subject group ($F_{1,132} = 128.3$,

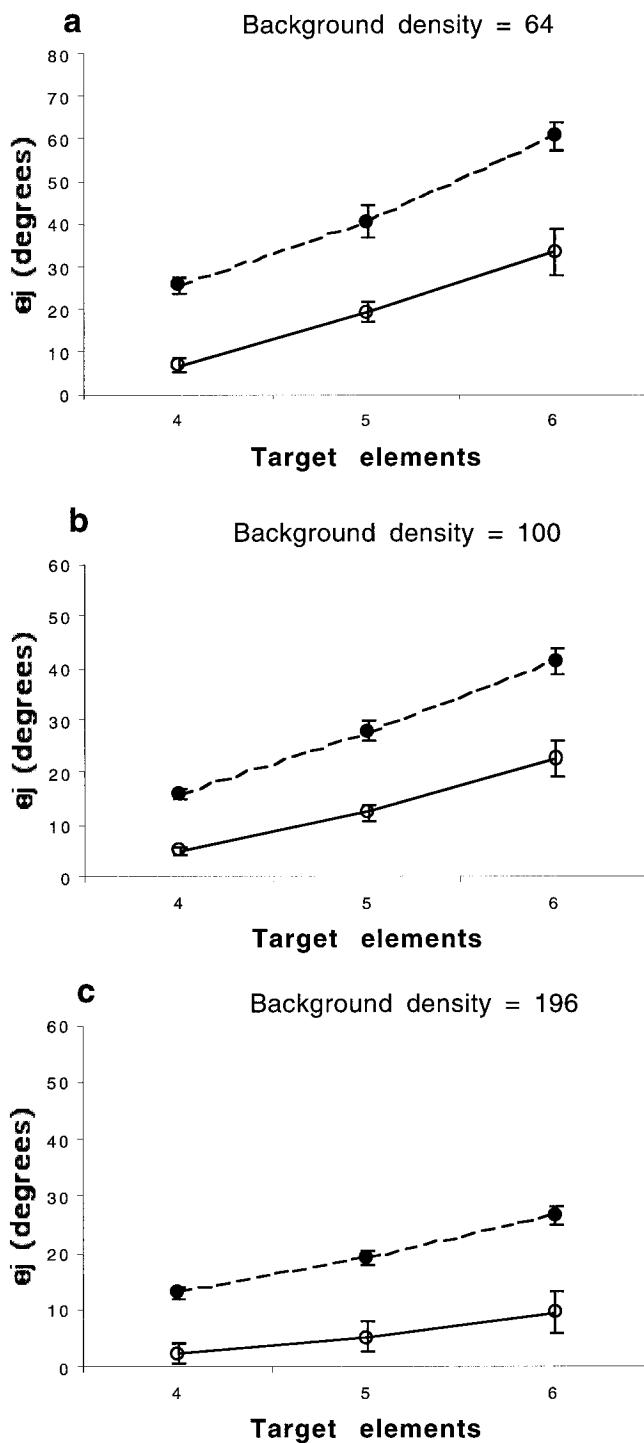


FIGURE 4. Detection of paths as a function of element density of (a) 64, (b) 100, and (c) 196 Gabor elements and number of target elements. (○) Observers with dyslexia; (●) control group. Sensitivity to a path was greatest when the elements were aligned to the contour and decreased as the orientation between adjacent path elements increased. The x-axis shows the number of target elements defining the path; the y-axis shows the range of orientation jitter of the local elements producing 75% correct detection of the path stimulus. Each data point is the mean of five threshold estimates. Error bars, SE.

$P = 0.0001$) and target elements ($F_{2,132} = 41.1, P = 0.0001$) and no significant interaction ($F_{2,132} = 2.1, P = 0.2$).

DISCUSSION

One possible central mechanism advanced recently in dyslexia is the presence of a generalized temporal processing deficit across sensory modalities⁶ with an impaired focus of attention.^{38,39} Is it possible, then, that the differences observed between subject groups in the present study were due to attentional mechanisms? The overall consensus with respect to the visual domain is that there is impaired attention with an increase in attentional dwell time⁴⁰—that is, it takes longer for dyslexic persons to disengage their attention from one visual target to the next. This has been found to be the case for sequences of rapidly presented stimuli at intervals of less than 1 second. Stimulus duration in this study was always 1 second, allowing sufficient viewing time in both subject groups and therefore giving no subject group an advantage.

In addition, much converging evidence indicates an asymmetric distribution of attention between the two visual fields, hypothesized as a left-side minineglect in dyslexia.^{38-39,41} Could some form of deficiency in the visual processing of only one side of the brain have been reflected in our anomalous results?

This is unlikely, because the adaptive staircase procedure used in this study increased the orientation jitter when observers correctly identified the interval containing the path and decreased orientation jitter when observers were unable to identify the interval containing the path. Therefore, for a threshold to be reliably and accurately obtained, both subjects groups would have had to be able to perform at 100% (stimuli equally presented to the right and left field) correct levels when the orientational jitter was 0°.

Furthermore, all observers were practiced in psychophysical testing, with the dyslexic subjects having completed a previous study in which spatiotemporal visual processing was investigated.⁴² The procedure in that study also consisted of a 2-alternate forced choice (AFC) paradigm with both stimuli being presented simultaneously. No significant difference in visual thresholds was demonstrable between the dyslexic and control groups. This appears to negate any general deficiency the dyslexic observers in the present study may have had in comparing two sides of a screen simultaneously, contradictory to any underlying weak cross-hemispheric connection.

It is interesting that several lines of recent work have also demonstrated in amblyopia impairments in contour integration, especially in persons with strabismus; in path detection³¹ and closed-circle paradigms,³² and in the perceptual grouping of elements.⁴³ There is little consensus, however, at this stage about whether these deficits are indicative primarily of poor perceptual integrative processes in the amblyope's visual system⁴³ due to anomalous long-range interactions between orientational detectors,⁴⁴ or are indeed a consequence of the disrupted positional coding that is thought to underlie the perceptual deficit in amblyopia.⁴⁵⁻⁴⁶ In the present study, it seems unlikely in the dyslexic subjects that a general deficiency would have been so systematically affected by stimulus variables.

Global precedence is a finding that supports the primacy of global information in conscious perception. Global information appears to be processed more efficiently in the right hemisphere,⁴⁷⁻⁴⁸ and it is particularly interesting that right parietal cortical dysfunction has been linked to dyslexia.^{6,41} Patients with lesions in the right hemisphere can accurately reproduce local elements but not the global configuration⁴⁹

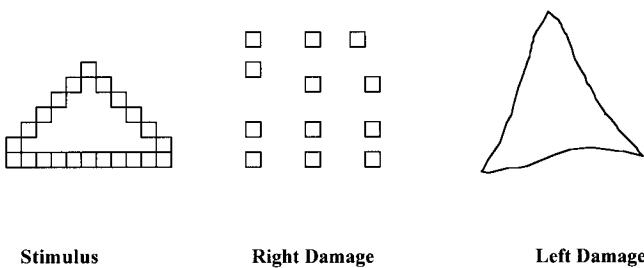


FIGURE 5. A cluster of smaller elements (local) produced a pattern in a distinct shape and orientation (global). Patients with damage to the right parietal lobe showed deficits in global processing (Δ) but reproduced the smaller local elements accurately (\square), whereas patients with left hemispheric damage perceived the global percept but not the smaller local elements that formed the shape. Adapted, with permission from Elsevier Science, from Delis DC, Robertson LC, Efron R. Hemispheric specialization of memory for visual hierarchical stimuli. *Neuropsychologia*. 1986;24:205-214.

(Fig. 5). It is possible that right hemispheric dysfunction in dyslexia predisposes to the deficits in global processing illustrated in this study (the integration of local elements = Gabor patches, producing a global percept = path) and in the difficulties encountered during the reading process, when single letters and words may be identified readily when masked but the overall appearance of text is at times confusing and even aversive.¹¹⁻¹²

In the present study we have described a visual deficit in a global integration task in which the stimuli used local orientation noise to ensure that observers were forced to integrate the path with facilitatory and inhibitory connections among low-level detectors.¹⁷ The pattern of deficits reported herein suggest that in dyslexia abnormal cooperative associations may be present, indicative of poor perceptual integration. If cooperative associations allow a more coherent visual experience, disruption of these may manifest in natural viewing as the visuoperceptual distortions and symptoms that characterize developmental dyslexia.

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