PERGAMON

Vision Research 40 (2000) 1775–1783

Vision Research

www.elsevier.com/locate/visres

A new test of contour integration deficits in patients with a history of disrupted binocular experience during visual development

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Received 21 April 1999; received in revised form 26 October 1999

Abstract

Previous studies have suggested that the integration of orientation information across space is impaired in amblyopia. We developed a method for quantifying orientation-domain processing using a test format that is suitable for clinical application. The test comprises a graded series of cards where each card includes a closed path (contour) of high contrast Gabor signals embedded in a random background of Gabor signals. Contour visibility in both normals and patients with histories of abnormal binocular vision depends jointly on the spacing of elements on the contour as well as background element density. Strabismic amblyopes show significant degradation of performance compared to normals. Small but significant losses in sensitivity were also observed in a group of non-amblyopic strabismus patients. Threshold measurements made with contrast reducing diffusers indicated that the amblyopic loss is not due to the reduced contrast sensitivity of the amblyopic eye. An abnormal pattern of long-range connectivity between spatial filters or a loss of such connectivity appears to be the primary source of contour integration deficits in amblyopia and strabismus. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Amblyopia; Strabismus; Spatial interactions; Contour integration; Grouping

1. Introduction

Abnormal binocular input ocurring within a critical period during development can lead to reduced visual acuity for optotypes and gratings as well as reduced spatial contrast sensitivity (Gstalder & Green, 1971; Hess & Howell, 1977; Levi & Harwerth, 1977; Bradley & Freeman, 1981), vernier acuity (Levi & Klein, 1982a,b). and spatial distortion (Hess, Campbell & Greenhalgh, 1978; Bedell & Flom, 1981, 1983; Lagréze & Sireteanu, 1991; Sireteanu, Lagréze & Constantinescu, 1993). A reduction of acuity in the presence of normal ocular structures is used clinically to classify patients as having amblyopia, but it is clear that abnormal visual experience during development may affect visual mechanisms other than those involved in letter recognition.

Several studies have reported that the integration of orientation information across space is degraded in amblyopia (Polat & Sagi, 1993b; Polat & Norcia, 1995a,b; Kovács, Polat & Norcia, 1996; Hess, McIlhagga & Field, 1997; Polat, Sagi & Norcia, 1997). The initial studies in this area utilized a lateral masking paradigm (Polat & Sagi, 1993a, 1994) to study spatial organization of lateral interactions occuring between oriented spatial filters. In normal observers, the visibility of a, small, foveally viewed Gabor patch is enhanced by laterally placed Gabor patches of similar orientation and spatial frequency (Polat & Sagi, 1993a, 1994; Polat & Norcia, 1996). Maximal facilitation in normals oc-

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0042-6989/00/$ - see front matter
PII: S0042-6989(00)00008-0

curs for collinearly aligned targets that are spatially separated by as much as several degrees. Conversely, foveal patch sensitivity in normals is suppressed by remote targets that differ significantly in orientation. Amblyopic observers show deviations from these normal patterns of interaction: the facilitation for collinear configurations is either lower than normal or it is replaced by inhibition (Polat et al., 1997).

In a preliminary study (Kovács et al., 1996) we examined the performance of a predominantly strabismic group of amblyopes on a contour integration task that may also rely on collinear facilitatory interactions (Kovács & Julesz, 1993; Pettet, McKee & Grzywacz, 1998; Yen & Finkel, 1998). Kovács et al. (1996) examined the detectability of a closed path (contour) defined by a chain of Gabor elements embedded in a random Gabor-element background (Kovács & Julesz, 1993). Using this task, we found a significant degradation of contour detectability in amblyopic eyes. Hess and coworkers (Hess et al., 1997; Hess & Demanins, 1998) have used a similar contour detection task to study contour integration in amblyopia — one involving the open ended chains introduced by Field et al. (Field, Hayes & Hess, 1993). Contour visibility was degraded by varying the degree of random orientation offset from the spine of the underlying contour. These studies found that performance was degraded in strabismic (Hess et al., 1997), but not anisometropic amblyopia (Hess & Demanins, 1998).

Our goal has been to develop a test of contour integration that is suitable for use with pediatric patients in a clinical setting. Our first design criterion was that the test should force the patient to use long-range correlations to detect the contour. To do this, contours were defined soley on the basis of orientation relationships (see below). We used closed paths, since they are particularly strong stimuli for the normal visual system, presumably because they elicit especially strong collinear facilitation along their length (Kovács & Julesz, 1993; Pettet et al., 1998). Closed paths also support detection over substantially longer ranges than do open ended paths (Kovács & Julesz, 1993) making it more likely that the task requires long-range integration of local orientation signals. A card format was chosen for its portability, internal calibration and low cost.

To ensure that detection was based on long-range correlations, other cues for the location of the contour had to be removed. Just as in the original version of the task (Kovács & Julesz, 1993), we used Gabor signals to generate the stimulus displays because they (1) allow for exact control over important spacing parameters, (2) help to rule out the involvement of large filters (we wished to study interactions among small foveal filters) and (3) help to rule out luminance artifacts that would arise in the presence of terminators with luminance defined targets. A card format is also suitable for use with clinical staircase procedures, such as those used for Preferential Looking tests of grating acuity.

In a preliminary experiment, the distance between adjacent Gabor signals along the path and the average distance between elements in the background were varied independently (for a similar procedure see also Braun, 1999). Contour delectability was measured as a function of these parameters in both normal and amblyopic observers. This study was used to determine the most sensitive range of parameters for detecting the amblyopic deficit. In a second study, thresholds were measured with a set of cards in which the spacing of elements along the contour was held constant and the density of the background Gabor elements was varied. Control experiments using contrast reducing filters were conducted to determine the extent to which performance on the contour detection task was limited by reduced contrast sensitivity in the amblyopic eye. The control experiment indicated that the amblyopic deficit is not due to lowered visibility of the elements making up the contours. Rather, the amblyopic deficit is specific to deficiencies in the long-range integration of orientation information. Portions of this work have been presented previously (Kovács et al., 1996; Pennefather, Chandna, Wood, Polat, Kovács & Norcia, 1998).

2. Experiment 1

2.1. Methods

2.1.1. Card design

Each card consisted of a smoothly aligned, closed path of Gabor elements embedded in a random array of Gabor elements of the same spatial frequency and contrast (see Fig. 1). The Gabor arrays with the embedded contours were generated on a Silicon Graphics Iris Indigo R 4000 computer. The images were then printed on a 1200 dpi printer. The position and orientation of the Gabor elements within the arrays were computed with a Monte Carlo technique adapted from molecular dynamics (Braun, 1999). Using this technique we had precise control over the spacing parameters and we were able to keep the smallest permitted separation between background elements while avoiding spurious spacings. A new random shape and a new background was computed for each card. The absolute length of the contours was kept constant. The angular difference between adjacent contour segments was assigned within a range of 0 to $\pm 30°$. Note that in experiment 2 we employed a different algorithm (see below).

The average spacing between adjacent elements in the background relative to the spacing between neighboring elements along the contour defines a parameter which we refer to as Δ. The parameter Δ is the ratio of

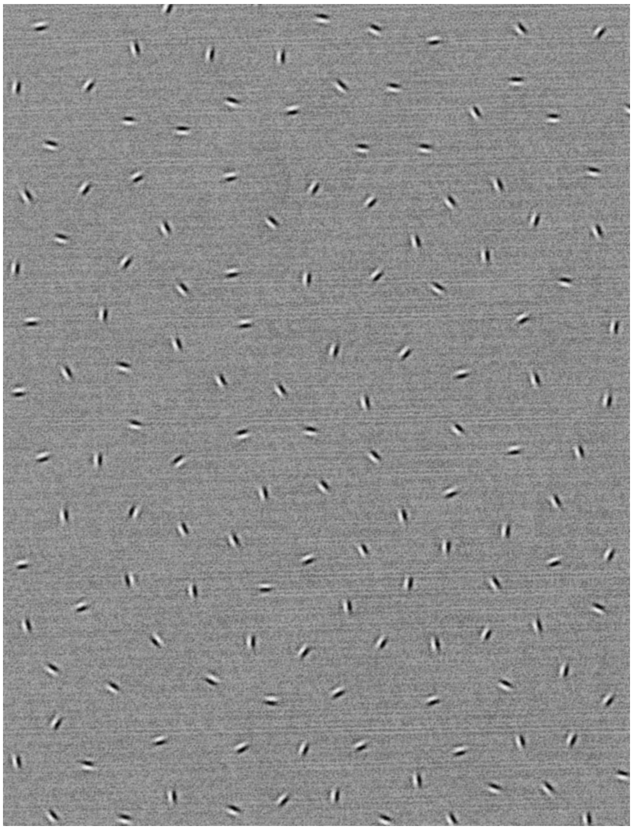

Fig. 1. Example of the test cards used to assess the strength of spatial interactions in amblyopia. A closed path of Gabor signals is embedded in noise. The observer is asked to indicate the location of the contour (the ratio of element spacing in the noise background and spacing along the contour is 1.0).

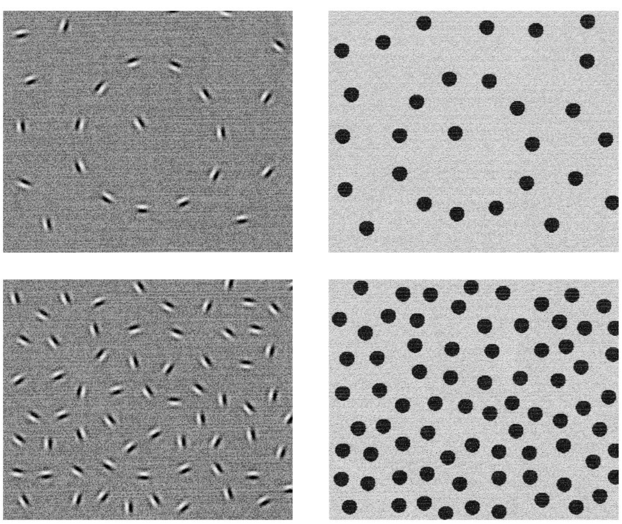

Fig. 2. Examples of Gabor-defined contours with different Δ values (top: $\Delta = 1.4$. bottom: $\Delta = 0.85$). In the right panels, Gabor elements were replaced by disks. Without orientation cues, the contour remains invisible at $\Delta \leq 1$.

background spacing over contour spacing. When $\Delta \geq 1$, the contour can be identified on the basis of a first-order texture density cue. This is illustrated in the right panels of Fig. 2 where the oriented Gabor elements are replaced with disks. In the top panels of Fig. 2, where $\Delta \geq 1$, the contour can be found on the basis of its higher element density, relative to the background. For $\Delta \leq 1$ (bottom panels), the path of the closed contour can only be perceived on the basis of the relative orientation of the Gabor elements along the contour. Long-range spatial interactions are expected to play a role in the latter case, which we call second-order contour integration.

2.1.2. Observers and procedure

Thirteen amblyopic adults (11 strabismic and two anisometropic) and ten adults with normal or corrected to normal vision participated. The optotype acuities of the amblyopic eyes ranged between 6/9 and 6/36. All observers were refracted for the test distance of 57 ± 5 cm. The observers' task was to determine whether the closed contour was located on the left third, right third or center third of the card. The observers were first familiarized with the task by showing them two practice cards with highly visible contours (Δ of ≈ 1.5).

Contour element spacing and average noise background element spacing was varied over the range of 3 to 9λ, where λ is the wavelength of the Gabor signal. There were five steps of each parameter, resulting in a a set of 25 cards that spanned Δ values between 3 (highly visible) and 0.3 (undetectable).

Testing began with the non-amblyopic eye with the card with lowest noise density and closest contour spacing followed by progressively more widely spaced contours, e.g. following the order of the rows from top to bottom in Fig. 3. Each card was presented and correct or incorrect answers were recorded. Patients were not forced to guess if they could not find the contour. The amblyopic eye was then tested.

2.2. Results

Fig. 3 shows results from the first set of 25 cards which varied both background and contour spacing. The amblyopic eyes of 13 amblyopic observers, their fellow eyes and the dominant eyes of ten normal observers are compared. The percentage of those observers who correctly located a given target is plotted on the Z-axis. Contour spacing is plotted on the X-axis and background spacing on the Y-axis. $\Delta = 1$ along the diagonal (white-faced columns in the graphs). The contours are defined by a first-order density cue to the left of the diagonal ($\Delta > 1$). To the right of the diagonal, the contours can only be seen based on the good continuity of adjacent elements ($\Delta < 1$). As Δ decreases (indicated with dark shading), long-range spatial interactions are assumed to be more and more involved. Notice that the strength of

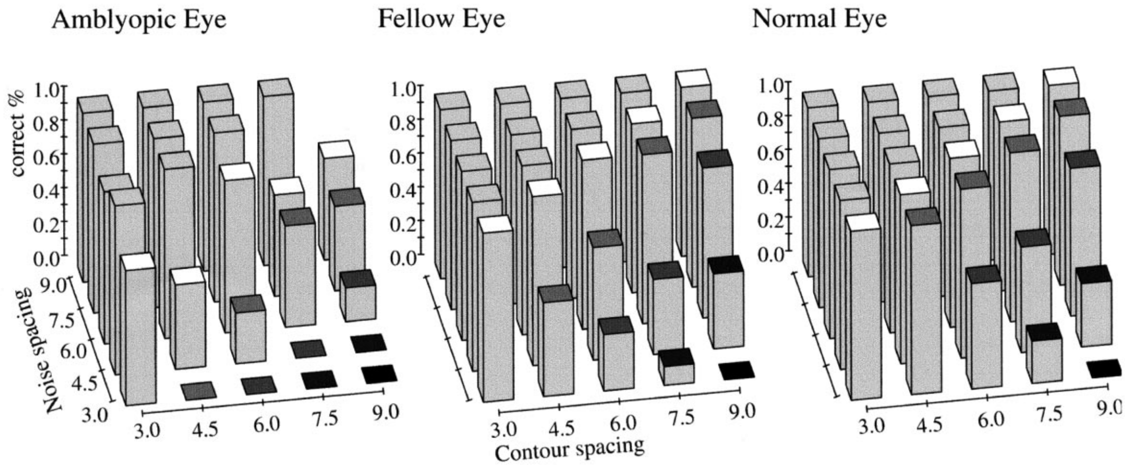

Fig. 3. Results from the first set of 25 cards which varied contour spacing (X-axis) and noise spacing (Y-axis) independently (spacing parameters are expressed in Gabor wavelength units). White-faced columns represent equal spacing in the background and along the contour ($\Delta = 1$). Dark shading indicates decreasing Δ values in the $\Delta < 1$ range, which is expected to increase the difficulty of contour integration. The amblyopic eyes show selective losses of contour detectability below $\Delta = 1$.

both the signal and the noise is inversely proportional to the spacing, therefore Δ also expresses the signal to noise ratio of each card.

As might be expected, both increased contour spacing and decreased background spacing reduces performance, however the critical parameter seems to be the ratio of these (Δ). In normals, performance is degrading slowly for $\Delta < 1$ contours. and at the same rate for the two dimensions of increasing contour spacing and decreasing background spacing. This indicates that the signal to noise ratio determines performance for normal eyes, and the absolute spatial range of interactions is not a limitation within the tested range. The latter would be indicated if contour spacing would have a larger effect relative to noise spacing.

Amblyopic and normal observers can perceive the first-order contours ($\Delta > 1$) almost equally well. The amblyopic deficit shows up most dramatically for $\Delta \leq 1$. Amblyopic observers have a mild deficit in this range even with their fellow eyes. Amblyopic observers seem to perform slightly better at large contour spacings, where noise density is lower. This might be related to their sensitivity to 'crowding' effects. However, the main effect is still in terms of Δ. This is consistent with the findings of Braun (1999) on normal observers with the same type of stimuli. In the followings, we treat Δ as a tool to isolate and quantify second-order contour integration processes.

3. Experiment 2

3.1. Methods

3.1.1. Card design

Based on the results with the first set of cards, a second set of 15 cards was designed. Contour spacing was constant (8λ) in the second set, and we only varied background spacing, resulting in a range of Δ values between 1.15 and 0.5. The second set had smaller steps in terms of Δ (stepsize = 0.05). We measured Δ thresholds in the figure-detection task employing a clinical staircase procedure.

Since Pettet et al. (1998) have shown that contour smoothness is an important constraint on contour visibility, we limited the orientation variation along the contour so that the second card set had continously positive curvature with no inflection points. All contours had the same general size and shape, therefore all differences in detectability must be related to changes in background noise density, rather than changes in contour salience per se.

We also wanted to avoid a possible, although probably very weak, density cue arising at small Δ values. where contour spacing is so much larger than background spacing that spurious empty spaces may help detection. To overcome this problem, we allowed background elements to intrude into contour spaces in the new set, and we took care not to let background elements align with the contour. Finally, the contours were restricted to the left or right hand sides of the cards for use with the two-alternative forced choice staircase procedure used to measure contour detection thresholds.

3.1.2. Observers

The second test group was comprised of 17 normal observers, 14 patients with strabismic amblyopia and six strabismic patients with equal logMar optotype acuity. Clinical details of the two patient groups are documented in Table 1. Patients were considered to be amblyopic if they had more than one line difference of letter acuity between the two eyes (> 0.1 log units on a LogMar scaled Bailey Lovie chart). Patients with less interocular acuity difference were not considered amblyopic. Each patient's visual acuity was measured while wearing optimal correction. Strabismic deviations were measured with cover–uncover, alternate cover and the four diopter base-out prism tests. Patients were considered to be strabismic if their deviation was greater than 2–4 prism diopters. which is our estimate of the quantitative sensitivity of the cover test. Amblyopic patients with current deviations of smaller than 2–4 diopters and no anisometropia who reported a history of childhood strabismus were classified as being strabismic.

3.1.3. Procedure

Contour detection thresholds reported here are taken from a study of repeatability and learning effects (Pennefather, Chandna, Kovács, Polat & Norcia, 1999). Three independently generated card sets were used to measure thresholds. Each eye was tested twice on all three card sets. The order of presentation of the card sets and the eye tested first was randomized across observers. The data reported are for the fourth threshold measured out of six for each eye. This procedure helped us to obtain more reliable data allowing for learning effect to occur in the first few measurements, and for a stabilized performance by the fourth measurement.

Table 1
Clinical details of the patients studied in experiment 2[a]

Deviation	Refraction	Dom VA	nDom VA	Dom contour	nDom contour
Strabismic amblyopia					
L esotropia (controlled with gls)	R +2.00 = +0.75 × 35, L +4.25 = +1.25 × 140	0.02	0.12	0.65	0.70
L exotropia	R +4.00, L +6.00	−0.06	0.18	0.70	0.70
L esotropia	R −6.00, L −6.00	−0.06	0.28	0.60	0.70
L esotropia	R +4.00 = +2.00 × 110, L +4.75 = +2.50 × 80	−0.06	0.30	*0.90*	*0.90*
L exotropia	R −2.25, L −5.00 = +2.00 × 170	0.02	0.58	0.70	*0.95*
Consecutive L extropia		−0.18	0.46	*0.75*	*0.80*
L esotropia	R +2.00, L +2.00	−0.10	0.78	0.70	0.70
R esotropia for near target	R +3.00 = +0.50 × 90, L +0.75	−0.02	2.04	0.65	*0.95*
R esotropia	R +2.00 = +1.50 × 110, L +0.50	0.02	0.98	0.55	*0.75*
R exotropia	R plano = +3.00 × 80, L plano = +2.50 × 105	0.02	0.84	0.65	*0.75*
R exotropia	R −0.75 = +0.75 × 170, L −3.50 = +1.75 × 180	−0.04	0.56	0.70	*0.75*
Consecutive for R exotropia	R +6.75 = +2.50 × 90, L +6.75 = +2.50 × 80	−0.04	0.56	*0.75*	*0.90*
Consecutive for R esotropia	R −5.50 = +5.00 × 110, L −0.25	0.00	0.50	0.70	*0.80*
R exotropia	R plano = +4.00 × 180, plano = +0.50 × 180	−0.08	0.08	*0.75*	*0.75*
	Average	−0.04	0.59	0.70	0.79
	SD	0.06	0.50	0.08	0.09
	SEM	0.02	0.13	0.02	0.03
Non amblyopic strabismus					
Consecutive L exotropia	R −1.75 = +1.00 × 15, L −1.50 = +0.50 × 160	0.20	0.22	*0.75*	*0.75*
R/alternating esotropia	R +0.50 = +3.00 × 100, L −1.00 = +0.75 × 95	0.00	−0.06	0.70	0.60
R esotropia	R +0.75 = +1.00 × 35, L plano = +0.50 × 97	0.06	0.00	*0.85*	0.70
R/alternating esotropia	R −5.50 = +3.50 × 155, L +0.50	−0.04	0.12	0.70	0.70
Consecutive R/alternating exotropia	R −1.50 = +2.50 × 150, L plano = +1.00 × 30	0.00	0.00	*0.75*	*0.90*
R/alternating esotropia	R −0.50 = +0.50 × 80, L −7.50 = +1.75 × 90	0.00	0.00	0.70	0.70
	Average	0.04	0.05	0.74	0.73
	SD	0.09	0.10	0.06	0.10
	SEM	0.04	0.04	0.02	0.04

[a] Italics indicate contour thresholds that are outside of the 95% confidence limits for normal observers.

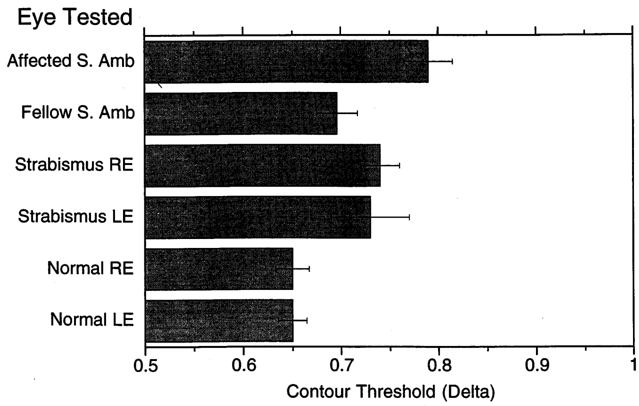

Fig. 4. Contour detection thresholds expressed in Δ units for normal observers (normal), strabismic amblyopes (S. amb) and patients with strabismus, without amblyopia defined by optotype acuity (strabismus). Contour detection thresholds are elevated by approximately 0.15 Δ units (three cards) in the amblyopic eyes of strabismic observers. Smaller elevations are seen in the non-amblyopic fellow eyes of the strabismic amblyopes as well as in both eyes of non-amblyopic patients with strabismus.

Thresholds were measured using a clinical staircase procedure. Within a given card series, the observer had to correctly identify the side (left or right) on which the closed contour was presented. The staircase required a correct response for at least two out of three presentations of the same card to allow progression, with three reversals required to define the threshold (cards were reversed on representation at random).

3.2. Results

Average contour detection thresholds, expressed in Δ units are presented in Fig. 4. Normal observers had an average threshold of 0.65 in the right and left eyes with standard deviations (SD) of 0.06 and 0.07, respectively. The amblyopic eyes of the 14 strabismic patients averaged 0.79 (0.09 SD) and their fellow eyes averaged 0.70 (0.08 SD). The six strabismus patients with no optotype deficit averaged 0.74 (± 0.06) in their right eyes and 0.73 (0.10) in their left eyes. Fig. 4 plots these means ± 1 SEM. The strabismic amblyopes showed elevated contour detection thresholds, relative to the normal eyes ($P = 0.0001$, Fischer's Protected LSD). The dominant eyes of strabismic amblyopes had also contour detection thresholds slightly higher than normal, but these effects were only marginally significant ($P = 0.07$). Both eyes of the strabismus patients without optotype differences between eyes had elevated contour thresholds compared to normals ($P = 0.006$ for right eyes; $P = 0.078$ for the left eyes; Fischer's Protected LSD). The mean acuities of these strabismus patients were equal to those of the fellow eyes of the strabismic amblyopes (0.04 ± 0.04 and 0.05 ± 0.04 vs -0.04 ± 0.02 for the fellow eyes of the strabismic amblyopes: $P = 0.09$ and 0.1, respectively on two-tailed t-tests). The slightly elevated contour thresholds of the 'non-amblyopic' strabismus patients relative to the fellow eyes of the strabismic amblyopes cannot be attributed to worse acuity, since the acuities across the two groups were equal.

3.3. Effects of experimental reductions of Gabor element visibility

Patients with amblyopia have reduced acuity and they can also have reduced contrast sensitivity at lower spatial frequencies. The individual Gabor patches have a carrier spatial frequency of 5 c/deg at a 57 cm viewing distance and thus the contrast of the individual elements could have been reduced in the amblyopic eye. The results of the first experiment suggest that Gabor patch visibility is not limiting performance since the amblyopic eyes perform at near normal levels when Δ is greater than 1. Nonetheless. we wished to determine if contrast sensitivity was limiting performance for Δ values that were less than 1. We reasoned that if contrast sensitivity was limiting contour detection, any reduction of retinal image contrast should raise the contour threshold even further. Image contrast was reduced using calibrated diffusers (Baengerter filter bar, The Fresnel Prism and Lens Co., Scottsdale, AZ).

Seven of the normal observers from experiment 2 participated, as did each of the 14 strabismic amblyopes tested in experiment 2. Each observer selected the maximal filter density that allowed them to detect a highly suprathreshold contour ($\Delta = 1.2$). Visual acuity was measured with this filter, as was contrast sensitivity (Pelli–Robson chart) and contour detection threshold. One of the strabismic amblyopes (VA = 2.04) could not detect the contour with the weakest Baengerter filter and her data were excluded. Table 2 presents the data for normal and amblyopic eyes. Filters that produced significant acuity losses and low spatial frequency contrast sensitivity losses do not have a significant effect on contour detection thresholds in the strabismic group.

4. Discussion

The contour integration cards used here were based on the contour detection tasks introduced by Field et al. (1993) and Kovács and Julesz (1993). As part of reducing these tasks to clinical practice, we have introduced a new measure of contour visibility — the parameter Δ, that is, the ratio of background spacing to contour spacing. For a similar approach on normal observers see Braun (1999), and Kovács, Kozma, Fehér and Benedek (1999). Variation of the parameter allows one to isolate first-order and second-order integration mechanisms, since the detection of the contour at values of $\Delta < 1$ is impossible using first-order cues alone. The advantage of using Δ as a parameter is that one can directly study the efficiency of long-range interactions that contribute to the integration of spatially distributed objects. By changing Δ, only the signal-to-noise ratio changes, while the shape of the contour, the global and local curvatures, the number of contour elements, the length of the contour, the spacing along the contour and the eccentricity of the elements are all kept constant. This is not the case in the alternative approach involving open ended chains introduced by Field et al. (1993) where the angular difference between adjacent elements is the threshold parameter. When the angular difference is varied, not only the local, but also the global curvature is changed and the general shape of the contours varies tremendously — from a straight line to an almost closed figure. Global curvature is an important determinant of contour visibility (Kovács & Julesz, 1993; Pettet et al., 1998) and the present measure ensures that this potentially confounding parameter does not vary across the cards used to measure the contour detection threshold.

Contour integration deficits were found predominantly when the task required second-order information — that is when the ratio of average background spacing over contour element spacing drops below 1. The losses in the strabismic amblyopes cannot be explained by reduced contrast sensitivity, since experimental reductions of test contrast fail to produce significant elevations of threshold over a range of contrast reductions that significantly reduces visual acuity and contrast sensitivity. A similar insensitivity of contour integration to contrast reduction in strabismic amblyopia has been reported previously (Hess et al., 1997). In normal observers, performance on a computerized version of the present task starts to degrade at contrasts below 7–10% (Kovács, unpublished observations). A similar result has been reported for the detection of open contours by normal observers (McIlhagga & Mullen, 1996). Amblyopic observers with more than about factor of ten contrast sensitivity loss at 5 c/deg may thus show effects of reduced Gabor element visibility and caution must therefore be used in interpreting the results from deeply amblyopic observers.

The present results are similar to those of Hess et al. (1997) who found that ten of 11 strabismic amblyopes ($91 \pm 9\%$) were abnormal on a contour detection task that used variations in the smoothness of the contour to control visibility. In our study, ten of 14 strabismic amblyopes ($71 \pm 12\%$) had thresholds outside of the 95% confidence range of normal observers. This difference between incidence of contour deficits in the two studies ($20 \pm 15\%$) is not statistically significant. The parameter Δ is thus a sensitive measure of contour integration deficits. Moreover, the card format is suitable for rapid and reliable threshold estimates in children 3 years of age and over (Kovács at al., 1999; Pennefather et al., 1999).

We found that contour integration deficits were strongest in the amblyopic eyes of patients with strabismus, but they were also measurable in both eyes of strabismus patients without optotype acuity losses. There was also a trend for elevated thresholds in the fellow eyes of the amblyopic observers. Contour integration deficits appear to be only loosely related to optotype acuity losses, the correlation between optotype acuity and contour thresholds was 0.46 for the amblyopic eyes in the present study. Dissociations were apparent in both directions — there were patients with substantial optotype losses who showed little effect on their contour thresholds and vice versa. The fact that strabismus patients without optotype acuity losses show small, but significant threshold elevations argues against the contour threshold being an insensitive measure of abnormal visual experience. Rather, the task appears to be tapping mechanisms that are, to a substantial degree, independent of those needed for letter recognition. Consistent with this, Hess and Demanins (1998) have reported that anisometropic amblyopes did not have significant contour detection deficits with open-chain contours.

Whether or not amblyopes show deficits in 'second-order orientation' processing appears to depend on a number of factors. The work of Hess et al. (1997) and Hess and Demanins (1998) suggests that the type of amblyopia is important in producing a deficit. Prior treatment history may also be important (Chandna, Pennefather, Wood, Polat, Kovacs & Norcia, 1998).

Table 2
Effects of experimental contrast reduction on visual acuity, contrast sensitivity and contour detection thresholds[a]

Observers	Difference in contour detection	*P* value	Difference in logMar VA	*P* value	Difference in contrast sensitivity	*P* value
Normals ($N = 14$ eyes)	−0.016 (SD 0.035)	0.828	−0.507 (SD 0.152)	<0.001	0.619 (SD 0.204)	0.001
Strabismis ($N = 13$ eyes)	0.015 (SD 0.077)	0.487	−0.206 (SE = 0.175)	0.001	0.485 (SD 0.185)	0.001

[a] Contrast reduction significantly reduces optotype acuity in contrast sensitivity, but does not affect contour detection thresholds in normal observers or strabismic amblyopes.

Deficits may also depend on the task used to probe second-order processing. The contour integration task is second-order in that it forces the observer to make long-range comparisons between oriented elements. The present results and those of Hess et al. (1997) suggest that strabismic amblyopes are selectively impaired in second-order contour integration (compare first- to second-order performance in Fig. 3). Polat et al. (1997) used three-element displays to study second-order processing psychophysically and electrophysiologically using the visual evoked potential (VEP). In the psychophysical task, the amblyopic observers showed reduced threshold facilitation or inappropriate suppression for collinear arrangements of the three patches. In the VEP study, amblyopic observers also showed inappropriate patterns of facilitation and suppression for both collinear and orthogonal patch configurations. More recently, Hess, Wang, Demanins, Wilkinson and Wilson (1999) have found that strabismic amblopes have deficits in judgements of the shape of suprathreshold rings. In contrast Levi and Sharma (1998) found normal enhancement of contrast thresholds for collinear arrangements of a 3×5 array of Gabor patches. Good, Carden, Candy, Polat and Norcia (1998) found that both strabismic and anisometropic amblyopes showed normal patterns of length and width summation for elongated Gabor patches and Good, Carden, Burden, Candy and Norcia (1999) have found a normal pattern of threshold enhancement in three-element Gabor patch displays where separation between the patches was varied over a wide range. Finally, Mussap and Levi (1999) have found that strabismic amblyopes show a normal ability to segregate orientation-defined textures. While each of these tasks requires the integration or comparison of orientation information across space, amblyopic observers appear to be deficient in only a subset of the tasks. As part of understanding why amblyopes are abnormal on only a subset of second-order orientation tasks, it will be important to better understand the relationship between tasks involving second-order effects on contrast detection versus those involving shape or contour judgements (see Kovács & Julesz, 1993; Williams & Hess, 1998). Within-observer comparisons across different task types should be performed to control for individual differences that may have existed across patients selected for study by different laboratories.

5. Summary

A novel clinical test of second-order contour integration is presented. The design of the test was based on the hypothesis that some of the amblyopic deficit is due to abnormal spatial interactions subserving early grouping mechanisms. We found a selective loss in the contour integration abilities of patients with strabismic amblyopia, which also occur to a small degree in both eyes of patients with a history of strabismus who were not amblyopic at the time of testing. The poor performance of amblyopic observers cannot be accounted for by deficiencies of a more local nature, such as a loss in visual acuity and in contrast sensitivity. The test-cards can also provide an efficient way to test amblyopic patients, adding a potentially valuable tool to the clinical test-battery.

Acknowledgements

The authors thank Ákos Fehér for developing the algorithm and software necessary for the generation of the contour cards, and Jochen Braun for making available his contour generating algorithm. This paper was supported by grants from the J.S. McDonnell Foundation 9560 to I.K., EY06579 to A.M.N. and a Rachel C. Atkinson Fellowship to U.P.

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