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Strabismic suppression depends on the amount of dissimilarity between left- and right-eye images

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Abstract

Suppression in strabismus is more likely to occur when the images for the left- and right-eye are similar. In this study the relationship between the depth of strabismic suppression and the amount of dissimilarity between the images was quantified. Six subjects with microstrabismus looked at two identical colorful, cartoon images via mirrors. In the middle of each screen was a circular aperture with an opal glass, which was illuminated from the back by a halogen lamp during 300 ms with a gradual on- and offset in intensity. In the circular aperture images that slightly differed in shape were presented to both eyes. The dominant eye was presented a circle, the squinting eye a circle that, in four steps, changed its shape into a square. Under each of these four conditions, the image for the dominant eye was attenuated progressively by neutral density filters. When the image for the squinting eye was perceived, the depth of the suppression was thereby measured. It was found that suppression decreased with dissimilarity of the images.

Keywords: Strabismus; Suppression; Binocular rivalry; Depth perception; Form perception

1. Introduction

When children develop squint before the age of six, suppression of the misaligned eye develops to avoid diplopia. Suppression is an active, cortical process that leads to a decrease in sensitivity in parts of the visual field, the suppression scotoma (von Graefe, 1854; Bielschowsky, 1900; Travers, 1938; Jampolsky, 1955; Lang, 1971). In the case of microstrabismus, which is defined as a convergent squint less than 6° (Lang, 1968), the central part of the visual field of the misaligned eye is suppressed. The sensitivity in other parts of the retina may remain normal (Sireteanu & Fronius, 1981).

Suppression is maximal under daily viewing conditions. To activate suppression the images need to be identical (Jampolsky, 1955; Pratt-Johnson, 1976; Schor, 1977): Suppression is reduced when there is some form of dissimilarity between the images for both eyes (Jampolsky, 1955; Bagolini, 1976; Schor, 1977). However, some dissimilarity is needed when suppression is to be measured in an experimental study (Jampolsky, 1955), otherwise the images for the right- and left-eye cannot be distinguished. This is an intrinsic problem in the experiments described below: The images must be similar for interocular interactions to occur, but dissimilar for the observer to be able to recognize which image is seen by which eye.

Schor (1977) examined the influence of stimulus orientation and spatial frequency upon binocular rivalry in normals and strabismics. He used $2\frac{1}{2}°$ circular fields. He used stimuli consisting of gratings of different orientations for the left- and right-eye (10°, 22.5°, 45°and 90°). These stimuli were presented for 60 s and subjects were asked to report whether they saw the left or the right grating or both gratings at the same time. He found more suppression with smaller orientation differences.

De Belsunce and Sireteanu (1991) used horizontal and vertical gratings with a field size of 5.8°. They found in normals that, with exposure times of less than 150 ms, superimposition of the orthogonal gratings occurred,

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rivalry begins after 150 ms and is complete at 1000 ms. In amblyopic subjects they found primarily that suppression was more likely to occur at longer exposure times.

Holopigian, Blake, and Greenwald (1988) examined the relation between the depth of suppression and the degree of amblyopia. Subjects viewed a horizontal grating with the squinting eye and horizontal or vertical gratings with the dominant eye, continuously. A contrast increment was added for 200 ms to the upper or lower half of the grating presented to the squinting eye. They found that in strabismic subjects there was hardly any difference in the depth of suppression for identical and orthogonal gratings and they found suppression to vary widely among the strabismic subjects.

In order to resolve the prior controversies and to quantify any relationship between suppression and similarity, we reexamined the issue. In the experiments described below, we measured the depth of suppression at different degrees of dissimilarity between the images for the left- and right-eye. We tried to approach daily viewing conditions as much as possible, since that is known to enhance suppression.

2. Methods

Two screens of 91 × 100 cm (42.3° × 45°) with identical colorful cartoon pictures of 93 × 62 cm (42.9° × 31.8°) were used. The screens were placed facing each other at a distance of 191 cm with two oblique-view mirrors halfway between them. The mirrors were positioned at an angle of 45° towards the screens and towards the subject, and at 90° relative to each other (Fig. 1). Approximately 1.5 m above the mirrors was a 75 W lamp to assure equal illumination of the screens, resulting in a mean luminance of the screens of 6 cd/m^2.

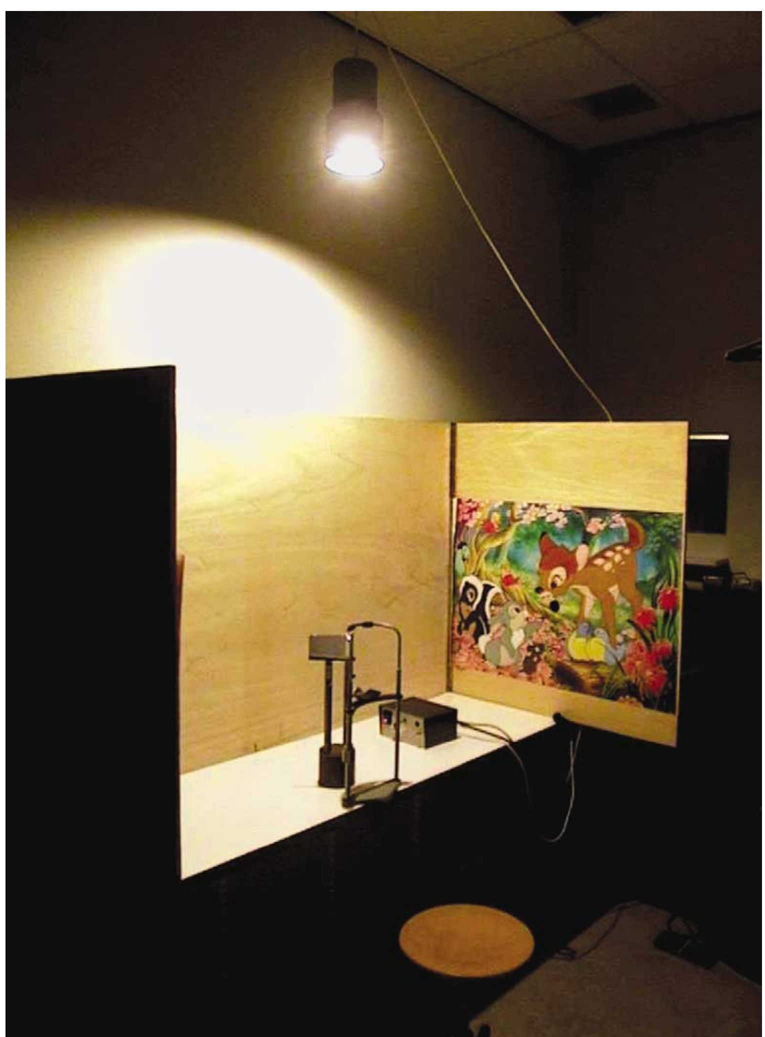

Fig. 1. Two screens with identical contrast- and colorful pictures were placed facing each other with two oblique-view mirrors halfway between them. Note the apparatus with a button for switching the two halogen lamps on for 300 ms.

In the middle of each screen was a circular aperture with a diameter of 35 mm (subtending 2° in the visual field) through which the test images were presented. These images were printed on a polyester transparent.

Joosse, Simonsz, Spekreijse, Mulder, and van Minderhout (2000) found 400 ms to be the optimal stimulus duration and that stimuli with a gradual increment and decrement were most suited to elicit suppression.

Accordingly, two halogen lamps were positioned behind the two images and were switched on for 300 ms when the subject pushed a button. Between the halogen lamp and the image presented (circle, square or a shape in between) was an opal glass. The lamps produced a maximal luminance of approximately 200 cd/m^2 of the opal glass. The light had a gradual on- and offset, however, so that the 200 cd/m^2 was only reached after 100 ms and lasted for about 100 ms. After being switched off, the luminance dropped to zero in approximately 100 ms (Fig. 2).

The subject sat in front of the mirrors with his chin in a chin rest. The subject was asked to position the mirrors horizontally and vertically so that he would fuse both pictures in the peripheral visual field with anomalous retinal correspondence (ARC). ARC is a compensation mechanism that occurs in small-angle convergent strabismus, whereby part of the objective angle of strabismus is compensated sensorically in the brain. It allows fusion of the images of both eyes outside the suppression scotoma. Hence, the mirrors were positioned by the subjects according to their subjective angle of deviation and single vision was obtained. The subjects fixated the aperture with the dominant eye. In the squinting eye, the image was projected into the nasal parafoveal region, the 'fixation point'. Since the suppression scotoma is expected to be approximately centered on the fixation point (Joosse et al., 1997), the aperture with the test images was projected in the scotoma of the squinting eye.

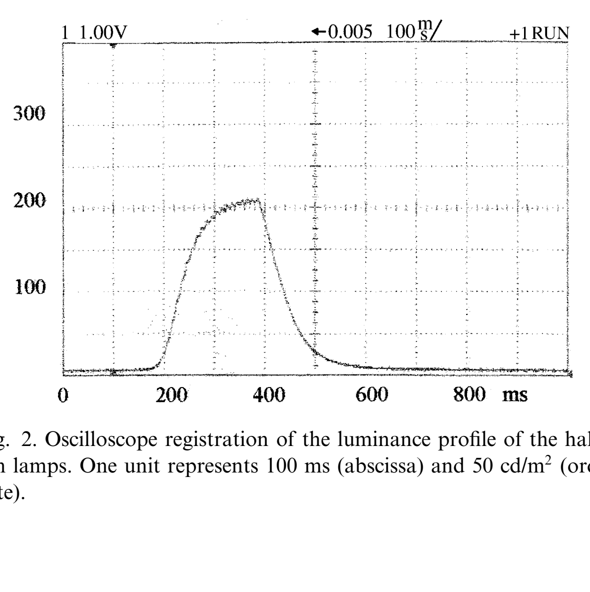

Fig. 2. Oscilloscope registration of the luminance profile of the halogen lamps. One unit represents 100 ms (abscissa) and 50 cd/m^2 (ordinate).

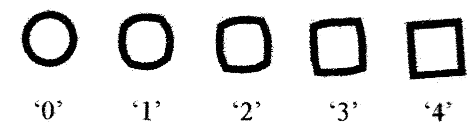

Fig. 3. The images presented to the controls and strabismics.

The images were produced with CorelDraw 3.0: A circle was transformed in four steps into a square, hence producing five images. The three transitional states (circle > square) thus consisted of a square with curved sides and curved corners. The five images were numbered: the circle was designated number '0', the square was designated number '4', the transitional images were given number '1'–'3', starting with the image that looked most like the circle (Fig. 3). The outer diameter of these images was 21 mm (subtending 1.2° of visual angle), the inner diameter was 15 mm (subtending 0.89° of visual angle).

One eye was presented a circle; the images 1–4 were presented to the other eye. The dissimilarity between the images for both eyes was marked as '0/1' (one eye viewed a circle, the other eye viewed image 1), '0/2' (one eye viewed a circle, the other eye viewed image 2), '0/3' (one eye viewed a circle, the other eye viewed image 3) and '0/4' (one eye viewed a circle, the other eye viewed a square) respectively. The subjects were asked whether they perceived one of the following conditions: one of both images seen, both images fused into one image (a distorted circle) and both images seen in separation.

In strabismic subjects the circle was presented to the dominant eye in all experiments.

At the start of each measurement, the images were equally luminant for both eyes. If the strabismic subject only saw the image for the dominant eye (always a circle) and thus suppressed the image for the deviating eye, the image for the dominant eye was darkened with neutral density filters in successive steps (LEE filters number 209: step width was log 0.301 neutral density, one filter let half of the light pass through) until both images were perceived. Accordingly, the subject would see a perfect circle change into a distorted circle or into two images. We then increased the light intensity until the image for the deviating eye was suppressed again.

In the control experiments the conditions and the protocol were the same but, whereas the strabismics initially suppressed the image for the deviating eye, the controls initially saw double: they fused the images into a distorted circle or they saw two images behind each other. Hence, in strabismics the appearance of binocular vision was recorded, whereas in controls the disappearance of binocular vision was recorded. In some controls, luminance was increased again until diplopia reappeared. That threshold did not significantly differ from the threshold of disappearance. In controls, instead of the circle the other image was attenuated, because the transition from a distorted circle to a perfect circle was more easily noted by the controls.

3. Subjects

Five controls (visual acuity at least 1.0 in both eyes, at least 60″ stereopsis) and six subjects with a convergent strabismus (maximum 6°) participated. All subjects underwent an orthoptic examination, consisting of refraction, visual acuity, angle of deviation, fixation, stereopsis (Titmus Fly) and Bagolini striated glasses test (Table 1). The subjects were asked to wear their corrective glasses, if necessary.

The findings in six subjects are described. One additional subject was excluded from the analysis, because the visual acuity of his squinting amblyopic eye was only 0.1, making it very difficult for him to discern the shape of the perceived object with the amblyopic eye. After attenuation of the stimulus for the dominant eye he saw the second image, however this image was projected above and left of the aperture instead of within the aperture. He needed much attenuation of the image for the dominant eye at all levels of dissimilarity.

4. Results

4.1. Control subjects

Without neutral density filters all controls perceived both images. In most cases they saw one image (a fused image: a distorted circle). They sometimes stated having difficulties differentiating between seeing one (a distorted circle, sometimes with perception of depth) or two images (with a depth-effect: the images were seen behind each other). By attenuating the stimulus for one eye with neutral density filters, the image for this eye disappeared and a monocular percept was obtained. No relation was found between the attenuation of the image and the dissimilarity of the images (Fig. 4). No difference was found between attenuating the image for the left-eye or attenuating the image for the right-eye, except may be in dissimilarity 0/1 where the image for the right-eye in most cases needed much more attenuation. The eyes were tested in random order.

One of the controls reported to see the transitional form first, then a fusion image, after which the transitional image was the first to disappear.

4.2. Strabismic subjects

Without neutral density filters all subjects suppressed the image for the squinting eye when the dissimilarity between the left- and right-image was small. In all subjects the amount of attenuation of the stimulus for the

Table 1
Characteristics of the subjects, with orthoptic examination

Subject	Sex	Age (y)	Diagnoses	Eye	Refraction	v.a.	Fixation	Hor. angle	Bagolini	Titmus fly	Observations
1	F	21	L microstrabismus	R	+0.25	1.0	Central		L central	Negative	Occlusion therapy; glasses at 2–12 y
			Anisohypermetropia	L	+4.50	0.8	Central	+2°	Suppression		
2	F	32	L microstrabismus	R	+0.50	1.0	Central		Alternating	Negative	Surgery at 4 & 21 y for exotropia, at 23 y for esotropia; occlusion therapy; contact lenses since 24 y
				L	+0.50	0.7	Central	+2°L/R 3°			
3	F	25	L microstrabismus	R	−0.25 = −0.50/160°	1.0	Central		L central	Negative	Occlusion therapy; glasses at 4–8 y
			Anisometropia	L	+0.50	0.6	Nasal above	+3°	Suppression		
4	M	35	R microstrabismus	R	−2.00 = −0.25/5°	1.2	Central	+4°(near 6°)	R central	Negative	Occlusion therapy; glasses since 16 y
				L	−2.50	1.2	Central		Suppression		
5	M	17	L microstrabismus	R	+2.50	1.0	Central		L central	Positive	Occlusion therapy; glasses at 6–14 y
			Anisohypermetropia	L	+3.50	0.8	±2° nasal	+3°	Suppression		
6	F	22	R microstrabismus	R	−0.75 = −0.50/155°	1.0	Central	+5°(near 6°)	R partial	Negative	Surgery at 2 y; occlusion therapy; glasses since 4 y
				L	−0.25 = −1.00/50°	1.2	Central		Suppression		

'F' denotes female, 'M' denotes male, 'R' denotes right-eye, 'L' denotes left-eye, 'v.a.' denotes visual acuity, 'hor. angle' denotes manifest horizontal angle of deviation determined with the prism-cover test, 'y' denotes age (in years), 'fixation' denotes fixation determined with funduscopy, 'Bagolini' denotes the Bagolini striated glasses test, 'refraction' denotes determination of the refraction with skiascopy or with the refractometer.

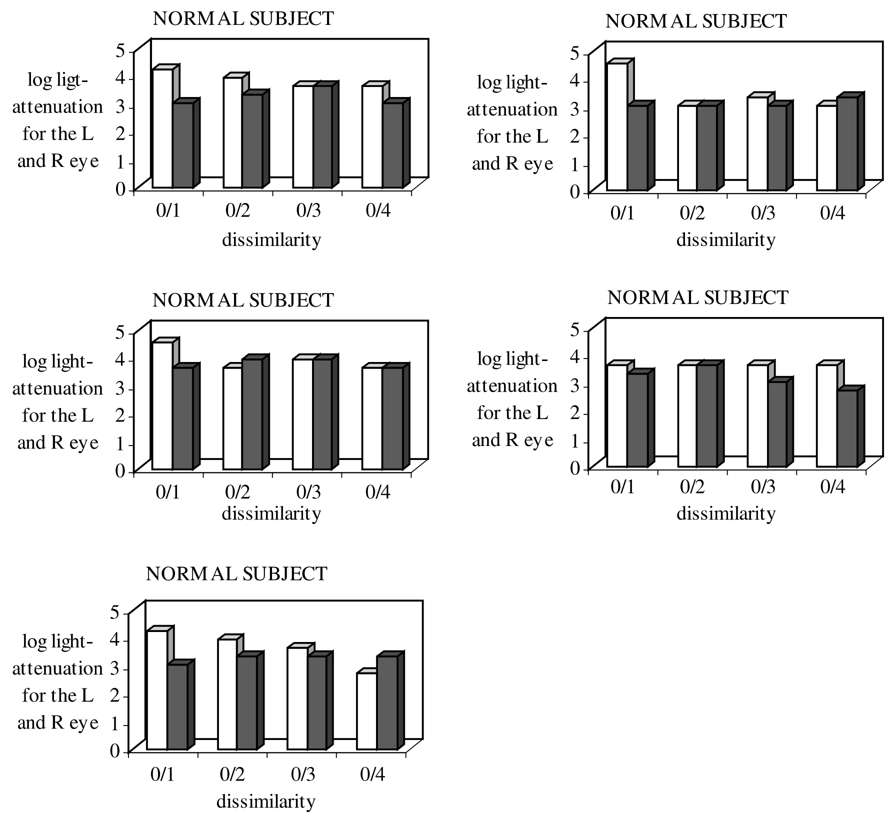

Fig. 4. Thresholds of attenuation of the light intensity of the image for the right- or left-eye, to reach a monocular percept, in controls. Ordinate: Log light-attenuation of the stimulus for the left- (dark columns) and right- (light columns) eye needed to reach a monocular percept. Abscissa: '0/1', '0/2', '0/3' and '0/4' denote different degrees of dissimilarity between the images for the left- and right-eye. In dissimilarity '0/1' the difference between the images of the left and right-eye is smallest, '0/4' corresponds to one eye seeing a circle and the other eye seeing a square. Apparently, in controls the perception of two images, whether in the form of diplopia or in the form of fusion, does not depend on the degree of dissimilarity.

dominant eye needed to eliminate suppression decreased with increasing dissimilarity. The amount of suppression differed markedly between the subjects (Fig. 5). In contrast to the controls, they did not report difficulties differentiating between seeing one fused image (a distorted circle) or two images. In the latter case, the strabismic subjects 1–4 and 6 experienced a depth–effect like the controls, although they had no stereopsis in conventional orthoptic testing. The only subject, who did have some stereopsis, subject 5 (Titmus Fly positive), could always fuse both images.

With dissimilarity 0/1, subject 4 saw the second image after attenuation of the stimulus for the dominant eye. When the light intensity increased again, he kept on seeing both images, even when the light intensity for both eyes was made equal. So suppression sometimes did not recur, probably because attention for the second image breaks suppression. With larger dissimilarities he always saw both images. In subject 5 the same phenomenon occurred with dissimilarities 0/3 and 0/4.

Usually, strabismics were able to fuse both images into one distorted image when the image for the squinting eye was perceived after attenuating the image for the dominant eye in successive steps. Most controls were able to fuse the images into one distorted image when both images were perceived. Occasionally however, strabismics and controls stated that they saw both images behind each other. Some of the controls had difficulty noting the difference between these two conditions, but it seems unlikely that these difficulties influenced the level of attenuation needed to obtain a monocular percept.

5. Discussion

It is a clinical finding that suppression as a consequence of microstrabismus is maximal under normal daily viewing conditions (Bagolini, 1976). In our study, we confirmed that the depth of strabismic suppression depends upon the similarity between the images for the left- and right-eye. In each of the measurements in strabismic subjects, the luminance of the circle presented to the normal eye was decreased in successive steps, and the transitional image or the square presented to the squinting eye was detected earlier when the two images were less similar.

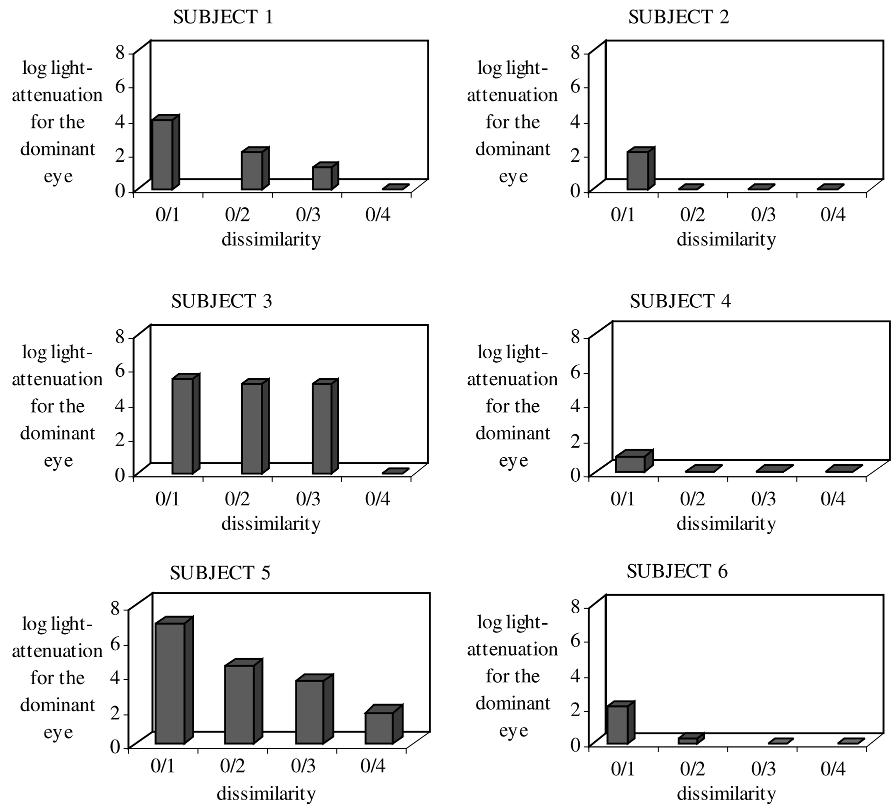

Fig. 5. Thresholds of attenuation of the light intensity of the image for the dominant eye, to elicit simultaneous perception in strabismic subjects. Ordinate: Log light-attenuation of the stimulus for the dominant eye needed to reach diplopia or fusion. Abscissa: '0/1', '0/2', '0/3' and '0/4' denote different degrees of dissimilarity between the images for the left- and right-eye. In dissimilarity '0/1' the difference between the images of the left- and right-eye is smallest, '0/4' corresponds to one eye seeing a circle and the other eye seeing a square. Apparently, in strabismics, suppression does depend on the degree of dissimilarity. In some cases the strabismic subjects perceived diplopia at threshold luminance with some form of depth: The two images appeared behind each other. Subjects 1, 2, 4 and 6 reported seeing a distorted circle at threshold luminance, indicating fusion, at some degrees of dissimilarity, whereas subject 5 (the only patient with Titmus Fly positive) reported seeing a distorted circle at threshold luminance at all degrees of dissimilarity.

A relation between similarity and suppression was found previously by Schor (1977), but not by Holopigian et al. (1988) and by Holopigian (1989). This discrepancy in findings may have been caused by differences in experimental setup, differences in duration of presentation of the stimuli, differences in size of the stimuli and differences in the diagnoses of the patients. In our experiments, subjects with microstrabismus fused identical, colorful cartoon pictures with most of the visual fields of both eyes, sparing only the central 2° where the test images were presented, before, during and after the 300 ms test period. Hence, the peripheral visual field was fused with ARC (present in all patients), while the center of the visual field of the squinting eye was suppressed.

In the studies by Holopigian et al. (1988) and by Holopigian (1989), the suppressed eye viewed a horizontal grating and the dominant eye viewed either a horizontal or vertical (Holopigian et al., 1988), or just a vertical (Holopigian, 1989) grating continuously, while a contrast increment was added to the upper or lower half of the grating presented to the amblyopic eye for 200 ms. When both eyes viewed a horizontal grating, the two images were labeled by two black spots above or below the center. The subjects were instructed to start the 200 ms presentation when they only saw the grating or the spot presented to the dominant eye, in other words, the 200 ms test period followed a period of rivalry.

Our subjects had microstrabismus with no more than a positive Bagolini test, only one had Titmus Fly positive, whereas five of the nine subjects in the study by Holopigian et al. (1988) had 50″, 50″, 100″, 140″ and 400″ stereopsis disparity threshold and the subjects studied by Schor (1977) all had normal retinal correspondence.

These are basic differences in experimental setup, and these differences could account for the discrepancies between results.

Our working hypothesis was that, for strabismic suppression to occur, the similarity of images has to be detected. This is in accordance with the general principle formulated by Bagolini (1976) and others and is demonstrated, for instance, with Bagolini's striated-glasses. If strabismic suppression occurs only if similarity is detected, two mechanisms must be at work, a 'similarity detector' and a 'suppressor'. The 'similarity detector' may be related to the disparity detector for fusion and stereopsis. This is not necessarily a purely binocular function, it may well detect similarities between objects seen monocularly: Kovács, Papathomas, Yang, and Felér (1996) performed a variation of the standard rivalry experiment, presenting 'scrambled' images to both eyes. They found that binocular rivalry can also be driven by pattern coherency, not only by eye of origin.

Where could the 'suppressor' and the 'similarity detector' be located? In a fMRI study, Lumer, Friston, and Rees (1998) found increased activity in the early visual centers during stereopsis, but rivalry caused increased activity in the lateral extrastriate and frontoparietal cortex.

In the lateral occipital complex, object shape is represented independent of the particular visual features like luminance, motion, texture or stereoscopic depth cues, that define that shape (Grill-Spector, Kushnir, Edelman, Itzchak, & Malach, 1998). These representations are largely invariant to changes in size or location (Grill-Spector et al., 1999). Kourtzi and Kanwisher (2001) found maximal adaptation in the lateral occipital complex when two images presented successively had identical shapes and different contours, but minimal adaptation when they had different perceived shapes and identical contours. Apparently, similarity of shape is detected in the lateral occipital complex, possibly guiding strabismic suppression.

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