The influence of cyclovergence on unconstrained stereoscopic matching

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Abstract

In order to perceive depth from binocular disparities the visual system has to identify matching features of the two retinal images. Normally, the assigned disparity is unambiguously determined by monocularly visible matching constraints. The assigned disparity is ambiguous when matching is unconstrained, such as when we view an isolated long oblique disparate line. Recently we found that in order to perceive a depth probe at the same depth as the oblique line, the probe needs to have the same horizontal disparity as the line (i.e. matching occurs along horizontal "search-zones" [Vis. Res. 40 (2000) 151]). Here we examined whether the depth probe disparity in unconstrained matching of long lines is influenced by cyclovergence, by cyclorotation between stereogram half-images, or by combinations of the two. We measured retinal rotation (>6 deg in cyclovergence conditions). We found that in those conditions in which the retinal images were the same (a condition with, say, both zero cyclovergence and zero cyclorotation between the half-images, creates the same retinal images as a condition with both 6 deg cyclovergence and 6 deg cyclorotation) assigned depth was the same too, i.e. independent of cyclovergence. Thus, the assigned depth of the test-line seems to be determined solely by the retinal test-line orientation, implying that the binocular matching algorithm does not seem to incorporate the eyes' cyclovergence when matching is unconstrained.
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1. Introduction

In stereoscopic vision the two retinae receive slightly different two-dimensional (2D) images of a visual scene. The three-dimensional (3D) lay-out of a scene is recovered from the spatial differences between the two retinal images. These spatial differences are called binocular disparities. The computation of disparities depends upon the correct identification of corresponding features in the two eyes' images (e.g. Julesz, 1971; see also Fig. 1). This identification process is commonly referred to as the *matching problem* and the features of the two eyes' images that are identified as corresponding are called *matching primitives* (for recent reviews see for instance Howard & Rogers, 2002 or Schor, 1999). Understanding what algorithms are used by the brain to solve the

matching problem is one of the main issues in the field of human stereoscopic vision. In artificial vision, too, it is of great interest to find efficient algorithms to describe the matching of the images of two cameras (e.g. Deriche, Zhang, Luong, & Faugeras, 1994; Faugeras, 1993). In fact, one potentially very efficient constraint on binocular matching found its origin in artificial vision—the epi-polar constraint (Faugeras, 1993; Koenderink, 1992; Prazdny, 1983).

1.1. The epi-polar constraint

The epi-polar constraint reduces the search for matching primitives to a one-dimensional problem and results in an enormous reduction in the computations required: corresponding points are confined to narrow bands, called epi-polar lines. To understand the impending analyses it will be useful to understand that a retinal epi-polar line belonging to a target in 3D-space is

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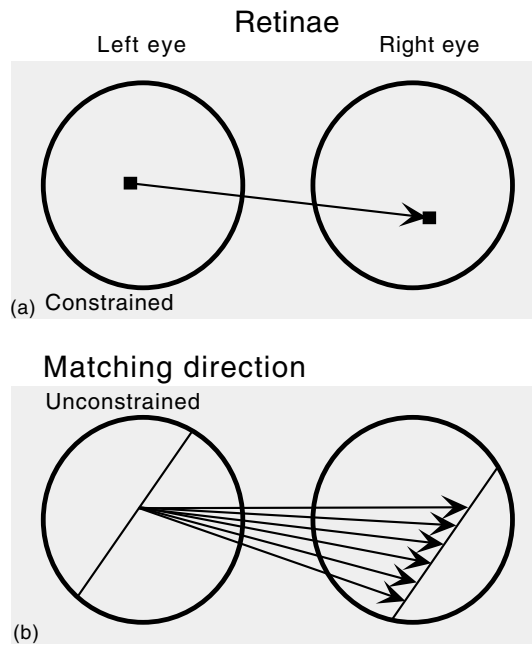
Retinae

Fig. 1. The identification of corresponding points in the two eyes' retinas is straightforward when monocularly visible constraints are present. Matching is then unambiguous (a). When there are no monocular constraints, such as is the case with long lines, matching is ambiguous (b). Each of the vectors in panel b represents a matching meridian along which matching can take place.

in fact the intersection line of the retina and the plane through the target and the inter-ocular axis. [1]

Nielsen and Poggio (1984) examined tolerance to vertical disparity for binocular matching and concluded that the human visual system employs the epi-polar constraint. [2] They used foveal viewing and 1 deg diameter stereograms that were flashed for 117 ms. The authors reported that vertical disparity is tolerated up to only 3.5 arcmin without monocular cues, and up to about 6.5 arcmin with these cues. Prazdny (1985, 1987) reported that the tolerance to vertical disparity in random dot stereograms (viewed without fixation limitation) is about 10 arcmin for stimuli that subtended 8 deg. Stevenson and Schor used relatively large centrally viewed dynamic random dot stimuli that were presented for 200 ms. They reported that tolerance to vertical disparity increases with display size and found that this

tolerance is on average about 30 arcmin for a 12 by 12 deg stimulus (Stevenson & Schor, 1997). In yet another study, using a 3 deg diameter patch, tolerance to vertical disparity was found to be about 20 arcmin (Adams, 1998). In sum, using a variety of stimuli it has now been demonstrated that binocular matching is not strictly constrained to narrow epi-polar lines.

1.2. The posture of the eyes

Up to this point we have not addressed the viewing geometry of the retinae relative to the epi-polar lines: when the eyes change their fixation point in space, the epi-polar lines migrate on the retina (Fig. 2). Thus, even although the search for matching primitives is restricted to horizontal bands, the visual system must know the eyes' posture in order to take advantage of this restriction. It is therefore of fundamental interest to ask whether the binocular matching process takes vergence (Adams, 1998; Rogers & Bradshaw, 1996) and cyclovergence [3] (Schreiber, Crawford, Fetter, & Tweed, 2001) into account.

In the first study on this issue (Rogers & Bradshaw, 1996), the vergence state of the eyes was manipulated in order to simulate a range of viewing distances from 28 cm to infinity. The authors did not find a significant effect of simulated viewing distance on binocular matching but eye posture was not measured. Adams (1998) attempted to manipulate information about the eyes' posture in two experiments. In the first experiment she altered the global vertical disparities to simulate different viewing distances. This manipulation failed to show significant effects on binocular matching. In the second experiment she varied the distance between the head and the stimulus, thereby producing vergence variations. This did produce large effects on binocular matching. She concluded, "that the visual system is exploiting the epi-polar constraint, in a weak form; matches are not strictly confined to one dimension but the regions over which matches are accepted are dependent upon prevailing viewing geometry. Changes in gaze angle are accompanied by a shift in the fusional area such that it remains centred upon the epi-polar line". In this study, too, eye posture was not measured.

Very recently, a specially designed paradigm has been utilized to examine whether the visual system takes cyclovergence into account in the matching process (Schreiber et al., 2001). The paradigm is based upon the following insights. When a human observer looks down while converging, the eyes incycloverge. When an observer looks up while converging, the eyes excycloverge.

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[1] Epi-polar geometry is based on the general class of bicentric perspective geometries (Koenderink, 1992): corresponding points of a target in 3D-space should always reside in one single epi-polar plane.
[2] The vertical tolerance to disparity for binocular fusion was described by Ogle (1950). The horizontal and vertical tolerance was described by Tyler (1975) and their dynamics by Schor and Tyler (1980). These studiers were primarily interested in disparity limits for fusion and used unambiguous matching features. We are primarily interested in the stimulus locations that become matched from the multitude of possible locations that can be fused in ambiguous matching stimuli.

[3] Opposed torsional rotation about the line of sight. Incyclovergence means that the vertical meridians rotate top in; excyclovergence means that the vertical meridians rotate top out.

Screen
Viewed images

Retinae

Left eye   Right eye   Superimposed

Screen
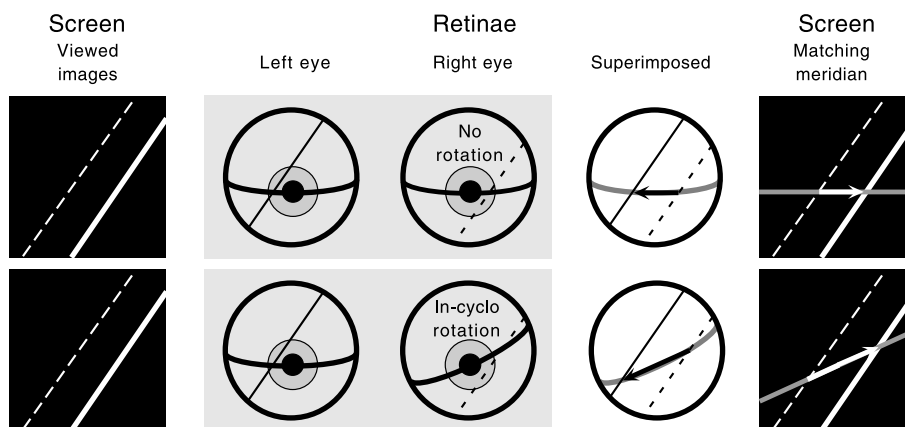Matching meridian

No rotation

In-cyclo rotation

Fig. 2. Epi-polar lines migrate on the retinae when the eyes' posture changes. In both the top and the bottom row the two eyes view the same disparate test-line on the screen. The dashed white line represents the right eye's image of the test-line. The other white line represents the left eye's image. In the top row the right eye's cyclorotation is zero. A horizontal epi-polar line on the right retina is cast on the screen as a horizontal meridian. In the bottom row the right eye is incyclorotated. In the lower situation the same epi-polar line on the right retina has migrated and therefore the matching meridian on the screen is rotated.

If the binocular matching algorithm compensates for eye posture, this cyclovergence should make no difference; but if the matching algorithm does not compensate for eye posture, fusion of incyclorotated stereogram half-images should be improved when the observer looks down, and fusion of excyclorotated stereograms half-images should be improved when the observer looks up. Schreiber et al. constructed random dot stereograms incorporating a hidden arrow that became visible only after correct fusion: the arrow could be fused only in downgaze (or in upgaze) when there was incyclorotation (or excyclorotation) between the two stereogram half-images. The authors measured eye posture and concluded that "the stereo-matching algorithm does not know where it is looking, and therefore does not move its search zones on the retinae when the eyes move; instead it uses eye-fixed search zones".

1.3. Unconstrained matching

So far in this introduction, our discussion of the literature has been restricted to unambiguous matching. Indeed, most natural images contain unambiguous matching primitives that are monocularly visible. When we view relatively short lines with clearly visible endpoints, the identification of corresponding points is unambiguous (Mitchison & McKee, 1985; van Ee & Schor, 2000). Matching of long oblique lines (Fig. 1b) is, however, highly ambiguous (Arditi, Kaufman, & Movshon, 1981; Blake, Camisa, & Antoinetti, 1976; Ebenholtz & Walchli, 1965; Ogle, 1950, Chap. 19; van Ee & Schor, 2000). There are no features that can guide the matching process if the retinal projections of the end points of the line are so eccentric that the peripheral visibility is insufficient to define a disparity between the end points of the lines. Theoretically speaking, there are an infinite number of possible matches between an indefinitely long

line in the left eye and a disparate retinal image of the line in the right eye (Fig. 1b). In fact we are dealing here with an aperture problem in stereoscopic vision (e.g. Morgan & Castet, 1997; Tyler, 1980). We will describe such a matching process as *unconstrained*. Unconstrained conditions do not often occur in daily circumstances. However, matching in ambiguous unconstrained cases informs us about the direction of the default matching meridian. This is a measure that should be explained by a complete model of binocular matching.

The finding that the stereo-matching algorithm does not know where the eyes are looking when constrained matching stimuli are employed (Schreiber et al., 2001) does not necessarily mean that it does not use cyclovergence with unconstrained matching stimuli. In unconstrained matching there is an extra ambiguity (matching direction) that is not present in constrained matching. In addition, from several studies it is known that the eyes' posture, in particular vergence and version, can be used for depth perception in situations where other cues are less informative (Backus, Banks, van Ee, & Crowell, 1999; Rogers & Bradshaw, 1995). The same might be true for matching: in those situations where there is complete ambiguity, the visual system might be able to incorporate the cyclovergence state. Also, the described novel finding of Schreiber et al. has not been replicated by any other independent evidence and it is interesting to ask if this important conclusion can be replicated for unconstrained matching.

van Ee and Schor (2000) developed an experimental method for examining binocular matching in situations where the stimulus does not impose monocular constraints. In their method observers are presented with an indefinitely long oblique line that provides no monocular cues for binocular matching. The horizontal disparity of a depth probe is then varied until the observer perceives it at the same depth as the line. The depth

probe method is based on the assumption that the disparity of the probe indicates the meridian along which the corresponding points of the disparate lines are defined, because the horizontal disparity of both the depth probe and the line must be identical to each other if they are perceived at the same depth (this assumption has explicitly been tested by van Ee and Schor using short lines and vertical disparities).

If matching is unconstrained, as is the case with long lines, the visual system could select a matching meridian from the entire set of possible matching meridians (Fig. 1b) within a horizontal search zone. Some tolerance for vertical disparity is necessary to accommodate vertical ocular misalignment, torsional misalignment, geometric perspective distortions of retinal images formed of near objects and to allow for anatomical differences in the retinal curvature of the two eyes. The default match in unconstrained matching is determined by the operating range of matchable horizontal and vertical disparities. This operating range could be regarded as being analogous to the 2D disparity range of Panum's area for fusion. [4] Van Ee and Schor computed the operating range of vertical matches that best fitted their data. They found that (1) the two-dimensional operating range is anisotropic for vertical and horizontal disparity and that (2) unconstrained matches are not based upon either epi-polar geometry or nearest neighbour constraints (they depend upon the mean of disparity estimates within the operating range for binocular matches). The authors developed a model for binocular unconstrained matching and according to their model the operating range of matchable vertical disparities is about 10 arcmin. [5] Note that this operating range can be extended vertically when matches are constrained by monocularly visible features (Stevenson & Schor, 1997).

Van Ee and Schor's method seems to be a powerful method for examining whether eye posture is taken into account in binocular matching in situations where no constraints are imposed by the stimulus. Adams and Banks (2000) used the method to measure matching of peripherally presented long lines while they manipulated the eyes' vergence and version. In the three subjects tested they found little effect of these manipulations (Adams, personal communication).

1.4. Aim of current study

Here we examined whether the depth probe disparity in unconstrained matching of long lines is influenced by cyclovergence, by cyclorotation between stereogram half-images, or by combinations of the two.

What is the disparity defined along a rotated matching meridian for the general class of oblique disparate test-lines? Consider a test-line of which the half-images have a nominal disparity δ (horizontal shift on the screen) and an angle ϕ relative to the horizontal. In this analysis we will refer to the angle between the matching meridian and the horizontal (the interocular axis) as angle α. We can find corresponding points along the rotated meridian by performing two steps. [6] Consider Fig. 3a. First, start a vector

$$\lambda \begin{pmatrix} \cos \alpha \\ \sin \alpha \end{pmatrix}$$

somewhere on the right eye's image of the test-line with angle ϕ (λ is a constant). Second, let this vector intersect the other half-image of the disparate test-line

$$\begin{pmatrix} \delta \\ 0 \end{pmatrix} + \gamma \begin{pmatrix} \cos \phi \\ \sin \phi \end{pmatrix},$$

with γ being a constant. Thus:

$$\lambda \begin{pmatrix} \cos \alpha \\ \sin \alpha \end{pmatrix} = \begin{pmatrix} \delta \\ 0 \end{pmatrix} + \gamma \begin{pmatrix} \cos \phi \\ \sin \phi \end{pmatrix}.$$

After substituting $\gamma = \lambda(\sin \alpha / \sin \phi)$, an expression for λ follows: $\lambda = \delta \sin \phi / (\sin(\phi - \alpha))$. The intersection point expressed in α and ϕ is:

$$\left(\delta + \frac{\delta \sin \alpha \cos \phi}{\sin(\phi - \alpha)}, \frac{\delta \sin \alpha \sin \phi}{\sin(\phi - \alpha)} \right).$$

The difference $(d\delta)$ between the horizontal disparity of the match along the rotated meridian and the match along the horizontal is:

$$d\delta = \frac{\delta \sin \alpha \cos \phi}{\sin(\phi - \alpha)}. \tag{1}$$

Expressed in words this equation means that the differential disparity $d\delta$ is linearly related to the nominal disparity δ. In addition, $d\delta$ increases when the test line angle ϕ decreases and $d\delta$ increases when the rotation α increases. For positive ϕ, α needs to be positive and smaller than ϕ (to ensure that the denominator is positive and small). Panel b of Fig. 3 demonstrates how $d\delta$ varies as a function of α (for a family of positive ϕs). Below we will explain panel b in more detail; at this point it is of primary interest to notice that (when ϕ is positive) a particular absolute value of $d\delta$, say 3 arcmin,

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[4] We stress that retinal correspondence does not change if the eye's posture is taken into account in determining the direction of the matching meridian (Hillis & Banks, 2001).

[5] This vertical range is approximately 1/6 the range of horizontal disparity that can be used to process static stereoscopic depth (Schor, Wood, & Ogawa, 1984) and 1/24 of the horizontal disparity range for dynamic stereoscopic depth (Richards & Kaye, 1974). During steady fixation the variability in cyclotorsion between the eyes is in the order of 5–10 arcmin (Enright, 1990; van Rijn, van der Steen, & Collewijn, 1994).

[6] Throughout this paper, Helmholtz coordinates are used (as opposed to rotation vectors) when referring to cyclovergence angles.
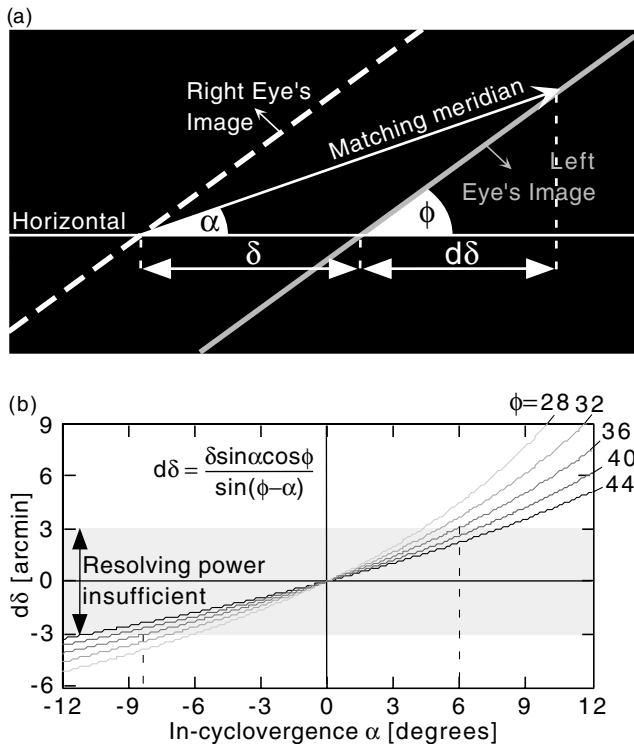
Fig. 3. (a) Definition of the variables used in the predictions. δ is the nominal horizontal disparity between the two stereogram half-images of the test-line. The orientation of the test-line with the horizontal is ϕ. α is the angle of the matching meridian. $d\delta$ is the incremental horizontal screen disparity of the match when the match is defined along the rotated meridian. (b) $d\delta$ as a function of incyclovergence α for a family of ϕ ranging from 28–44 deg. The grey area represents the domain in which the resolving power of our set-up is insufficient to measure $d\delta$. According to this calculation, for a ϕ of 36 deg one needs either 6.0 deg of incyclovergence or 8.3 deg of excyclovergence to ensure that a change in $d\delta$ is measurable.

is created by either a 6.0 deg or a -8.3 deg rotation (α) of the matching meridian. To create significant differential disparity it therefore seems to be more effective to use positive rather than negative rotation. As we will see in the discussion that follows, the fusional capacities of human binocular vision constrain the parameters α, ϕ and δ. Other constraints on parameters are imposed by technical limitations of the experimental set-up described in the following section.

2. General methods

We use a *depth probe* procedure (Mitchison & McKee, 1985; Richards, 1971; van Ee & Schor, 2000) [7] to systematically examine the horizontal disparity that is

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[7] Richards (1971, 1972) used a physical probe, seen with free eye movements, in order to estimate the apparent distance of a bar as it appeared to move in and out through the fixation plane. The probe was a one-cm-diameter disk and was carried by glider on a rail. The glider could be moved manually by the subject.

consistent with the match preferred by the visual system when matching is unconstrained. The rationale of the depth probe method as we use it is based on the assumption that the horizontal disparity of both the depth probe and the line are identical when they are perceived at the same depth. In previous research (van Ee & Schor, 2000) this assumption was validated explicitly (by using short line lengths as well as vertical probe shifts) in a set-up that resembles the one we use in the current study.

To understand in more detail how we use the depth probe in measuring the matching of unconstrained lines, consider again one indefinitely long diagonal test-line displayed on a screen by means of an anaglyphic (red–green) stereogram in an otherwise dark room. Suppose that the test-line is perceived either in front or behind the screen. In other words, there is a horizontal disparity (a horizontal shift on the screen) between the test-line's red and green half-images. The magnitude of the effective horizontal disparity—which is the disparity used by the brain to determine the perceived depth—will depend upon the meridian of the match. Now consider a probe consisting of a single dot that is presented on the screen at a short lateral distance from the test-line (see Fig. 4b). Assume that the probe is perceived at the same depth as the test-line. If the visual system's default match of the red and green test-line half-images is in the horizontal meridian, then the horizontal disparity of the probe will equal the horizontal shift of the test-line. However, if the default match is in any other meridian (e.g. the nearest neighbour), the horizontal disparity of the probe match will differ from the horizontal shift between the red and green test-line half-images.

We will make use of a staircase procedure to determine the horizontal disparity between the probe's stereogram half-images that is needed to perceive the probe at the same depth as the test-line. The location of the probe in the right eye's half-image remains the same but its location in the left eye's half-image varies in the horizontal direction (depending on the subject's response in the staircase). Five subjects took part. They had normal or corrected-to-normal vision and they participated in a recently developed stereo test (van Ee & Richards, 2002).

2.1. Apparatus

The stimuli were presented dichoptically in the form of stereograms. Observers viewed these stereograms that were rear-projected onto a large flat screen (62×51 deg), at a fixed viewing distance of 200 cm. Pixels subtended 3×3 arcmin. The stereograms were presented to the two eyes using the standard red–green anaglyph technique. The intensities of the red and green stereogram half-images were adjusted until they appeared equally bright when viewed through the red and green filters placed before the eyes. There was no visible crosstalk between

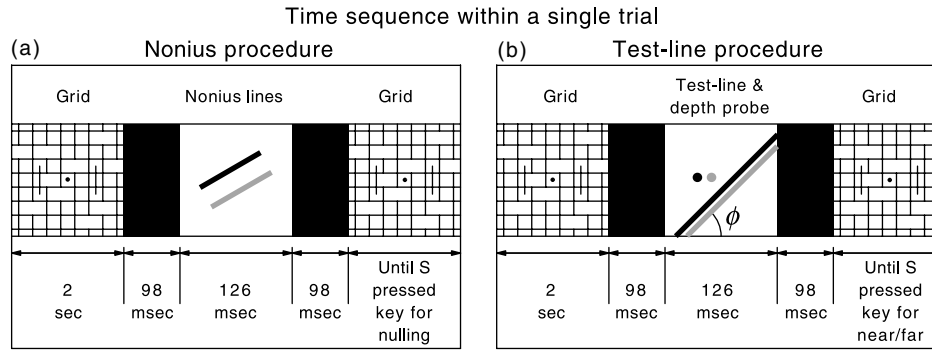Time sequence within a single trial

Fig. 4. Time sequence of patterns within a single trial for the nonius procedure (a) and the test-line procedure (b). Every trial commenced with the presentation of the rectangular grid for 2 s. The grid was irregular and contained two additional vertical lines to disambiguate matching. It also contained a fixation disk in its center. After a blank time interval of 98 ms either the nonius-lines or the test-line were flashed for 126 ms. After another blank interval the grid was again visible until the subject pressed a key. In the nonius procedure key presses varied the relative orientation of the nonius lines. In the test-line procedure a key press indicated whether the subject perceived the probe either in front or behind the test-line. ϕ indicates the slope of the test-line. The black dot in panel b represents the right eye's image of the depth probe. The grey dot represents the left eye's images of the probe, its location varying along a horizontal path depending on the subject's responses in the staircase procedure.

the half-images. Photometric measurements showed that insignificant amounts of the green and red light leaked through the red and green filter, respectively. The room was dark; nothing but the displayed stimulus was visible. The head was stabilized with a chin rest and a bite bar. We used an oscilloscope to measure the refresh frequency of the stimuli; a frame gets refreshed in 14 ms.

2.2. Stimuli

Three different patterns (Fig. 4) were used in this experiment. A background grid pattern was used to bring the eyes into horizontal, vertical and torsional alignment. The horizontal and vertical alignment remained constant across various stimulus manipulations but the torsional alignment was varied across conditions in a well-controlled way. The grid subtended 52×45 deg in visual angle and every square of the grid subtended 4.3×4.3 deg. We used a large grid because cyclotorsional responses increase with display size (Howard, Sun, & Shen, 1994; Kertesz & Sullivan, 1978). And we used quite a number of horizontal contours because horizontal contours in the display area are reported to induce cyclovergence (Nagel, 1868; Rogers, 1992; Verhoeff, 1934). The grid pattern contained a fixation disk in its centre with a diameter of 15 arcmin. The horizontal and vertical relative disparity of the disk and the grid were zero (so they were perceived in the plane of the screen). As can be seen in Fig. 4, the grid pattern was not fully regular; this was to prevent subjects from experiencing the wall-paper effect (i.e. fixation in the wrong depth plane): not every grid element was shown and the grid contained two additional vertical lines (8.6 deg length) at an eccentricity of 8.6 deg.

A second pattern consisted of flashed dichoptic nonius-lines (see Fig. 4a) that were used to measure the torsional state of the eyes (Hofmann & Bielschowsky,

1900; Verhoeff, 1934). The nonius-lines had a length of 17.6 deg and a vertical separation of 3.2 deg (so that they could not be fused). The offset between the nonius-line and the horizontal was 30 deg. An angle of 30 deg was chosen because for variations around 30 deg the anti-aliasing of lines on the screen was optimal.

A third pattern, the actual test-line stimulus, consisted of the depth probe and the test-line. The depth probe was circular and had a diameter of 24 arcmin. The slope of the test-line was 36 deg. The test-line width was always 18 arcmin. The test-line length could be either 0.5 or 65.2 deg. The shortest test-line length (0.5 deg) was about the size of the depth probe. This line length was used as a control to check if an observer showed a bias in responses. The rationale of this bias measurement is that there is no matching ambiguity in this shorter test-line: if this shorter line has a horizontal disparity of X arcmin then one would expect the depth probe to have exactly the same horizontal disparity (X arcmin) if it is seen at the same depth. So in this way a bias in subject's responses can be measured. (It turned out to be the case that our subjects did not show a response bias that was significantly different from zero.) The largest test-line length was chosen because at this line length the end points cannot be resolved and therefore matching is unconstrained. The horizontal shift between the half-images of the infinite test-line on the screen (the horizontal disparity) was always 18 arcmin. The separation between the test-line and the fixation disk was 1.1 deg and the distance between the test-line and the probe was also 1.1 deg. The probe's horizontal disparity (and the corresponding perceived depth) was varied.

2.3. Task and procedure

We asked subjects to judge whether the depth probe lay in front of, or behind, the test-line. Before we pre-

sented the very first trial in the experimental sessions, the binocular rectangular grid was shown for 27 s in order to stabilize cyclovergence, horizontal vergence and vertical vergence. This period should be sufficient to stabilize vergence because a vergence response to considerable torsional as well as vertical and horizontal disparities can be completed within 27 s (Sullivan & Kertesz, 1978).

The rest of an experimental session consisted of a nonius procedure and a stimulus procedure. First, we describe the nonius procedure. Every trial in this procedure started with the presentation of the rectangular grid and the fixation disk for 2 s. Then, after a blank interval of 98 ms, the two nonius-lines were flashed simultaneously for 126 ms. The fixation disk was no longer visible during the presentation of the nonius-lines. A nulling procedure was used in which the torsional disparity between the nonius-lines was varied until they appeared parallel. Subjects were instructed to vary the relative torsion between the two nonius-lines by key presses. This was done with repeated flashes of the nonius-lines interleaved with the grid. The rationale of the nulling method is twofold. First, the amount of rotation between the two nonius-lines, as measured in a nulling task, is a relatively good indicator of the amount of static relative cyclotorsion (Crone & Everhard-Halm, 1975; Howard, Ohmi, & Sun, 1993). Second, briefly flashed stimuli do not influence cyclovergence of the eyes because cyclovergence is a relatively slow process (Sullivan & Kertesz, 1978). After the subject was satisfied that the nonius-lines appeared parallel s/he accepted the null-setting. Then the stimulus procedure commenced.

A trial in the stimulus procedure also started with the presentation of the rectangular grid and the fixation disk for 2 s. Then, again after a blank interval of 98 ms, the test-line and the probe were flashed simultaneously for 126 ms (and the fixation disk was no longer visible). Afterwards, both the grid and fixation disk were again visible until the subject pressed a button to indicate that s/he perceived the probe either in front or behind the test-line. Then the next stimulus trial was presented. After five stimulus trials the nonius procedure began again. The nonius procedure and the five-stimuli procedure were repeated until the end of an experimental session.

A staircase procedure was used to determine the horizontal disparity at which subjects perceived the depth probe at the same depth as the test-line. Distinct conditions were represented by interleaved staircases. Interleaving the staircases had the result that the different line-probe configurations appeared completely at random. In a particular line-probe configuration the horizontal disparity of the depth probe was varied using a 1-up/1-down staircase. Step size in the staircases was initially 2 pixels, but was reduced to 1 pixel after the second reversal.

2.4. Data analysis

The 1-up/1-down staircase yields the 50% point of subjective equality on a psychometric curve. The horizontal disparity (and the standard error) of the probe that was perceived at the same depth as the test-line was determined from the average of disparities for the last 12 reversals of a staircase.

3. Experiment 1: incyclovergence induced by the grid stimulus

In the first experiment we examine how much cyclovergence we are able to induce. By the gradual rotation of a display, clockwise for one eye and anti-clockwise for the other, a cyclovergence response is obtained which follows these rotations (Crone & Everhard-Halm, 1975; Howard & Zacher, 1991; Nagel, 1868). In this experiment we used only two of the above-described stimulus patterns: the nonius lines and the grid. The nonius lines were used to measure the cyclovergence induced by the rotated grid. As outlined in the theory section (Fig. 3b), for the test-line angle that we used (ϕ is 36 deg) a particular absolute value of dδ, say 3 arcmin, is created by either a 6.0 deg or a -8.3 deg rotation (α) of the matching meridian. We therefore studied incyclotorsion rather than excyclotorsion.

At the beginning of this experiment subjects viewed (for 27 s) a grid in which the two half-images were unrotated. By means of a key press the rotation between the two half-images started slowly and gradually in steps of 0.25 deg per 2 s. The left eye's half-image was rotated clockwise and the right eye's image anti-clockwise until the differential rotation of the grid was 1 deg. The nonius nulling method described above was employed to measure the cyclovergence induced by the rotated grid. We did these cyclovergence measurements repeatedly after each degree of grid rotation up to a rotation of 11 deg. While the grid rotated, subjects were asked if they continuously perceived a single stable grid.

Fig. 5a portrays the eye's incyclovergence versus the grid's incyclorotation across five participating subjects. Error bars represent one standard error across the subjects. The standard errors increase with the grid's incyclorotation because not all subjects were able to perceive a single and stable grid when the grid's incyclorotation exceeded 8 deg. It can be concluded from these results that the correlation between the grid rotation and eye rotation is linear up to the point at which the subjects can no longer fuse the grid. The gain is similar to previously reported gains (Howard & Rogers, 2002). The differences across subjects are quite small. Fig. 5b shows the mean of three measurements for subject LD. These latter measurements were performed on three different days. From the small standard error
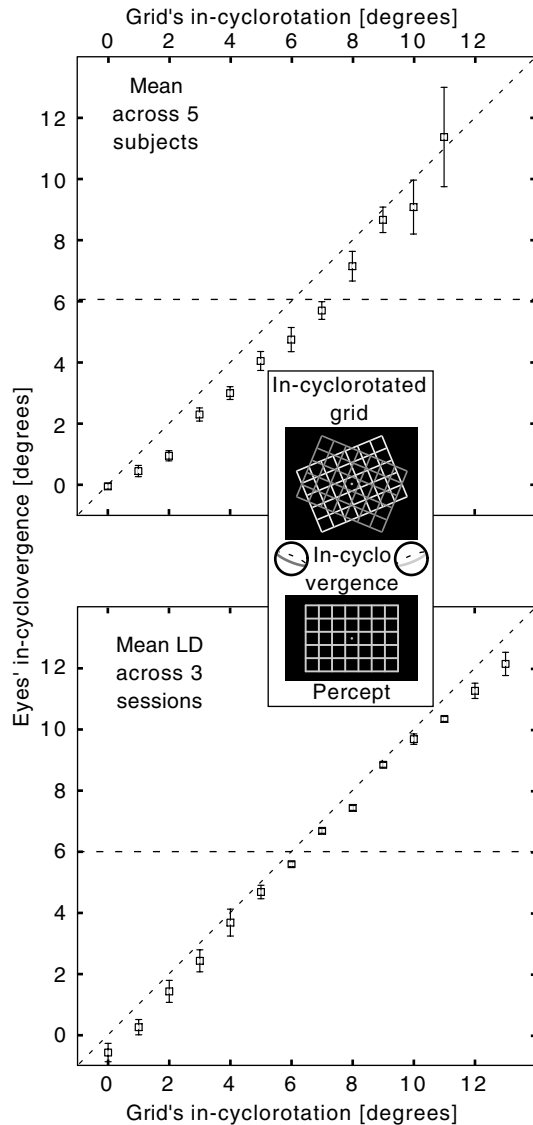
Fig. 5. Incyclovergence as a function of the grid's incyclorotation. The top and bottom panels portray the mean across five subjects and the mean for subject LD across three experimental sessions, respectively. Error bars represent one standard error.

bars it can be concluded that the incyclotorsion can be fairly constant within this subject.

4. Experiment 2: cyclotorsion and unconstrained matching

The purpose of this experiment, which is the main experiment described in this paper, is to examine unconstrained matching of long oblique lines when either the two eyes, or the two half-images of the stereogram are in different cyclorotational states.

4.1. Stimulus and procedure

How can we derive the optimal stimulus parameters given the physical limitations imposed by both the set-

up and the human visual system? Panel b of Fig. 3 shows how $d\delta$ varies as a function of α for five different ϕs. In this graph δ is 18 arcmin (identical to the disparity that was used in the experiments described in this paper). When ϕ increases, the growth of $d\delta$ with α decreases; at $\phi = 90$, $d\delta$ is zero for all α as can be understood from Fig. 3a. In our set-up the major physical limitation is imposed by the pixel size, which is 3 arcmin. Therefore, if we wish to measure a change in perceived depth of the test-line for a nonzero cyclovergence amplitude relative to no cyclovergence, $d\delta$ should ideally be either of the order of 3 arcmin or larger. The domain in which the resolving power of our set-up is too small is represented by the grey area in Fig. 3b. On the bases of the plots in Fig. 3b one must choose a small ϕ because then a change in the matching meridian can be detected for relatively small rotation α. However, stereoscopic thresholds increase with decreasing ϕ (Blake et al., 1976; Ebenholtz & Walchli, 1965; van Ee, Anderson, & Farid, 2001). More specifically van Ee and Schor showed that when ϕ is smaller than 30 deg the noise in subjects' responses increases substantially. If we choose ϕ equal to 36 deg then α needs to be 6 deg in order to obtain a $d\delta$ of 3 arcmin (Fig. 3b). In other words, at this combination of ϕ and α we predict significant differences between matching along the horizontal meridian and matching along the rotated meridian with regard to the perceived depth of the test-line. Fig. 5 shows that even untrained subjects have no difficulty in reaching an incyclovergenal state of 6 deg. As we saw in Fig. 5 the relationship between incyclorotation of the grid and incyclovergence has a slope smaller than unity. So in order to reach 6 deg of incyclovergence we must present an incyclorotated grid that is rotated by at least 7 deg (see also Verhoeff, 1934 who reported similar results). Therefore we undertook our measurements at a ϕ (test-line angle) of 36 deg and an α (incyclorotation of the grid) of 7.5 deg.

There were four conditions consisting of the possible permutations of the pairs rotated grid/unrotated grid and rotated test-line/unrotated test-line. Fig. 6 depicts the four stimulus conditions for the long test-line (length of 65.2 deg). The left column depicts the grid rotation. In panels a and b the grid is unrotated (denoted by Ug) and in panels c and d it is rotated (denoted by Rg). Nonzero grid rotation was always anticlockwise for the right eye and clockwise for the left eye (incyclorotation). The second column of Fig. 6 depicts the screen half-images of the test-line. In panels a and c the test-line is unrotated (Ul) and in panels b and d it is rotated (Rl). In panel b the line is excyclorotated by 6 deg; in panel d it is incyclorotated by 6 deg. The abbreviations that we used to denote the individual conditions are given to the right of the second column. The first capital in the abbreviations denotes the unrotated (U) or rotated (R) grid, the other capital denotes the unrotated (U) or rotated (R) test-line. To create the differential cyclotorsions of both
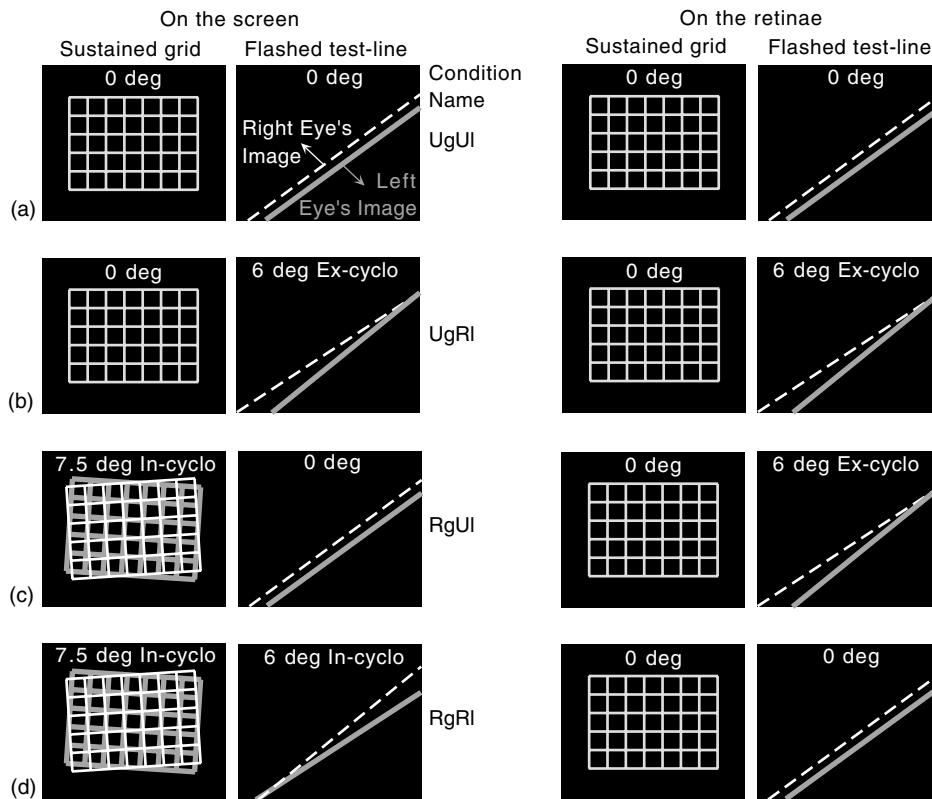
Experimental conditions

Fig. 6. Experimental conditions in Experiment 2. The two left columns portray the images as they were presented on the screen. The two right columns portray the stimuli as they are cast on the retinae (in panels c and d the eyes are incycloverged). The dashed white line represents the right eye's image of the test-line. The grey line represents the left eye's image. The abbreviations on the right of the second column represent the condition names. In order, from top to bottom, UgUl denotes the condition of the unrotated grid and the parallel half-images of the test-line (a). UgRl denotes the unrotated grid and test-line with excyclodisparity of 6 deg (b). RgUl denotes the rotated grid (7.5 deg incyclorotation) and the parallel half-images of the test-line (c). RgRl denotes the rotated grid and test-line with incyclodisparity of 6 deg (d). Note that the conditions in panels a and d and in panels b and c produce similar retinal images. The test-line conditions in panels a and c are identical on the screen.

the grid and the test-line the location of the fixation disk, which was also the location of the (binocularly fused) probe, was used as the rotation point.

Each half-image of the grid was rotated in steps of 0.125 deg per 2 s (relative cyclotorsion 0.25 deg per 2 s) up to a relative cyclotorsion of 7.5 deg. After the grid had been rotated by 7.5 deg—and after the subject had stated that s/he had stable fusion—the rest of the procedure was again very similar to the procedure described above. So the grid was shown for another 27 s in order to stabilize cyclo, horizontal and vertical vergence. Then the nonius procedure and the test-line procedures were employed to measure cyclovergence and the horizontal disparity of the match, respectively.

For every condition we used two staircase series, one in which the perceived depth of the probe started in front of the test-line and one in which it started behind the test-line. The four grid-line rotation conditions (in fact eight staircases) were presented in two experimental sessions, one in which the grid rotation was zero and one in which it was 7.5 deg (the reason for the separation into two sessions is that cyclovergence is a slow process;

thus rotation and no-rotation conditions cannot be interleaved).

Of the five subjects (CE, CV, JE, LD, and MK) who participated, only LD was not naive as to the purpose of this experiment.

4.2. Predictions

Of primary interest is whether the binocular matching process takes the cyclovergenal state into account in the matching algorithm. If, on the one hand, cyclovergence is entirely disregarded in the matching algorithm, the most convenient reference to use in the description of binocular matching is a retinal-coordinate (*retino-centric*) reference. If, on the other hand, the cyclovergenal state is entirely compensated for in the matching algorithm, the most convenient reference to use in the description of binocular matching is a screen-coordinate reference. Other terms that are often used for "screen coordinates" are "world coordinates" or "epi-polar coordinates". In our experiment head movements are

restricted, so screen-, world-, and epi-polar-coordinates are the same as *head-centric* coordinates.

Our experiment indicates whether either head-centric or retino-centric coordinates are more convenient to describe binocular matching. First consider the situation in which cyclovergence is entirely disregarded.

Cyclovergence entirely disregarded—In this case it is as if the matching direction rotates with the eyes, without having any information about the eye rotation. So matching is then determined solely by the retinal projections of the line (two right-most columns of Fig. 6). For this case the paired conditions depicted in both Fig. 6a and d and Fig. 6b and c should give the same matching results because in retinal terms these pairs are indistinguishable.

Cyclovergence entirely compensated—In this case it is as if the matching direction does not rotate with the eyes but stays fixed relative to the head and, thus, to the stimulus on the screen. The conditions UgUl and RgUl, depicted in Fig. 6a and c, should give the same matching results because the screen images (see second column in Fig. 6) are the same.

4.3. Results

The horizontal disparities at which subjects perceived the probe at the same depth as the test-line are portrayed in Fig. 7. Fig. 7a shows the mean results across the five subjects. The horizontal probe disparity—needed to perceive the probe at the same depth as the test-line—is similar both in the UgUl and the RgRl conditions (panels a and d of Fig. 6) and in the UgRl and the RgUl conditions (panels b and c of Fig. 6). In other words, the horizontal probe disparity depends upon the retinal orientation of the test-line. The probe disparity does not seem to be determined solely by the appearance of the test-lines half-images on the screen. [8]

The error bars in panel a represent the standard error across the five subjects. These error bars are relatively large. It is therefore hard to draw firm conclusions from the mean data. In Fig. 7b the individual results of the five subjects are shown. The error bars represent the

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[8] On the basis of introspection observers reported after the experiment that the flashed isolated test-line was perceived in the frontal plane throughout the experiment. Although this result is in line with earlier reports (Collewijn, van der Steen, & van Rijn, 1991; Howard & Zacher, 1991) it is noteworthy because in some conditions the test-line's horizontal (shear) disparity varies in the same way as when we view a line slanted in depth (Ogle & Ellerbrock, 1946). We repeated Experiment 2 with the addition of an objective recording of the slant estimated (van Ee & Erkelens, 1996a). The preliminary results show that observers are indeed able to perceive slant in the horizontal shear trials. Although the perceived slant is small (<10 deg) it is significantly different from zero. The slant is, however, too small to have influence on the probe disparity because the probe is presented very close to the fixation (rotation) point.
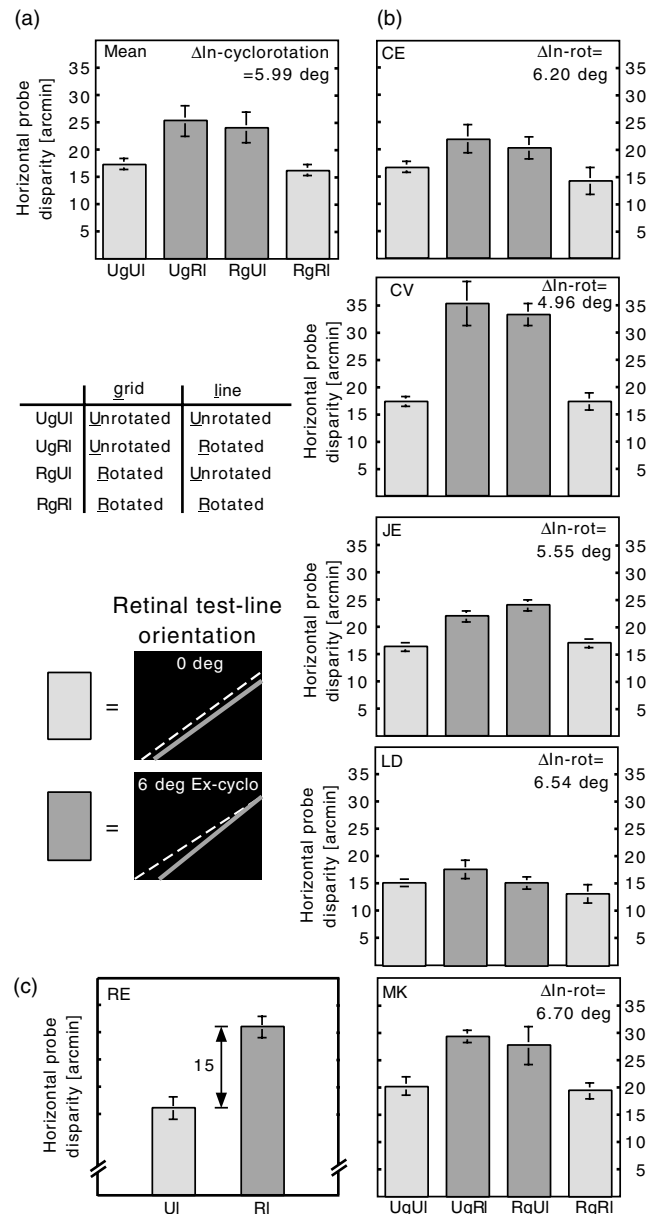

Fig. 7. The results of Experiment 2 are portrayed in panels a and b. Panel a shows the mean across five subjects. Panel b shows the individual subject data. The number 'ΔIn-rot' represents the incyclovergence of the eyes in the rotated grid conditions. In the light grey bar conditions the test-lines were as much rotated as the retinae were: so the test-lines were cast on the retinae as if they were parallel on the screen. In the dark grey bar conditions the test-lines were cast on the retinae as if they were 6 deg excyclorotated on the screen. Error bars represent one standard error. Panel c depicts the results of subject RE, who has non-stimulus-induced rotated retinae in the dark.

standard error across the two staircases. The significance within a subject was tested using a two-sided mean difference test with a normal distribution as the underlying distribution. For subject CE the results are not significantly different from each other ($P > 0.05$), but he shows the same trend as subjects CV, JE and MK. In fact, all subjects, except LD, show the same tendency as

we saw in the mean data: for subject LD the only pair of conditions for which the P-value is below 0.05 (but above 0.01) is the pair UgRl vs RgRl.

5. Experiment 3: unconstrained matching and non-stimulus-induced rotated eyes

It seems to be the case that we may conclude from Experiment 2 that the horizontal probe disparity that is needed to see the probe at the same depth as the test-line is not primarily determined by orientation of the test-line relative to the head (i.e. its projection on the screen). Instead it seems to depend primarily upon the retinal orientation of the test-line.

A patient [9] whose eyes are rotated in the dark (without the need for corresponding features to induce cyclovergence) provides interesting circumstances to test this conclusion. We studied such an observer. In the dark, the left eye and the right eye of observer RE, are rotated by about −2 (left-excyclotorsion) and about 6 (right-excyclotorsion) deg, respectively. So, in all, the excyclovergence is 8 deg. Under normal viewing conditions, including experimental conditions in the lab, RE's vision, and in particular binocular matching, is usually more precise and more accurate than the vision of normal subjects. Under unconstrained matching conditions, however, the rotated retinea are supposed to bring about anomalous matching if the above conclusion—that the retinal test-line orientation is the important factor—is correct.

We repeated Experiment 2 for observer RE. The primary difference with respect to the procedure that the other subjects followed is that we first cyclorotated the half-images of the grid: the left-eyes' half-image of the grid was excyclorotated by 2 deg; the right eyes' half-image was excyclorotated by 6 deg. Thus, the grid was cast on the retinae such that the retinal images were similar to the retinal images of an unrotated grid in a normal observer. There were two experimental conditions. In one condition we presented lines that were cast on the retinae as parallel lines (comparable to the conditions in Fig. 6a and d). Note that on the screen these lines were cyclorotated over 8 deg (−2 in the left and 6 in the right half-image). In the other condition we presented lines that were cast on the retinae as 6 deg excyclorotated lines (comparable to the conditions in Fig. 6b and c). On the screen these lines were cyclorotated

over 14 deg (−2 − 3 in the left and 6 + 3 in the right half-image). The two stimulus icons in Fig. 7 portray the retinal images.

The results for unconstrained matching of RE are given in Fig. 7c. In retinal test-line projection terms, the results are very similar to the results of the other subjects in Fig. 7, which is consistent with the conclusion that it is indeed the retinal test-line orientation that matters. In Fig. 7c we omitted the absolute scale along the vertical axis. The reason is that although the difference between the magnitudes of the light and the dark bars is quite stable across different experimental sessions, the absolute values differ. Although we do not have a good explanation, this difference across sessions is probably due to instability in the retinal torsional states that, in turn, is caused by the lack of contribution of the superior oblique muscles to keep the eyes stable.

6. General discussion

In their attempts to understand the algorithms that the visual system uses to define binocular disparities authors have given considerable attention to both unconstrained (Adams & Banks, 2000; van Ee & Schor, 2000) and underconstrained (Anderson, 1994; Malik, Anderson, & Charowhas, 1999; van Ee & Anderson, 2001; van Ee et al., 2001; van Ee, in press; and finally Farell, 1998, but see Anderson, 1999) binocular matching. However, in these studies the role of cyclovergence has not yet been examined.

Here we examined how in unconstrained matching of a long test-line binocular matching is influenced by cyclovergence between the retinae, by cyclorotation between stereogram half-images, or by combinations of the two. We found that for those conditions in which the retinal images were similar (when cyclovergence was just as much as cyclorotation of the test-lines) assigned depth was similar too, i.e. independent of cyclovergence: (1) the data for the pair of conditions in which there is a differential rotation between the grid and the test line (the UgRl and RgUl conditions in Fig. 6b and c) are very similar and (2) the data in the pair of conditions where there is no differential rotation (the UgUl and RgRl conditions in Fig. 6a and d) are also similar but differ from the pair where there is differential rotation. On the basis of these paired similarities we may conclude that the binocular matching algorithm does not incorporate the eyes' cyclovergence when matching is unconstrained.

In addition, the results of Experiment 3 for the anomalous subject, with non-stimulus-induced rotated retinae, are fully consistent with our conclusion and imply a lack of neural plasticity: these results are significant in showing that binocular matching is not

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[9] A typical result of a severe head-concussion can be that the 4th eye muscle nerve (one of the thinner nerves) is damaged which, in turn, means that the superior oblique muscle does not receive the correct signals to help incyclorotate the retinea. As a consequence, the retinaes have differentially cyclorotated resting positions. The inferior rectus, the antagonistic muscle, is usually still able to help rotate the eyes, although to a lesser extent than in normal observers.

adaptable even by prolonged exposure, and thus is set by an early critical period and is, therefore, subsequently impervious to visual contingencies.

Our results are in agreement with the results of a recent study (Schreiber et al., 2001). In this study random dot stereograms were constructed in which a hidden feature became visible only under particular cyclotorsional eye postures. Schreiber and co-workers also concluded that the stereo-matching algorithm uses retina-fixed matching zones. They studied constrained matching. In unconstrained matching there is an extra ambiguity (matching direction) that is not present in constrained matching. From several studies it is known that the eyes' posture, in particular vergence and version, can be used for depth perception in situations where other cues are less informative (Backus et al., 1999; Rogers & Bradshaw, 1995). The same might be true for cyclovergence: in those situations where there is complete ambiguity, the visual system might be able to incorporate the cyclovergence state. Here, using a completely different experimental paradigm, we replicated and extended the findings of Schreiber et al. to unconstrained matching.

Our findings and those of Schreiber et al. are consistent with another recent claim (Banks, Hooge, & Backus, 2001) that the visual system does not seem to use an extraretinal cyclovergence signal in stereoscopic slant estimation. One could hypothesize that not incorporating an extraretinal cyclovergence signal in disparity processing has a number of benefits that serve the stability of stereoscopic vision, an issue discussed in detail by van Ee and Erkelens (1996b) and Erkelens and van Ee (1998).

Finally, the invariant matching results are significant in showing that even when rotated to non-vertical orientations, it is the (mainly) horizontal retinal disparities that are relevant for human vision. This property places a strong constraint on neurophysiological models of stereopsis, which should show the same pattern of orientation dependence if they are to form an explanatory basis for the human visual properties.

Acknowledgements

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