Bi-stability in perceived slant when binocular disparity and monocular perspective specify different slants

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We examined how much depth we perceive when viewing a depiction of a slanted plane in which binocular disparity and monocular perspective provide different slant information. We exposed observers to a grid stimulus in which the monocular- and binocular-specified grid orientations were varied independently across stimulus presentations. The grids were slanted about the vertical axis and observers estimated the slant relative to the frontal plane. We were particularly interested in the metrical aspects of perceived slant for a broad spectrum of possible combinations of disparity- and perspective-specified slants. We found that observers perceived only one grid orientation when the two specified orientations were similar. More interestingly, when the monocular- and binocular-specified orientations were rather different, observers experienced perceptual bi-stability (they were able to select either a perspective- or a disparity-dominated percept).

Keywords: stereopsis, bi-stability, binocular vision, ambiguous figures, binocular disparity

Introduction

Each of our eyes views a scene from a slightly different position. The resulting binocular disparities enable us to reconstruct the 3-dimensional (3D) lay-out. The processing of disparities is, however, not essential for the 3D reconstruction because we are often able to perceive depth solely on the basis of monocular vision. For example, monocular perspective (including texture, outline, and linear perspective) is a powerful cue for surface slant (Clark, Smith, & Rabe, 1955; Cutting & Millard, 1984; Freeman, 1966; Stevens, 1981). How much depth do we perceive when viewing a depiction of a slanted plane in which binocular disparity and monocular perspective provide opposite slant information? Recently, we examined this question in a metrical (quantitative) way and we found for a range of disparity-perspective cue conflicts that observers experience bi-stability when viewing such depictions (van Ee, Hol, & Erkelens, 2001). Although, quite interesting, phenomenological aspects of bi-stability in stereoscopically perceived slant were reported in the early days of stereoscopic research, little progress seems to have been made since then, and the metrical aspects have never been investigated systematically.

The literature on perceptual bi-stability is vast. However, almost all demonstrations of bi-stability are essentially monocular, even when they are viewed binocularly. Figure 1 shows the well-known Necker cube, which is an example of a stimulus that evokes perceptual bi-stability. The literature on bi-stability that requires stereopsis is surprisingly sparse, even though quite a few studies have addressed conflicts between monocular and binocular specified depth (see "Discussion"). A survey of the literature reveals interesting findings. First, as far as we know, only two studies have reported that bi-stability occurs in slant perception for extreme disparity-perspective cue conflict situations (Wheatstone, 1852; Schriever, 1925). These studies were phenomenological in nature and did not address metrical aspects of perceived slant. Wheatstone, in particular, reported bi-stability for a variety of different 3D stimuli in which perspective and disparity provided opposite depths.[1] Second, a couple of studies did examine estimated slant when disparity and perspective provide opposite slant information but they did not report bi-stability (Allison & Howard, 2000a; Allison & Howard, 2000b; Gillam & Cook, 2001).

In sum, there seem to be no studies in the literature that investigated how much depth is perceived (i.e., the metrical aspects) in stimuli that engender bi-stability. On the phenomenological aspects, however, Wheatstone (1838, 1852; i.e. over 150 years ago) reported a wealth of information about and insights into bi-stability. Because many of his findings are relevant for our study, we will use them as a central thread through this introduction.

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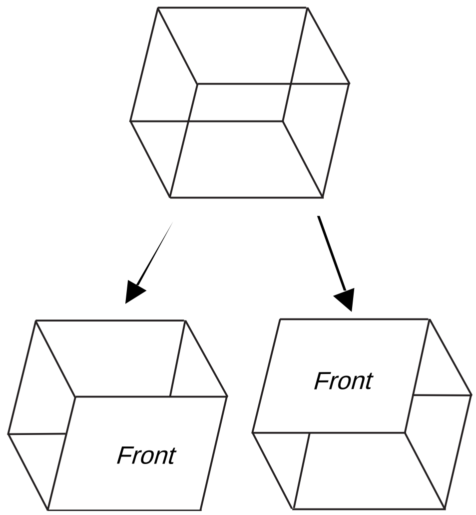

Figure 1. Necker cube bi-stability example. A constant stimulus gives rise to two alternative 3-D interpretations. Although eye movements play a role, the general consensus is that the bi-stability is predominantly central. Stereopsis is not required to experience bi-stability in this stimulus: the bi-stability is essentially monocular.

Wheatstone, using the stereoscope that he constructed, was one of the first to study stimuli in which binocular disparities and monocular perspective provided opposite slant information (Wheatstone, 1838, p. 377): “A very singular effect is produced when the drawing originally intended to be seen by the right eye is placed at the left hand side of the stereoscope, and that designed to be seen by the left eye is placed on its right hand side. A figure of three dimensions, as bold in relief as before, is perceived, but it has a different form.” He called this the “converse figure” (1838) or “conversion of relief” (1852); nowadays, we call it “reverse perspective” (reviewed in Howard & Rogers, 2002). “Those points which are nearest the observer in the proper figure are the most remote from him in the converse figure” and he continues, ”but it is not an exact inversion, for the near parts appear smaller, and the remote parts larger than the same parts before inversion (Wheatstone, 1838, p. 377).”[2] And then he explains that in the case of simple line drawings, the reverse perspective figure is “as readily apprehended as the original one, because it is generally a figure of a frequent occurrence.” He also states that the reversals “seem entirely to depend on our mental contemplation of the figure intended to be represented, or of its converse.” In the Bakerian Lecture (Wheatstone, 1852, p. 14), he is extraordinarily explicit about the occurrence of bi-stability (which he calls “the two ideas in the mind”) in binocular vision[3]: “I know of nothing more wonderful, among the phenomena of perception, than the spontaneous successive occurrence of these two different ideas in the mind, while all external circumstances remain precisely the same,” and he goes on to state that an object “becomes converted into another totally dissimilar object uncouth in appearance, and which gives rise to no agreeable emotions in the mind; yet in both cases all the sensations that intervene between object reality and ideal conception continue unchanged.”

Figures 2 and 3 demonstrate the two 3D percepts that observers are able to distinguish when (monocular) perspective and (binocular) disparity specify very conflicting slants: one percept in which the grid’s slant is positive (Figure 3b) and the other in which the slant is negative (Figure 3c). The two percepts are never present simultaneously.

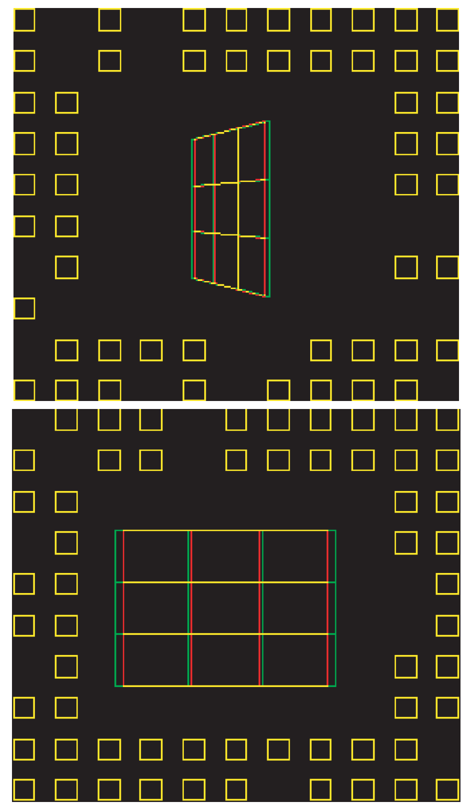

Figure 2. Demonstration of bi-stability in stereoscopic perception. In these stereograms, both perspective and binocular disparity specify surface slant about the vertical axis. Red/green filters are required to view them. When the red filter is over the left eye, two relatively stable percepts can be distinguished. In the first percept, the grid recedes in depth with its left side further away (it is perceived as a slanted rectangle). In the other percept, the right side of the grid is further away (it is perceived as a trapezoid with the near-edge shorter than the far-edge). In fact, the perceived slant depends on the viewing distance; however, when the red filter is over the left eye, their signs are always conflicting. When the red filter is over the right eye, perspective and disparity specify similar slants and the observer perceives a single stable slanted grid with its right side closer. In the lower stereogram, the conflict between disparity and perspective-specified slant is relatively small and observers generally perceive one slanted plane (no bi-stability). More demonstrations can be found on our Web site: http://www.phys.uu.nl/~vanee/

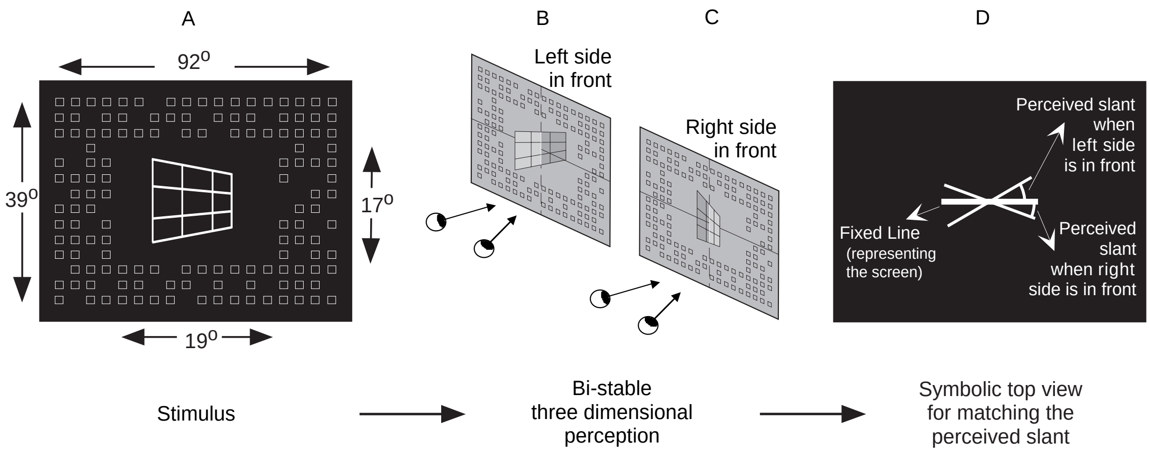

Figure 3. Experimental procedure. The drawing is schematic. A. The stimulus consisted of a grid (subtending 15 x 11 deg when perspective specifies a frontal - unslanted - grid). The grid was viewed against a large surrounding reference (92 x 39 deg) consisting of unslanted squares (1 x 1 deg). The window in the center of the surround was 19 x 17 deg. Perspective-specified slant and disparity-specified slant could be either in conflict (B and C) or in agreement (in which case panels B and C are identical). D. The stimulus was followed by a display in which subjects matched the perceived slant(s) to the angle(s) between the fixed horizontal line and the rotatable intersecting line(s).

Most observers with normal stereovision have no difficulty in focusing their attention on either of the two 3D percepts. However, during pilot studies and during presentations at conferences, we have asked at least 60 observers to report their perceptions while viewing ambiguous slant stimuli; as in many other studies in binocular depth perception, we found considerable variability between observers (reviewed in Howard & Rogers, 2002). Some of the observers were able to perceive both the perspective and the disparity-dominated percept (bi-stability), some observers perceived solely the perspective-dominated percept, and some solely the disparity-dominated percept (see also Stevens, Lees, & Brookes, 1991, for the same finding in a comparable study for surface curvature).

Roughly speaking, about 30% of the 60 pilot observers tested were able to perceive both the perspective-dominated and the disparity-dominated percept directly. The other 70% of the observers initially perceived solely the perspective-dominated percept (even if they knew that bi-stability would be possible). Only after they had been told they were looking at a stimulus that they could see in reversed perspective were they able to perceive bi-stability. About 10% to 20% of the 60 observers kept seeing solely the perspective-dominated percept even after they had been coached in trying to perceive the disparity-dominated percept. Two observers (very experienced colleagues in stereo vision research, but not the authors) perceived solely the disparity-dominated percept, and they were unable to alternate between the disparity- and the perspective-dominated percept.

Bi-stability in stereoscopic vision is an interesting phenomenon because it creates the rare opportunity of having two states in neural processing that are related to the percepts rather than to the stimulus. To enable future theoretical analyses on how both perspective- and disparity-specified slant contribute to bi-stable 3D perception, we collected systematic data on metrical aspects for a broad spectrum of possible combinations of disparity- and perspective-specified slants. We asked observers to view ambiguous stereoscopic images in which both disparity and perspective specified different orientations of a grid in 3D space. Grid rotation was about the vertical axis, and we manipulated perspective and disparity independently.

Methods

Stimuli and Apparatus

The stimuli (Figures 2 and 3) were planar grids (subtending 15 × 11 deg in unslanted conditions) presented dichoptically by a conventional red-green anaglyphic technique. The correct perspective and disparity distortions of the stimuli were generated using OpenGl libraries. The stimuli were rear-projected onto a large screen (92 × 77 deg). A surrounding pattern (92 × 39 deg) consisting of small squares (1 × 1 deg) provided a zero-slant reference and prevented depth contrast illusions. Only 80% of these surrounding squares were shown to prevent fixation in the wrong depth plane (wallpaper effect). Subjects were seated at a viewing distance of 114 cm. The head was stabilized with a chin and forehead rest. Subjects were free to move their eyes.[4] Line widths were 6.3 arcmin. The intensities of the red and green half-images were adjusted until they appeared equiluminant when viewed through the red and green filters. Photometric measurements showed that miniscule amounts (0.3%) of the green and the red light leaked through the custom-made red and the green filter, respectively. The room was completely dark, so only the grid and the reference were visible.

Task and Procedure

To investigate systematically how both perspective- and disparity-specified slant contribute to bi-stable 3D perception, we varied both disparity-specified slant (-70 to 70 deg in 10 steps) and perspective-specified slant (–70 to 70 in 6 steps). Positive slants are defined as right side away. In each block of 77 trials, all of the stimulus conditions appeared once in random order for 10 s. There were five trial blocks. The subjects were instructed that both ambiguous (flip) and nonambiguous (non-flip) stimuli would be presented and that the stimuli could be either trapezoidal or rectangular.

The subjects' task was to estimate the perceived slant of the grid. The slant estimation procedure (van Ee & Erkelens, 1996) is depicted in Figure 3. The subject initiated the stimulus onset by a mouse click. A subject was instructed first to decide whether he or she was able to see either the left side in front or the right side in front. Then the task was to estimate the respective slants and to remember the estimated angles. After presentation of the stimulus (10 s), three frontoparallel lines were presented on the screen (Figure 3d). One of the lines was horizontal and the other two lines could be rotated about their center. The horizontal line was fixed and represented a top view of the unslanted reference; each of the other lines represented the top-view of the perceived grid in either the perspective-dominated percept or in the disparity-dominated percept (Figure 3d). Subjects were instructed to match the angles between the rotatable lines and the horizontal line to the two perceived slants. If observers were not able to experience bi-stability, they matched both angles to the (single) slant they perceived. Because the lines were displayed in the plane of the screen, the lines also served as a zero-slant reference between successive stimuli.[5]

Subjects

Observers who were able to perceive bi-stability are particularly interesting for the purposes of this work. We therefore carried out a complete experiment with five subjects who were able to perceive bi-stability. In order to obtain a reasonably complete overview of the spectrum of possible results, we asked one only-perspective-dominant observer and one only-disparity-dominant to participate in a complete experiment. Both the five observers who were able to perceive bi-stability and the only-disparity-dominant observer had excellent stereo vision: their stereoacuities were lower than 10 arcs, and they were also able to distinguish disparities of different signs and magnitudes within a range of –1 to 1 deg in a stereoanomaly test (van Ee & Richards, 2002). The only-perspective-dominant observer participating was unable to distinguish disparities of different signs and magnitudes even while making eye movements. Prior to participation, the candidates were also tested for consistency in their responses when estimating the slants of both real and dichoptically presented planes. The seven subjects knew that they were participating in an experiment containing ambiguous (flip) and nonambiguous (non-flip) stimuli, but they were not informed about the purpose of the experiment.

Results

Figures 4, 5, and 6 show the mean perceived slants for a range of varying perspectives and disparities. Figure 4 shows the mean perceived slants across the five subjects who were able to perceive bi-stability. The data show clearly that there are two different domains. In one domain (when disparity-specified slant and perspective-specified slant were similar) only one slant is perceived. In this domain, slants derived from perspective and disparity have been reconciled, engendering an intermediate perceived slant (in Figure 4, this situation is represented in the left part of the three top panels and the right part of the three bottom panels). The reconciled data in this domain show the often reported slant underestimation. In the other domain (when disparity-specified slant and perspective-specified slant were quite different) a subject experienced bi-stability and was able to select one of the two perceived slants.[6] The occurrence of such a clear bifurcation has been reported before for an ambiguous vertical disparity stimulus (Porrill, Frisby, Adams, & Buckley, 1999), though that study did not report on bi-stability.

In general, after the onset of the stimulus, all five observers first perceived the perspective-dominated slant (see also Schriever, 1925, and Stevens et al., 1991, for very similar findings in bi-stable slant and curvature, respectively). After a couple of seconds, the disparity-dominated percept almost literally "kicked in." During the rest of the presentation period, the two percepts remained present: although spontaneous flips could not be prevented, subjects were able to select either of the two percepts and to flip between them by switching their attention. Another study that looked at stereo-perspective conflicts also reported that perspective dominated initially before disparity took over (Allison & Howard, 2000a). Other relevant studies on the timing issues in perspective-disparity conflict are concerned with slant reversals (Gillam, 1967; Gillam, 1993). Gillam reported perceived slants to be in the direction opposite to that predicted when subjects view a stimulus with rich perspective cues (such as a brick wall) while one of the retinal images was horizontally scaled relative to the other. Those slant reversals also involve perspective-specified slant dominating the disparity-specified slant in initial stages of viewing (Seagrim, 1967). Van Ee conducted a perceptual learning experiment. One of the subjects showed reversed slants only for roughly the first 25 responses of an experimental session. The rest of his responses were in

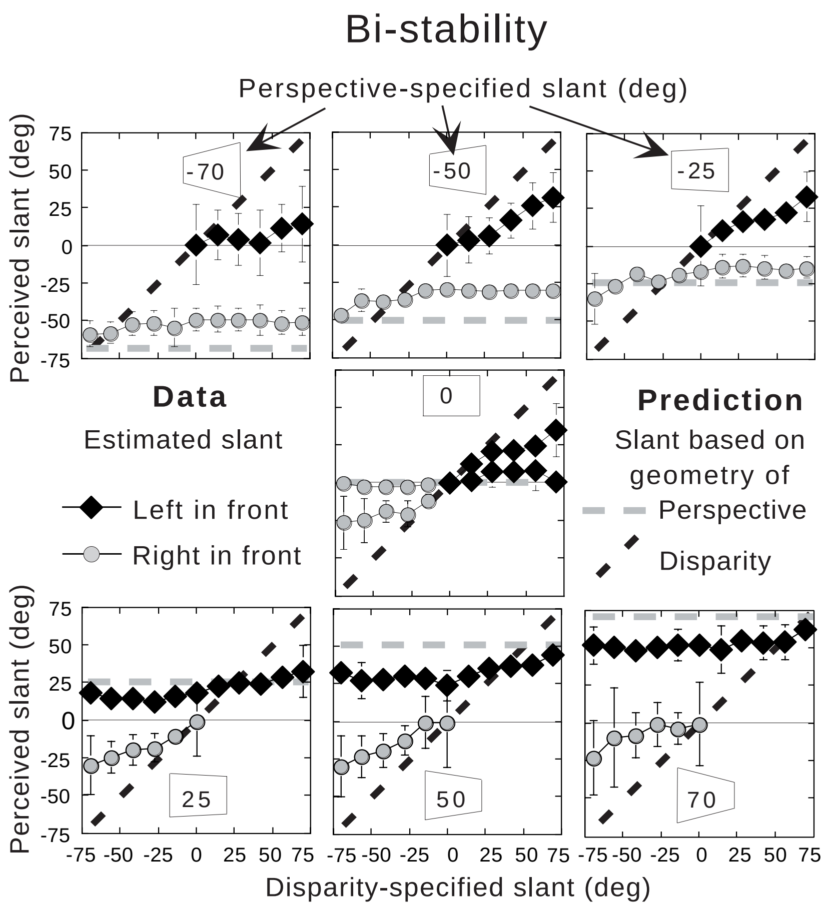

Figure 4. Experimental results for five observers who perceived bi-stability. The graphs depict perceived slant as a function of disparity-specified slant (i.e., slants that were geometrically present in the stimulus). Error bars represent ± 1SD in the mean across the five subjects. The subjects perceived the grid with the left side either behind (grey disks) or in front (black diamonds) of the unslanted reference. The trapezoid-shaped icons depict perspective-specified slant.

the predicted direction. The number of initial slant reversals decreased over one-week interval sessions but did not disappear (van Ee, 2001).

The fact that bi-stability occurs when the conflict between perspective and disparity is small (see particularly the center panel of Figure 4 when perspective is zero) seems to be at odds with the literature on stereo slant perception. Most studies (including our own) report reconciliation of slant cues in such conditions. There are at least two explanations for this difference. First, we used grid stimuli with stronger perspective cues than those that are usually used in research. Second, we explicitly asked subjects to focus on the occurrence of bi-stability (see "Discussion").

Figure 5 shows the mean perceived slants across five trial repetitions for the observer who was able to experience only the perspective-dominated percept. This pattern of data resembles the pattern of data of Figure 4 for the perspective-dominated percept in bi-stability. Figure 6 shows mean perceived slants across five trial repetitions for the observer who was able to experience only the disparity-dominated percept. Although bi-stability occurred occasionally, this pattern of data resembles the pattern of data of Figure 4 for the disparity-dominated percept in bi-stability.

All the data figures show that the observers follow neither the disparity-specified slant nor the perspective-specified slant. So far we have considered only disparity and perspective as cues for grid slant. In a stereoscopic experiment in the laboratory, there are, however, more slant cues available to the visual system; some of them are inevitably conflicting (e.g., accommodative blur, the fixed graininess of the pixels on the screen, or the brightness gradient). In our experiment, these residual cues specify zero slant - often called *flatness* - of the grid. The presence of the flatness cues explains why subjects deviate from both the disparity-specified and the perspective-specified slant even when the two specify the same slant.

In the "Introduction," we referred to considerable differences across subjects during pilot studies. Such differences are commonly found in stereo studies (for a review, see Howard & Rogers, 2002). More relevant for the current study is the fact that two of the studies that reported bi-stability in perception when monocular and

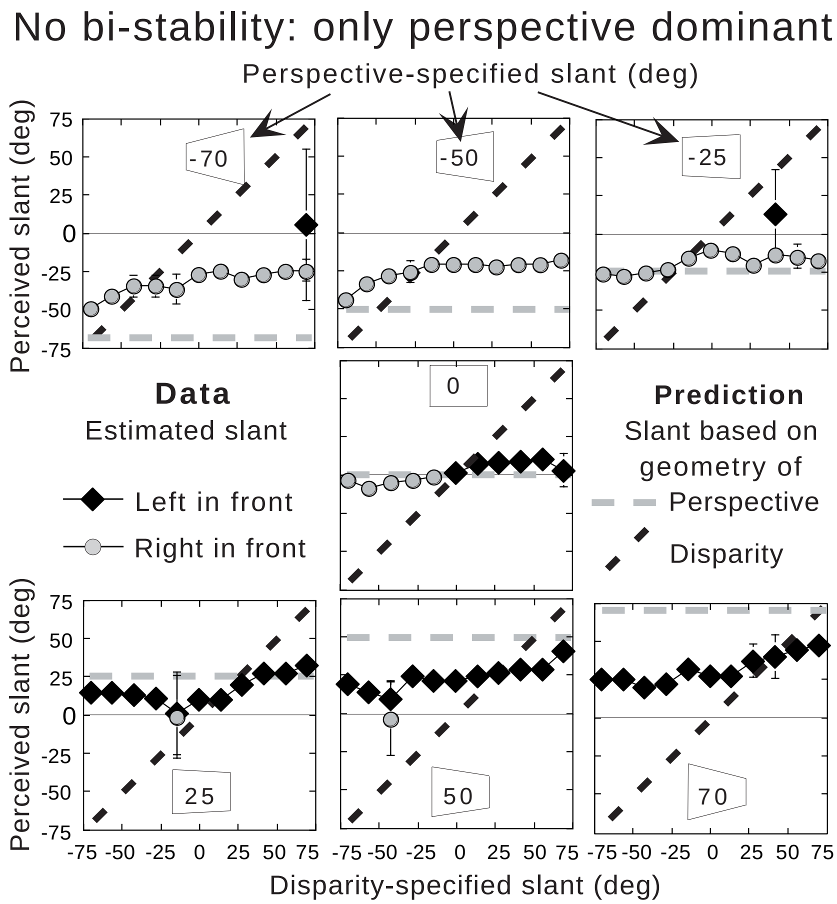

Figure 5. Same as Figure 4 but for a perspective-dominant observer. This observer hardly perceived bi-stability.

binocular cues conflict also found such differences (Schriever, 1925; Stevens et al., 1991). A couple of studies have related the differences across subjects to stereoanomaly (Harwerth, Möller, & Wensveen, 1998; van Ee & Richards, 2002; Rouse, Tittle, & Braunstein, 1989). We found that the differences across subjects were considerably reduced if we selected subjects who were able to distinguish disparities of different sign and magnitude in a recently developed stereoanomaly test (van Ee & Richards, 2002). The subject who continued to see the perspective-dominated percept was unable to distinguish disparities of different sign and magnitude in this test (even while making eye movements).

Discussion

We have examined the metrical aspects of perceived slant for a broad spectrum of possible combinations of disparity- and perspective-specified slants. Observers perceived only one slant when the perspective- and disparity-specified grid orientations were similar. More interestingly, observers with normal stereopsis were able to select either a perspective- or a disparity-dominated slant when the specified orientations were rather different.

Why have so few studies reported on bi-stability in stereo vision? Many investigators have been interested in the interaction of binocular and monocular cues. Quite a few have varied monocular cues (Banks & Backus, 1998; Buckley & Frisby, 1993; Clark, Smith, & Rabe, 1956; Cumming, Johnston, & Parker, 1993; Frisby, Buckley, & Horsman, 1995; Frisby, Buckley, & Freeman, 1996; Gillam, 1968; Gillam & Ryan, 1992; Harwerth et al., 1998; Johnston, Cumming, & Parker, 1993; Ryan & Gillam, 1994; Smith, 1967; Stevens & Brookes, 1988; van Ee, Banks, & Backus, 1999; Youngs, 1976), and others have gone so far as to present binocular cues that specified a depth sign that was opposite to the depth sign specified by monocular cues (Allison & Howard, 2000a; Allison & Howard, 2000b; Braunstein, Andersen, Rouse, & Tittle, 1986; Bülthoff & Mallot, 1988; Bülthoff & Mallot, 1990; Dosher, Sperling, & Wurst, 1986; Gillam & Cook, 2001; Rogers & Collett, 1989; Turner, Braunstein, & Andersen, 1997; van der Meer, 1979). Most of the above-mentioned studies, however, were not concerned primarily with the study of bi-stability. Therefore, they did not employ disparity and perspective stimuli that consisted of large differences in depth magnitude. This might be a first reason why so few studies explicitly report on bi-stability. Second, most

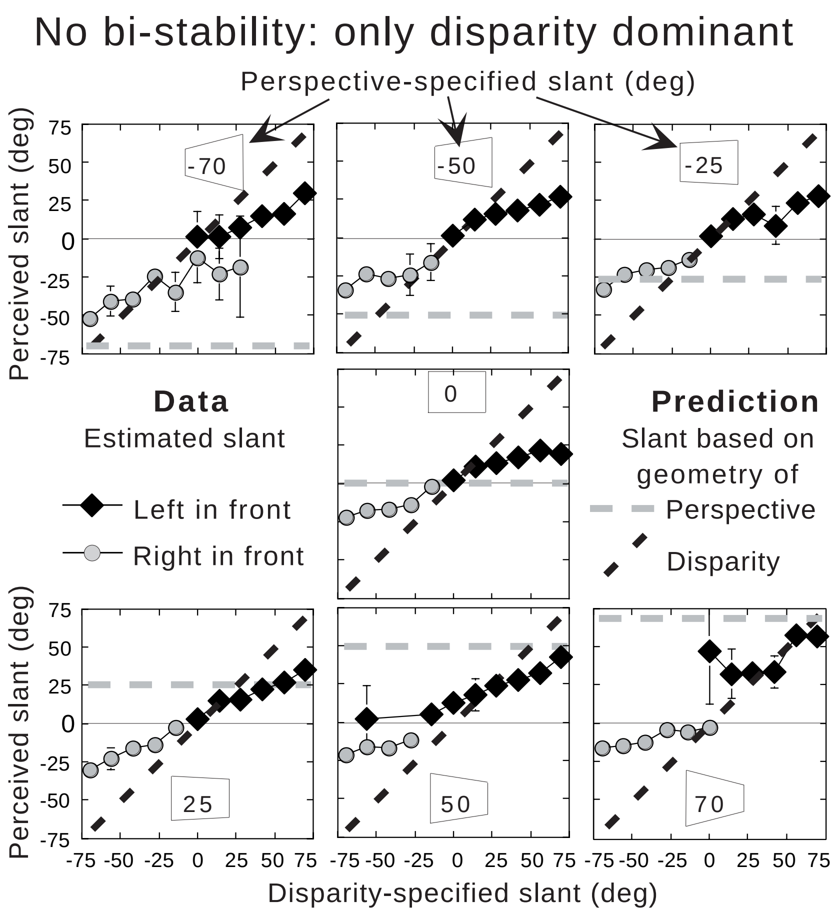

Figure 6. Same as Figure 5 but for a disparity-dominant observer. Just as the observer in Figure 5, this observer hardly perceived bi-stability.

studies that employed rather conflicting cues used short presentation times, which did not leave time to build-up the bi-stable percepts. Third, we used grid stimuli with perspective cues that are stronger than those used in most existing studies. Finally, and perhaps most importantly, we explicitly asked subjects to focus on the occurrence of bi-stability. This relates to the classical question of cognitive intervention in perceptual responses and is difficult to rule out. Some naïve observers might not perceive bi-stability when they are not explicitly instructed to look for it.

Why is it interesting to study bi-stability? Wheatstone (1852, p. 13) wrote[7] "the relief and distance of objects is not suggested to the mind solely by the binocular pictures and the convergence of the optic axes, but also by other signs" (nowadays called cues), "which are perceived by means of each eye singly. One idea being therefore suggested to the mind by one set of signs, and another totally incompatible idea by another set, according as the mental attention is directed to the one and abstracted from the other, the normal form or its converse is perceived." Generally, and often in psychophysics, it is beneficial to study signal interaction under conflicting conditions. Another way of studying perception is to expose the visual system to an ambiguous stimulus that generates bi-stable perception because it creates the rare opportunity of having two states in neural processing that are related to the percepts rather than to the stimulus. Although to our knowledge Brewster and von Helmholtz were not explicit about the occurrence of bi-stability in binocular vision, it might be of historical interest to compare their analyses of reverse perspective. Brewster stated that the reverse perspective illusion "is the result of an operation of our minds, whereby we judge the forms of bodies by the knowledge we have acquired" (quoted in Wheatstone, 1838, p. 383) and von Helmholtz noted that we see objects as those that "produce the same impression on the nervous mechanism under ordinary normal conditions" (von Helmholtz, 1866, Vol. III, §26). These authors understood that we use prior knowledge of the world (and not just the information on the retinae) to infer the object that would most likely have produced the stimulus, an analysis that is now advanced in Bayesian-like analyses of the visual system.

The use that is made of prior knowledge is evident in one of the most striking examples of depth inversion, namely a hollow relief mask which can be seen in reversed perspective despite stereopsis (Yellott & Kaiwi, 1979). Yellott and Kaiwi report that if a random-dot stereogram is projected onto such a mask, stereopsis can be achieved for the stereogram, and its depth planes can be seen correctly while the mask itself, including the region covered by the stereogram, is simultaneously perceived with depth inverted. Frisby and Mayhew (1979) published another striking example on depth inversion in random-dot stereograms. Their observers viewed, by crossing their eyes, a classical Julesz random-dot stereogram that contained a square that receded relative to the surround. If their observers stared at the square while at the same time they forcibly converged their gaze even further, then there came a point at which the depth direction of the square changed and it appeared to protrude in front of the surround, rather than recede. Their explanation for the depth inversion was as follows: “the deliberate act of verging away from the square’s proper depth plane disturbs the usual fusion of the two halves and permits a new fusional state to come about which carries with it depth inversion.” Such an explanation does not account for our results because in our stimulus there is no fusion problem. First, the disparities are relatively small, and there is no matching ambiguity such as occurs in random dot stereograms.

Although spontaneous flips could not be prevented, the flips between the two percepts were attention-driven.[8] Our study does not make clear what happens in a subject’s mind while he or she flips between the two percepts. One way of viewing bi-stability is in terms of the brain constructing an a posteriori probability of the world’s state of affairs conditional on the image data (Kersten, Bülthoff, Schwartz, & Kurtz, 1992). Such a Bayesian approach[9] is consistent with the general notion that the visual system is picking rational and plausible interpretations of scene properties causing the image. An example for a rational interpretation of scene attributes is the finding that a binocularly viewed curved surface is only perceived as glossy if the specular highlight is close to the correct (geometrically derived) distance from the surface (Blake & Bülthoff, 1990).

In our study, subjects were instructed that both ambiguous (flip) and nonambiguous (non-flip) stimuli would be presented and some observers noted “I just wanted to see left in front or right in front” (again, see Schriever, 1925, and Stevens et al., 1991, for very similar findings). Subjects were also informed that the stimuli could be either trapezoidal or rectangular, and some observers explicitly used this information and noted that they switched their attention from attempting to see a trapezoid to attempting to see a rectangle.[10] All stimuli were consistent with a real-world object, which may be trapezoidal or rectangular. It is only by using this type of assumption that linear perspective can be informative. Elsewhere we present a coherent Bayesian model for bi-stability in which it is assumed that observers flipped between the two perceived slants by changing the strength of the rectangularity assumption (van Ee, Adams, & Mamassian, 2002). In the strong-rectangularity mode, the observer is assuming that the object in the world was a rectangle, and deviations from rectangularity in the image are a consequence of perspective projection. In the disparity dominant mode, it is assumed that the observer is implementing a weak rectangularity assumption. In the Bayesian bi-stability model, there is one set of parameters (at the chosen viewing distance) that can explain perceptual bi-stability in stereoscopic vision for the complete spectrum of combinations of perspective and disparity.

Acknowledgments

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Footnotes

1.See also Stevens, Lees, and Brookes (1991), who reported bi-stability in stereoscopic curvature perception; no metrical analyses were involved. Two more studies reported bi-stability for a 3D stimulus in which disparity was varied (Virsu, 1975; and Harris, 1980). They studied the effect of disparity adaptation on the probability of seeing the Schröder staircase either from below or from above. This bi-stability is different from that in our study because the Schröder staircase bi-stability is essentially monocular. Also, to observe a reversal for the Schröder staircase, the observer would have to assume that the relative position of the observer and the object had been altered (for other work on bi-stability, see Gregory, 1970; Papathomas, 2000; Papathomas, 2002; and Wade & Hughes, 1999).

2.Wheatstone (1838) also described the shape deformations in rotating stimuli as was described in 1951 by Ames (for the famous rotating trapezoidal window). Such shape deformations can be compared with the nonrigidity that is experienced when cues from stereo and structure-from-motion interact while a rotating figure is observed in reversed perspective (Turner, Braunstein, & Andersen, 1997).

3.In his 1838 study, Wheatstone is not entirely clear about bi-stability in binocular vision. On page 381, he writes that the bi-stability “phenomenon takes place, though less decidedly, when the drawing is seen with both eyes,” and there are a couple of examples. But on page 382, he states very clearly that “no illusion of this kind can take place when an object of three dimensions is seen with both eyes.” In 1839, about 6 months after the appearance of the 1838 study, photography was being introduced and shortly afterwards Wheatstone used photographs of objects in his stereoscope. The use of photographs enabled him to use more realistic monocular cues to depth.

4.Although eye movements play a role, the general consensus is that the bi-stability is predominantly central (for a review, see Howard, 1961). We are currently measuring eye movements while subjects experience bi-stability in our grid stimuli. Our preliminary conclusion is that flips between the two percepts in the bi-stability evoked by our stimuli can occur by effort of will while subjects keep strict fixation.

5.A reasonable objection to this metrical slant estimation method is that it is hard to interpret the data because a slant angle that is estimated to be 35 deg in one trial might look like 40 deg in another trial. Previous work has demonstrated, however, that subjects have a relatively constant internal reference and that they do not regard this task as difficult. This estimation method has been used previously for real planes (van Ee, Banks, & Backus, 1999) and when subjects wore distorting lenses (Adams, Banks, & van Ee, 2001). In addition, a similar metrical depth estimation method was successfully used for volumetric stimuli (van Ee & Anderson, 2001).

6.A reviewer posed the interesting question as to whether observers are able to perceive bi-stability in monocular stimuli. We found that subjects did not perceive bi-stability when we presented them with monocular trapezoids and rectangles (van Ee, Hol, & Erkelens, 2001). We provided controls for monocular images for both the right (green) eye and the left (red) eye and also for synoptic presentation in which the images were presented in yellow for vergence posture, as if the stimulus was located at infinity.

7.Note that as early as 1852, he explains the resulting percepts in terms of cue combination.

8.See Wheatstone, 1852, and particularly see McDougall, 1906, and Flügel, 1913, for seminal discussions about the role of attention (or central processing as opposed to an influence of eye movements).

9.Bayesian modeling has been successfully applied in computer vision (for a review, see Knill & Richards, 1996), and in the last decade, several investigators have started to apply this framework to human vision (Porrill, Frisby, Adams, & Buckley, 1999; Bülthoff & Yuille, 1991; Bülthoff & Mallot, 1990; Clark & Yuille, 1990; Yuille & Bülthoff, 1996; Freeman, 1994; Freeman, 1996; Bülthoff & Yuille, 1990; Bülthoff, 1991; Yuille, Geiger, & Bülthoff, 1991; Ascher & Grzywacz, 1999; Hogervorst & Eagle, 1998; Kontsevich & Tyler, 1999; Mamassian & Landy, 1998; Mamassian & Landy, 2001; Read, 2002).

10.This is related to the generic viewpoint assumption that observers make while viewing visual objects (Freeman, 1994; Nakayama & Shimojo, 1992).

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