3

The influence of monocular regions on the binocular perception of spatial layout

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Early observations by Leonardo da Vinci (*c.* 1508) noted that the two eyes can see different parts of the background at the edges of occluding surfaces. This is illustrated in Leonardo's drawing (Figure 3.1) and for two cases in Figure 3.2. In Figure 3.2a, an occluder hides the dotted region of background from both eyes, but there is a region on the right which only the right eye can see and a region on the left which only the left eye can see. Figure 3.2b shows a similar effect of looking through an aperture. In this case, a region on the left of the background seen through the aperture is visible to the right eye and vice versa. It is only since the early 1990s or so that there has been any serious investigation of the perceptual effects of such monocular occlusions, and a whole new set of binocular phenomena, involving the interaction of binocular and monocular elements in determining spatial layout, have been demonstrated and investigated (Harris and Wilcox, 2009). In this chapter, I shall concentrate on four novel phenomena that exemplify different ways in which unpaired regions influence binocular spatial layout.

(1) *Da Vinci stereopsis*. This will be defined as the perception of monocular targets in depth behind (or camouflaged against) a binocular surface according to constraints such as those shown in Figure 3.2.
(2) *Monocular-gap stereopsis*. In this case, monocular regions of background influence the perceived depth of binocular surfaces.
(3) *Phantom stereopsis*. This refers to the perception of an illusory surface in depth "accounting for" monocular regions in a binocular display.

Vision in 3D Environments, ed. L. R. Harris and M. R. M. Jenkin. Published by Cambridge University Press.

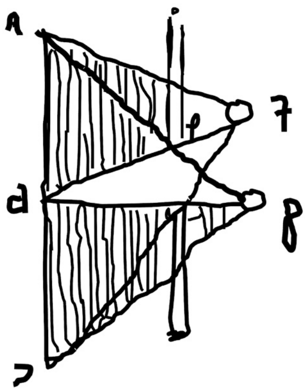

Figure 3.1 Adapted from Leonardo's drawing. Two eyes on the right looking through an aperture to a surface on the left.

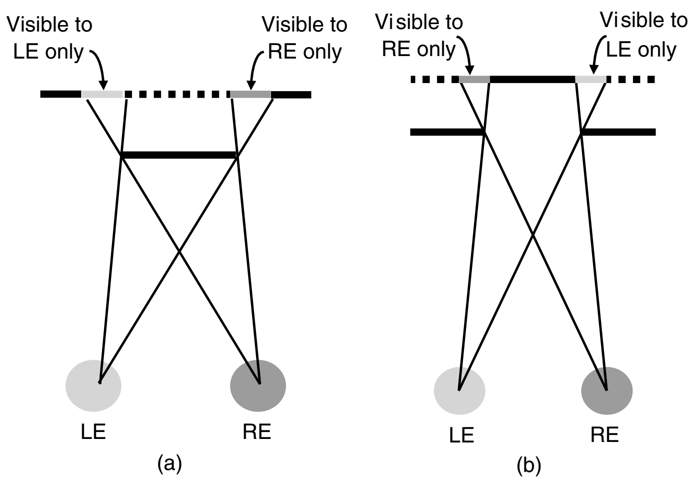

Figure 3.2 Different views to different eyes. (a) Two eyes looking at a background behind an occluding surface. The right eye (RE) sees more of the background on the right and the left eye (LE) sees more on the left. (b) Two eyes looking through an aperture at a background surface. The right eye sees more of the background on the left, and vice versa.

(4) *Ambiguous stereopsis*. This refers to the interesting situation in which there is not an explicit monocular region, but the visual system treats a disparate contour as either slanted or occluded depending on the context. In the latter case, the extra width in one eye's image is attributed to differential occlusion in the two eyes rather than to slant.

A major theme of this chapter is the relationship between monocular-occlusion-based binocular depth perception and regular disparity-defined depth perception.

This issue involves three questions:

(1) To what extent is depth caused by monocular occlusion explained *directly* by disparity-based depth? In other words, regular disparity is present but overlooked. For an example in which this turned out to be the case, see a series of articles on the phantom rectangle by Liu *et al.* (1994, 1997), Gillam (1995), and Gillam and Nakayama (1999).

(2) Given that regular disparity-based depth is ruled out, to what extent does depth based on monocular occlusion resemble disparity-based depth in its effects? For example, how quantitative and precise is it? How is it constrained?

(3) How does monocular occlusion depth interact with depth based on regular disparity?

3.1 Da Vinci stereopsis

The term "da Vinci stereopsis" was introduced by Nakayama and Shimojo (1990) to describe the depth seen for the monocular bar in the stereogram of Figure 3.3. They found that a monocular bar, for example to the right of the right eye's image of a binocular surface, appeared behind it to a degree that is predicted by the geometry of a "minimum-depth constraint," a useful concept they introduced. The minimum-depth constraint is illustrated in Figure 3.4 for a monocular bar on the left of the left eye's view. To be seen only by the left eye, the bar would have to be behind the binocular surface to a degree determined by its separation from that surface. This represents the minimum

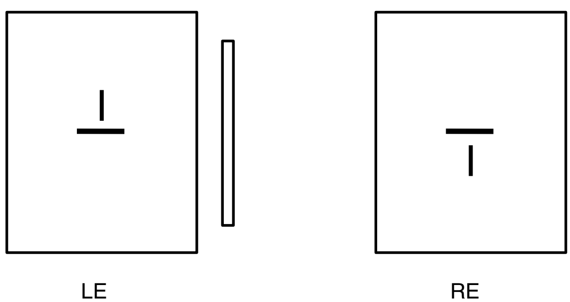

Figure 3.3 Nakayama and Shimojo's stimuli for da Vinci stereopsis. Uncrossed fusion.

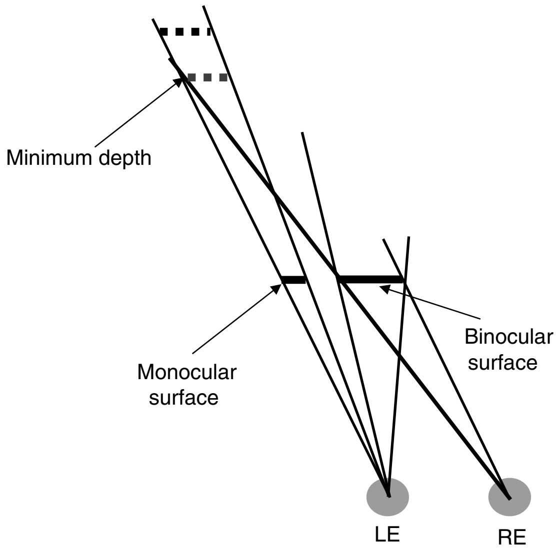

Figure 3.4 Minimum-depth constraint for a monocular surface to the left of a binocular surface. The depth of the inner edge, as well as the outer edge of the monocular surface, is constrained.

depth satisfying the geometry, although the depth could be greater and still be within the monocular occlusion zone on that side. Note that the position of the inner edge of the bar is also constrained by the angular separation between it and the binocular surface.

It appears, however, that the stimulus used by Nakayama and Shimojo (1990), which consisted of long vertical contours for both the monocular bar and the binocular surface, contains the potential for a form of regular, disparity based stereopsis. This is an instance of Panum's limiting case (Panum, 1858) in which a single contour in one eye can fuse with several contours in the other eye. Häkkinen and Nyman (1997) and Gillam *et al.* (2003) provided experimental support for this view, each group showing that a monocular target that was within the monocular constraint zone of a binocular surface but not fusible with its edge failed to produce quantitative depth, although it did look somewhat behind the binocular surface (Figure 3.5). Assee and Qian (2007) have modeled the data of Nakayama and Shimojo (1990) as a form of Panum's limiting case.

Is quantitative depth for a monocular da Vinci target that is not attributable to regular stereopsis possible? For an indication that it is, we must go back to the demonstrations of von Szily (1921), whose work was almost unknown until recently. Figure 3.6 shows a von Szily stereogram. When the right pair is cross-fused or the left pair is fused uncrossed, the monocular tab appears to be

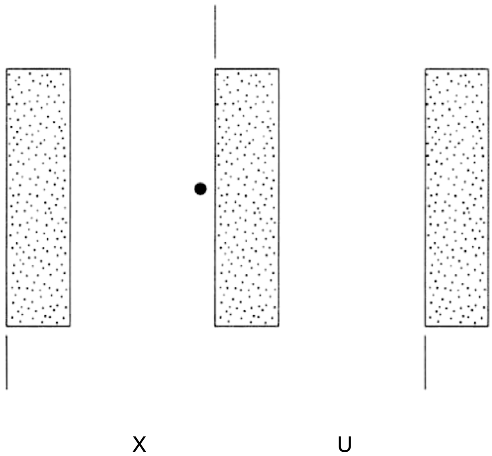

Figure 3.5 Stimulus used by Gillam *et al.* (2003). The dot appears behind, but the depth in not quantitative.

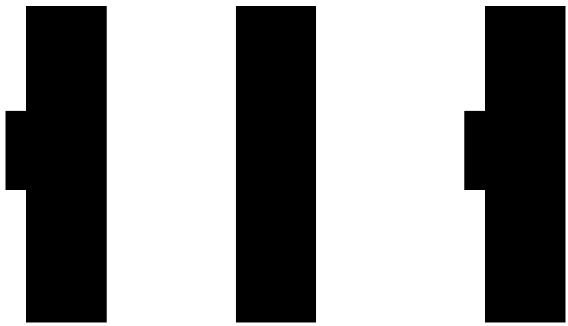

Figure 3.6 Stimulus from von Szily (1921) with attached monocular tabs. Fuse either the left or the right pair.

behind. When the reverse occurs, the tab appears in front. A strong indication that fusional stereopsis between the edge of the binocular surface and the edge of the tab is not responsible for the perceived depth is that the tab appears in depth but in the frontal plane, whereas fusional depth should cause it to slant. In the von Szily figures, unlike those of Nakayama and Shimojo (1990) and Gillam *et al.* (2003), the tabs are attached to the binocular surface. A consequence of this is that only the position of the outer side of the tab is subject to the minimum-depth constraint (Figure 3.7). The other (inner) side could be anywhere behind the binocular surface. (As Figure 3.4 shows, a detached bar has two constraints, one for each side.) Note also that in the in-front case the unseen partner of the monocular tab must be treated as camouflaged against the binocular

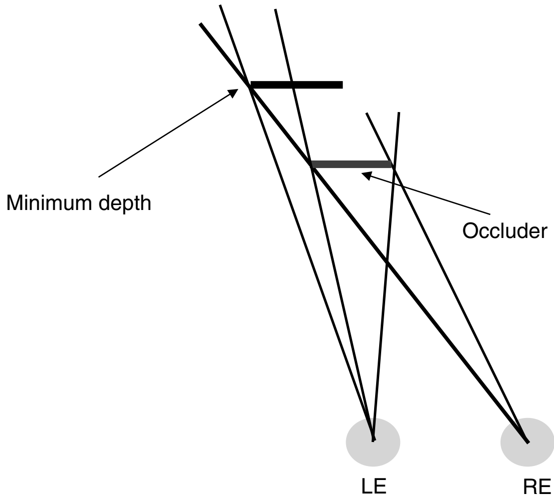

Figure 3.7 Minimum-depth constraint for a tab attached to a binocular surface. Note that only the left side of the monocular tab is constrained.

surface rather than occluded by it. Nakayama and Shimojo (1990) did not obtain depth in a camouflage configuration, although it was demonstrated by Kaye (1978).

Figure 3.8a is a demonstration of a series of attached monocular tabs (extrusions) in near and far da Vinci configurations next to a binocular surface illustrating occlusion (both tab colours) and camouflage (black tabs only). For red tabs, camouflage should not be possible (red cannot be camouflaged against black) and, indeed, the near responses, which depend on camouflage, occur readily with the black tabs but seem to be lacking for the red tabs. Figure 3.8b shows the case of monocular "intrusions." When the intrusion is on the right side of the binocular surface for the left eye or vice versa, the intrusion stimulus resembles the situation illustrated in Leonardo's original diagram (Figure 3.1). The binocular surface is seen through an aperture, and the tab is seen behind the aperture on the black surface. As with the extrusions, the far conditions depend on occlusion of one eye's view of the tab, so its color does not matter, whereas, for the near condition, the tab depth depends on camouflage against the white background and the tab cannot validly be red. As expected, the depth effect seems attenuated in this case.

An empirical study of da Vinci depth using the intrusion type of monocular element was carried out by Cook and Gillam (2004). They compared depth for attached tabs and detached bars with the same edge displacement from the binocular surface (Figure 3.9). In each case, observers had to set a binocular

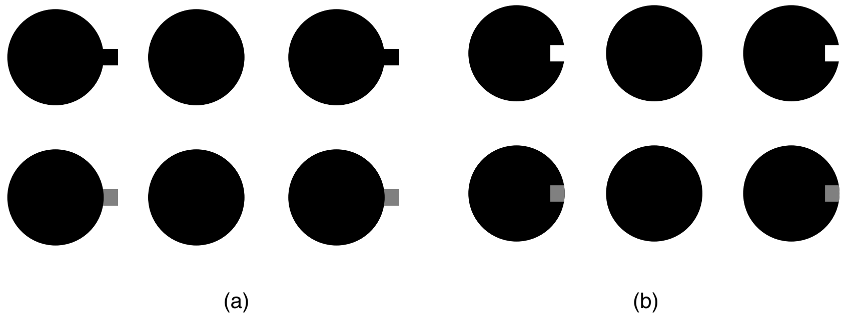

Figure 3.8 Monocular extrusions and intrusions. (a) Monocular extrusions. Cross-fusion of the left pairs causes the tabs to appear behind. Cross-fusion of the right pairs causes the black tab but not the red tab to appear in front. (b) Monocular intrusions. Cross-fusion of the right pairs causes both tabs to appear behind. Cross-fusion of the left pairs causes the white tab but not the red tab to appear in front. A color version of this figure can be found on the publisher's website (www.cambridge.org/9781107001756).

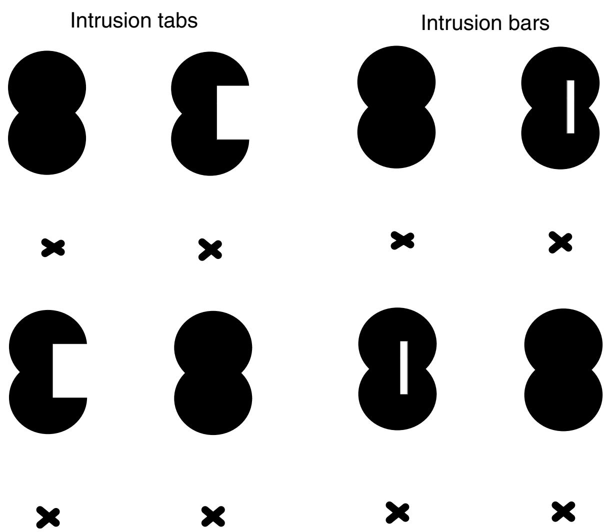

Figure 3.9 Four of the stereograms used in Cook and Gillam's (2004) experiment using monocular attached tabs or detached bars.

probe to the apparent depth of the edge of the bar or tab. Figure 3.10 shows data for seven individual observers. All seven showed a lack of quantitative depth for the bar and a clear quantitative effect, following the minimum-depth constraint, for the equivalent tab. However, whereas five observers (Type 1) were

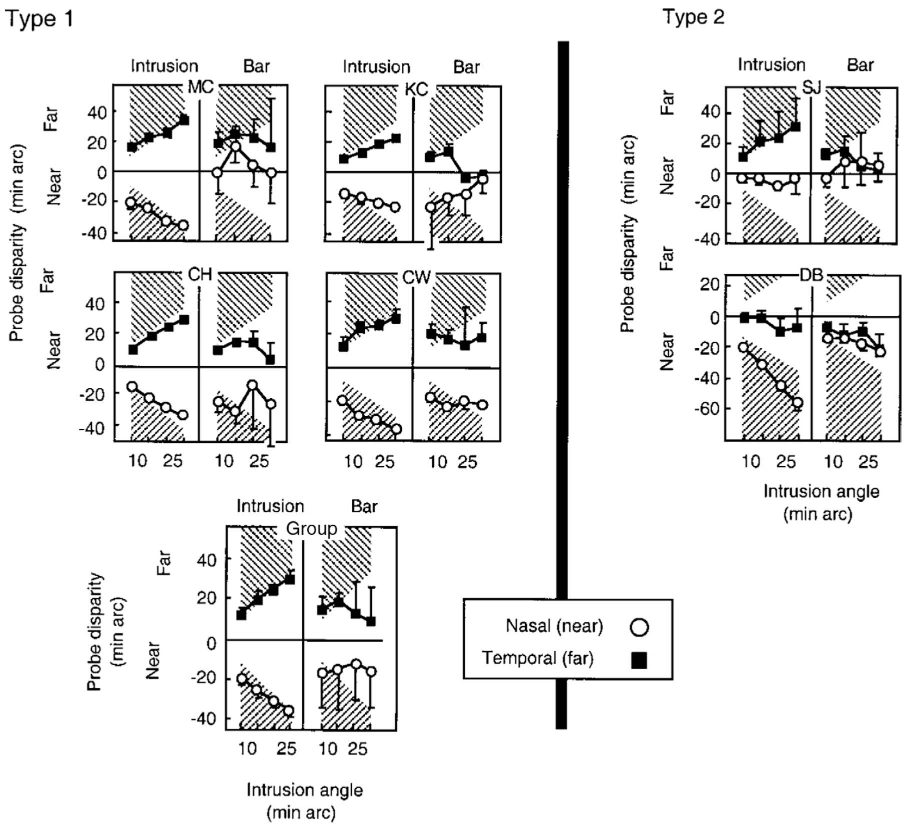

Figure 3.10 Data for Cook and Gillam's (2004) experiment. Gray-shaded areas represent monocular occlusion zones and their edges represent minimum-depth constraints. Intruding tabs but not detached bars (see Figure 3.9) follow this constraint.

able to see both a case where the tab appeared nearer than the dumbbell and a case where it was seen through the dumbbell as an aperture, two observers (Type 2) could not see depth in the aperture case (upper left stereogram in Figure 3.9).

Cook and Gillam (2004) proposed that the critical factor necessary to obtain quantitative depth in a da Vinci situation is the presence of cyclopean T-junctions, which are present only for the attached tabs. This term refers to T-junctions formed when left- and right-eye stereoscopic views are superimposed. This is illustrated in Figure 3.11. These seem to suppress a fusional depth response. This view is supported by a control experiment made possible by the dumbbell configuration. Cook and Gillam showed that fusional depth does not

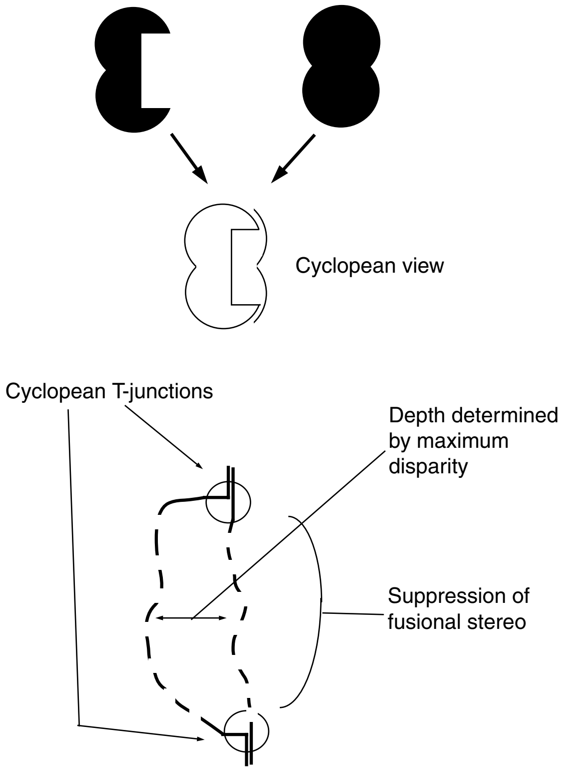

Figure 3.11 A fused monocular intrusion figure results in cyclopean T-junctions.

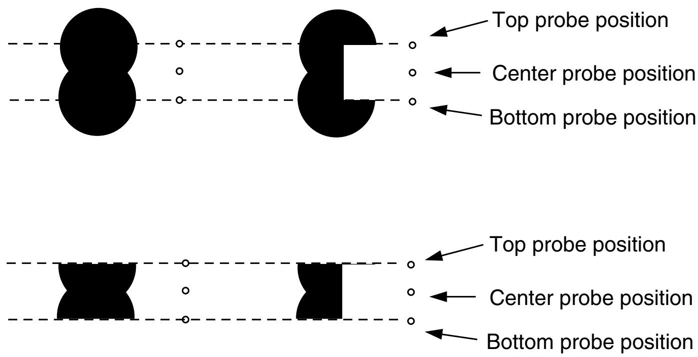

Figure 3.12 Stimuli for Cook and Gillam's (2004) control experiment. (See text.)

occur when cyclopean T-junctions are present but emerges for the same contours when they are absent. The cyclopean T-junctions were eliminated by using only the center of the dumbbell figure (Figure 3.12). Three depth probes were used as shown to measure depth along the vertical edges of the intrusion and

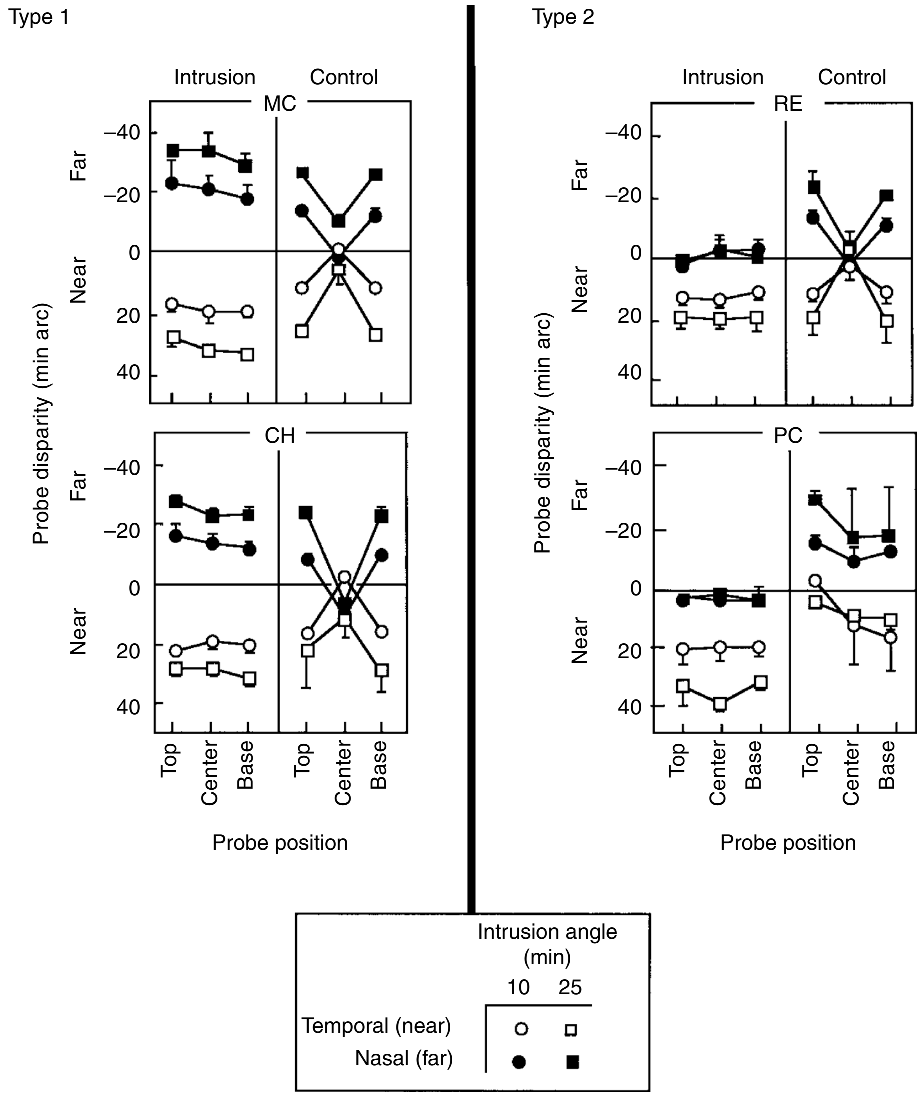

Figure 3.13 Data for Cook and Gillam's (2004) control experiment showing that variation in depth across probes (fusional stereo) occurs for the control condition only.

the control. Disparity-based depth should result in a greater depth for the middle probe than for the upper and lower probes, following variations in disparity. Occlusion-based depth, on the other hand, should result in a constant depth for the three probes. Figure 3.13 shows the results. It is clear that the depth variation is present only for the control figure and not for the full figure with the cyclopean T-junctions.

To summarize our conclusions concerning da Vinci stereopsis:

(1) It can be quantitative and precise if a monocular element is attached to the binocular surface. If the monocular element is detached, it can appear behind but its depth is nonquantitative.
(2) Cyclopean T-junctions seem to initiate da Vinci type depth for a monocular tab and to inhibit regular disparity-based depth.
(3) To be valid for near depth (camouflage configuration) an extrusion needs to match the luminance and color of the binocular surface and an intrusion needs to match the luminance and color of the background. It appears that near da Vinci depth effects require these matchings (Figure 3.8). This issue needs quantitative investigation, but the demonstrations suggest a new form of binocular matching – of surface properties rather than of contours.

3.2 Monocular-gap stereopsis

Figure 3.14 shows a bird's eye view of two black rectangles at different depths viewed in front of a white background. The inner ends of the black rectangles are abutting in the left-eye view, whereas the right eye can see between them. A stereogram of this situation is shown beneath the layout represented. This is an interesting situation because only the outer vertical edges in the right eye's view have matches in the left eye's view. Based purely on

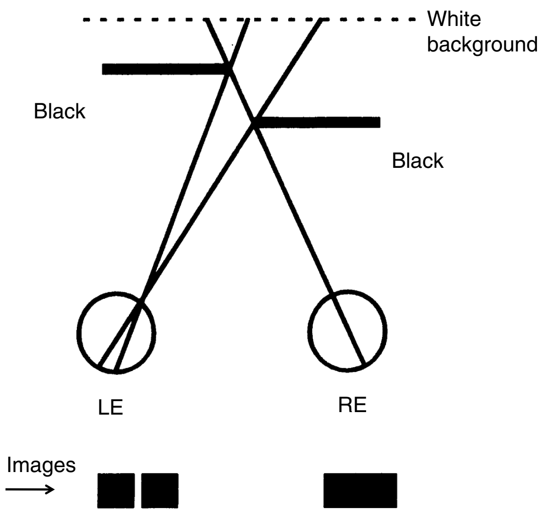

Figure 3.14 The basic stimulus for Gillam *et al.*'s (1999) monocular-gap stereopsis.

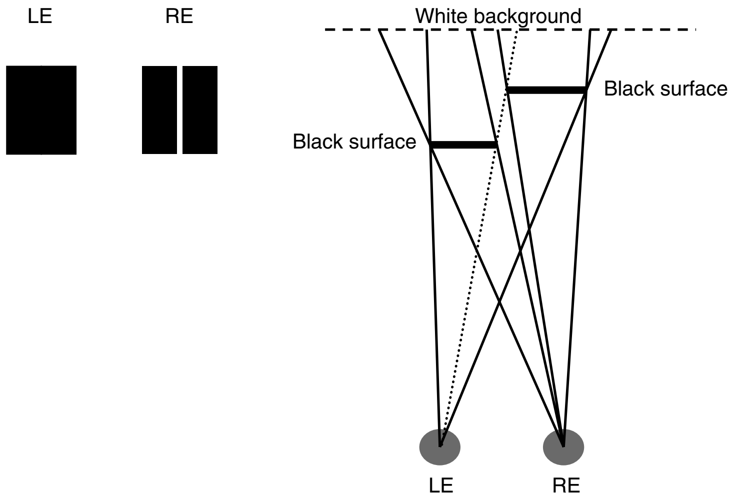

Figure 3.15 In the right diagram, the dotted line represents a hypothetical division of the solid rectangle in the left eye's view. Binocular geometry then predicts the perception of frontal-plane rectangles at different depths.

regular stereoscopic principles, one might expect to see a slanted surface with a rivalrous inner whitish patch. However, considering all the information as informative about spatial layout, it becomes clear that a monocular region of background could only arise from two surfaces, separated in signed depth, with the more distant rectangle on the side of the eye with the gap. Indeed, this is what is seen. If the rectangles are assumed to be abutting in the image of the eye without the gap, the gap becomes equivalent to a disparity, and the surfaces should appear to have depth accordingly. The geometry is shown in Figure 3.15. Gillam *et al.* (1999) measured the depth for this stimulus and found that it could be quantitatively predicted by treating the gap as a disparity. Grove *et al.* (2002) found that, for the depth to be optimal, the monocular gap had to be of the same color and texture as the background. This is clearly a form of binocular depth due to the application of occlusion geometry. It cannot be attributed to regular disparity-based stereopsis, since there is no disparity at the gap where depth is seen.

We asked two questions:

(1) What is the nature of the depth signal? Is it generated at the gap, or is it a depth signal given by the disparity at the edges of the configuration and merely displaced to the gap?
(2) What information is the depth signal based on, and what constraints are applied?

3.2.1 Nature of depth signal

Pianta and Gillam (2003a) investigated the nature of the depth signal in two experiments using the stimuli shown in Figure 3.16. In the first experiment, we compared depth discrimination thresholds as a function of exposure duration for a monocular-gap stimulus (Figure 3.16b), an equivalent binocular-gap stimulus with a disparity equal to the gap (Figure 3.16a), and a third stimulus (Figure 3.16c) with no gaps but with an edge disparity equal to that of the other two. The results are shown in Figure 3.17. The depth thresholds for monocular-gap and binocular-gap stimuli were very similar for all three observers, whereas the threshold for detecting the edge disparity (slant) was greatly raised, despite it sharing the (only) disparity present in the monocular-gap stimulus (at the edges). This finding refutes the idea that the depth at the monocular gap is merely the depth signal at the edges displaced to the gap. This idea is embodied in the Grossberg and Howe (2003) model of this phenomenon. We conclude that the presence of a monocular gap not only locates depth away from the location of the disparity but also greatly improves the depth signal. Similar mechanisms appear to mediate depth discrimination for monocular and normal stereo stimuli in this case.

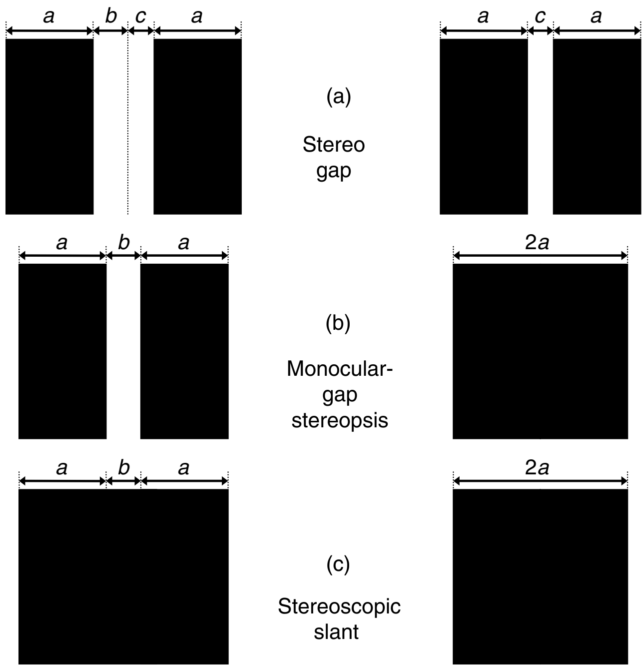

Figure 3.16 Stimuli used in the experiments of Pianta and Gillam (2003a). In all cases, the edge disparity equals *b*.

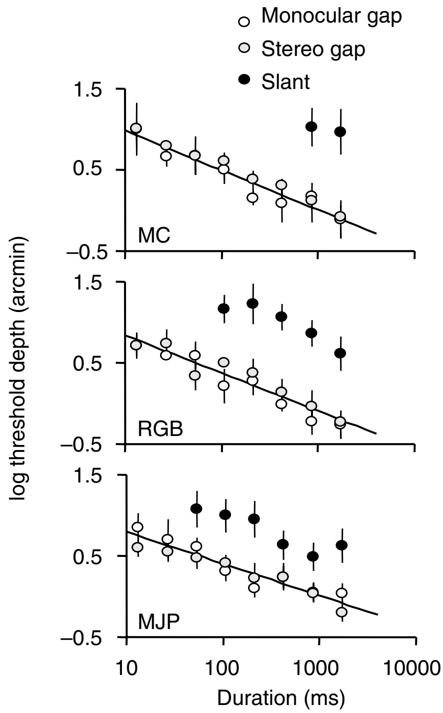

Figure 3.17 Thresholds for detecting depth for the three stimulus types shown in Figure 3.16. (Three observers.)

To test this last assertion, our second experiment compared depth aftereffect transfer to the regular stereo stimulus shown in Figure 3.16a using all three stimuli shown in Figure 3.16 as inducing stimuli. We used a Bayesian method with multiple staircases (Kontsevich and Tyler, 1999) to track the adaptation over time. The results are shown in Figure 3.18. The aftereffect was identical for monocular-gap and stereo-gap stimuli, but there was no aftereffect for the stimulus with edge disparity only. Adaptation therefore cannot be attributed to the disparity per se. It appears to affect a depth signal that is common to unpaired and normal stereo stimuli but not the edge-based (slant) stimulus, despite its common edge disparity with the monocular-gap stimulus.

3.2.2 *What constraints are used?*

The monocular gap constrains the response to include a signed depth step at the gap. The edge disparity constrains the depth at the outer edges of the figure. However, any monocular-gap stimulus is ambiguous. In Figure 3.15, for example, the rectangles seen in depth could be slanted or even differently

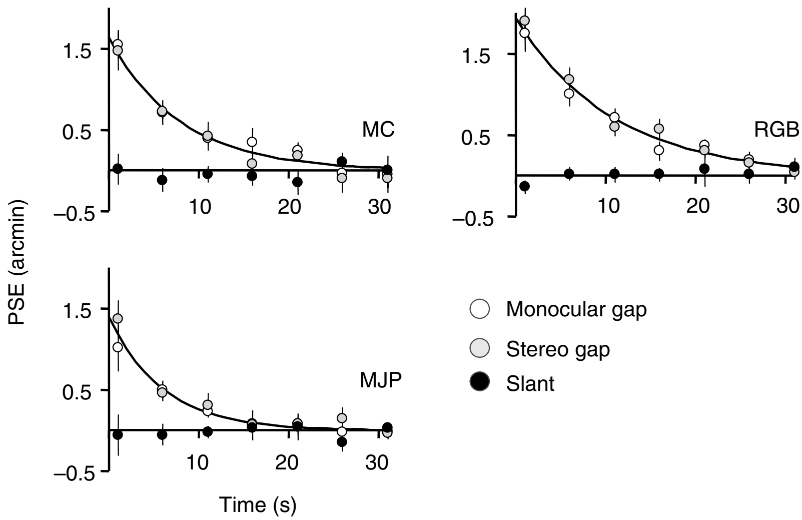

Figure 3.18 Decay of aftereffects for the three stimuli shown in Figure 3.16. The two gap stimuli (monocular and stereo) gave very similar results, while the slant stimulus had no aftereffect (Pianta and Gillam, 2003a).

slanted and not violate the geometry but the depth accompanying a slanted solution would have to be larger than that predicted by the frontal plane solution. The finding that the frontal plane solution rather than one of the possible slanted solutions could be due to either a minimum-depth constraint or a minimum-slant constraint. In our next experiment (Pianta and Gillam, 2003b), we examined this question, exploring the roles of edge disparity and gap size independently in determining depth and attempting to determine what constraints are imposed.

We used three types of stimuli, shown at the bottom of Figure 3.19. They varied in the width of the solid rectangle. Figure 3.19a shows the monocular-gap stimulus used in our previous experiments, in which the gap width and edge disparity were the same. The stimulus shown in Figure 3.19b has no edge disparity. The only depth resolutions compatible with the geometry for this stimulus are slanted. This stimulus has no disparity anywhere. The final stimulus (Figure 3.19c) was critical in revealing constraints. It had an edge disparity twice as great as the gap for each gap size. This allowed separation of the predictions of the minimum-depth and minimum-slant constraints. The minimum-depth constraint would predict slanted rectangles with the same depth as in Figure 3.19a, whereas the minimum-slant constraint would predict frontal-plane rectangles with twice the depth of that in Figure 3.19a. Both of these solutions are compatible with the geometry. The results are shown in Figure 3.20, where parts (a),

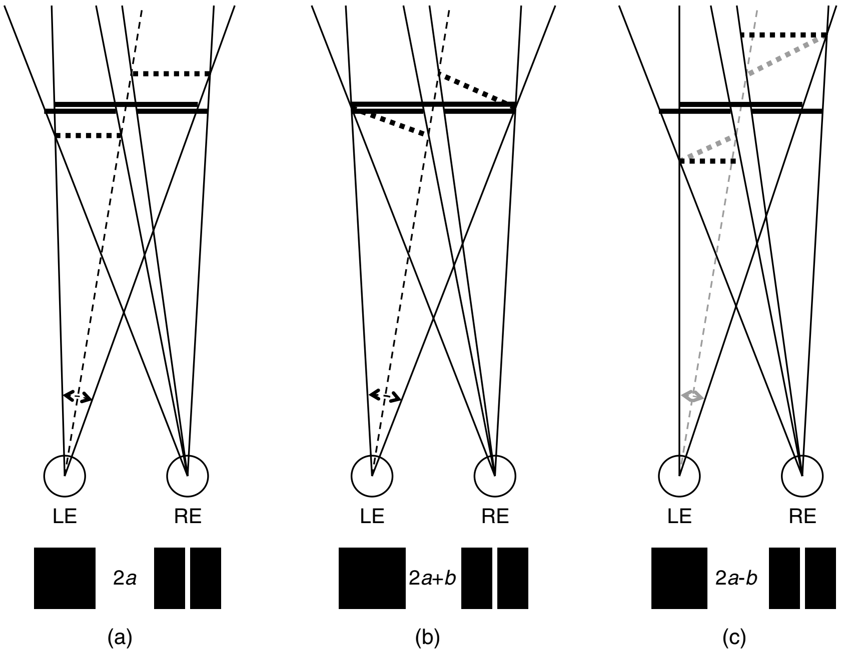

Figure 3.19 The types of stimuli used in the depth-matching experiment of Pianta and Gillam (2003b). The width of the solid rectangle is given with each pair of stimuli: *a* refers to the width of each rectangle in the eye with a gap, and *b* refers to the width of the gap. Possible resolutions are shown by the dotted lines in each case.

(b), and (c) correspond to the three stimuli shown in Figure 3.19. Figure 3.20a confirmed our previous data, with quantitative depth predicted by both the minimum depth and the minimum slant constraints. Figure 3.20b, despite the complete absence of disparity, showed increasing depth as a function of the gap but for two observers the depth was less than that predicted by the minimum-depth constraint. For Figure 3.20c, the depth clearly followed the minimum-slant constraint in that the depth was twice as great as the prediction of the minimum-depth constraint (which would have required a slanted solution). It is interesting that the minimum-slant solution is favored even though it implies overlapping rather than abutting images in the eye with the solid rectangle.

This experiment shows that depth is always seen when there is a monocular gap. When the geometry would require a slanted solution, however, the geometry is not fully realized perceptually. This could be the result of conflicting perspective. When the edge disparity is greater than the gap width, a frontal-plane solution is always possible and is strongly preferred over a slanted

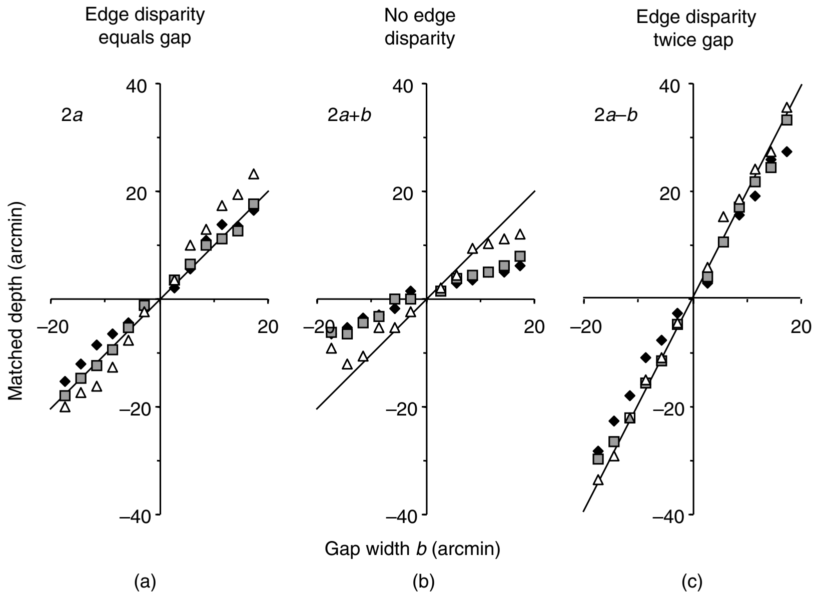

Figure 3.20 Results of the Pianta and Gillam (2003b) experiment measuring perceived depth in monocular-gap stereograms, where the width of the solid rectangle was varied. (See text and Figure 3.19 for details.)

solution with a smaller depth. We conclude that a minimum-slant constraint is applied where possible and that gap size and edge disparity jointly determine the highly metric depth seen at the gap.

3.3 Phantom stereopsis

This phenomenon was discovered by Nakayama and Shimojo (1990). When a few monocular dots were placed next to a set of sparsely spaced binocular dots on the valid side for a monocular occlusion zone, a ghostly contour was seen at the edge of the binocular dots, apparently "accounting for" the monocularity of the extra dots. Anderson (1994) showed that vertical lines that are different in length in the two eyes produce oblique phantom contours that account for the vertical difference. Gillam and Nakayama (1999) devised a very simple stimulus completely devoid of binocular disparity, consisting of a pair of identical lines in the two eyes but with a middle section of the left line missing for the right eye and a middle section of the right line missing for the left eye. This gives rise to a phantom rectangle in front of the middle section of the lines,

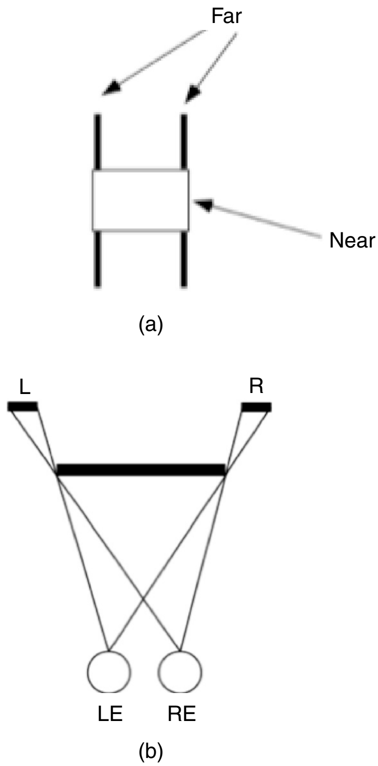

Figure 3.21 (a) Rectangle in depth hiding the center of the left line for the right eye, and vice versa. (b) Geometry of minimum-depth constraint for this stimulus.

accounting for the missing middle sections in each eye as shown in Figure 3.21a. Figure 3.21b shows the geometry of the minimum-depth constraint for this stimulus. The wider the lines, the greater the depth of the rectangle would have to be to hide each of the middle sections of the lines from one eye only. Figure 3.22 is a stereogram demonstrating the phantom rectangle for uncrossed and crossed fusion. Gillam and Nakayama (1999) showed that the depth of the rectangle is quantitatively related to the width of the lines, but they and several other investigators (Grove *et al.*, 2002; Mitsudo *et al.*, 2005, 2006) found that the perceived depth is greater than the minimum-depth constraint. Furthermore, Mitsudo *et al.* (2005, 2006) found that the phantom rectangle but not its inverse (the same stimulus with eyes switched) is more detectable in disparity noise, has a lower contrast detection threshold, and supports better parallel visual-search performance than does an equivalent disparity-defined stimulus. They attributed these results to the greater apparent depth of this stimulus and argued that a long-range surface process based on unpaired regions is resolved

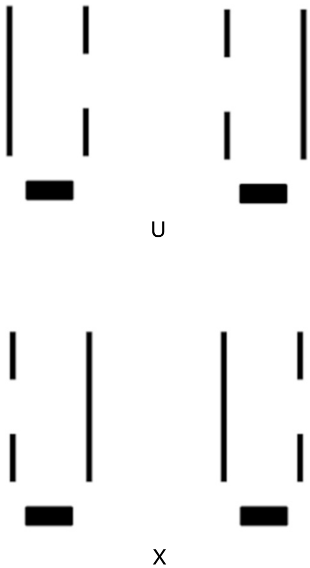

Figure 3.22 Left and right images for the situation shown in Figure 3.21. For crossed fusion, use the lower images.

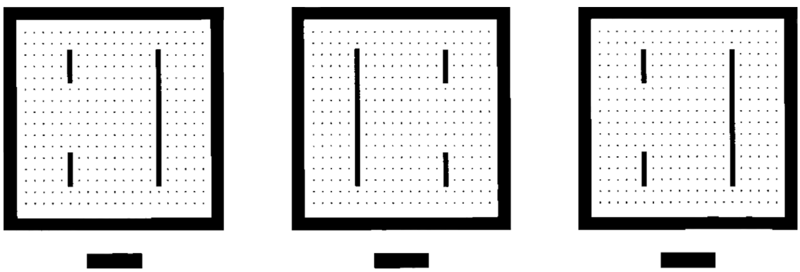

Figure 3.23 The regular dotted texture in the background is remapped to show capture by the apparent depth of the phantom rectangle. Left pair for crossed and right pair for uncrossed fusion. Reprinted from Häkkinen and Nyman (2001).

early in the visual system. The phantom rectangle behaves like disparity-defined stereopsis in several other ways. Häkkinen and Nyman (2001) showed that it supports visual capture (Figure 3.23). It also shows scaling with changes in vergence that are very similar to those found with an equivalent disparity-defined rectangle (Kuroki and Nakamizo, 2006). These many similarities with disparity-based stereopsis for a stimulus that has no disparity anywhere are particularly challenging to the view that depth based on monocular regions is a distinct process from disparity-defined depth.

3.4 Ambiguous stereopsis

Unlike the phantom-stereopsis stimulus, which has no disparity at all, the final case to be considered has horizontal disparity that can be shown to support regular stereopsis perfectly well. Because of the context, however, the visual system prefers instead to attribute the horizontal difference or differences in the image not to slant but to differential occlusion in the two eyes. Figure 3.24 shows how the same horizontal disparity could be produced by a slant or an occlusion.

Häkkinen and Nyman (1997) were the first to investigate responses to this ambiguity, showing that when a taller binocular surface was placed next to a disparate rectangle in a valid position for its partial occlusion, the perceived slant of the rectangle was significantly attenuated.

Gillam and Grove (2004) used sets of horizontal lines aligned on one side (Figure 3.25.) The lines were made longer in one eye's view either by horizontally magnifying the set of lines in that eye (not shown) or by adding a constant length to that set (middle set in Figure 3.25). In the former case, uniform slant was seen, consistent with the uniform magnification of the lines in one eye's view. In the latter case, a phantom occluder appeared in depth, accounting for the extra constant length in one eye's view. This only occurred, however, when the longer lines were on the valid side (right in the right eye or left in the left eye) as in the left pair shown in Figure 3.25 viewed with crossed fusion. If the views were switched between eyes, the lines all appeared to have different slants, since an extra constant length magnified each line differently in the two

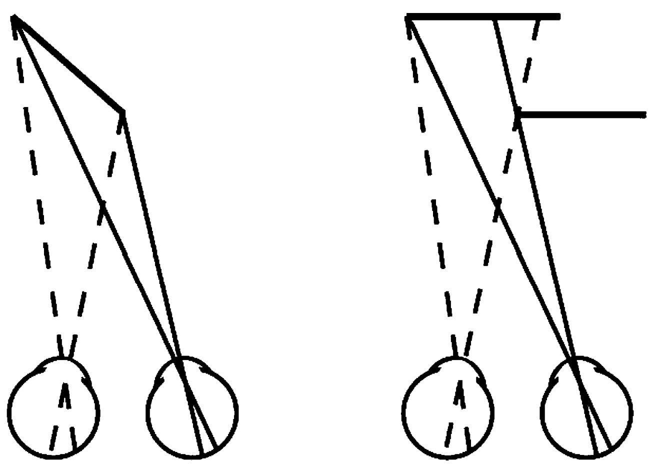

Figure 3.24 The same horizontal disparity produced by a slant and an occlusion.

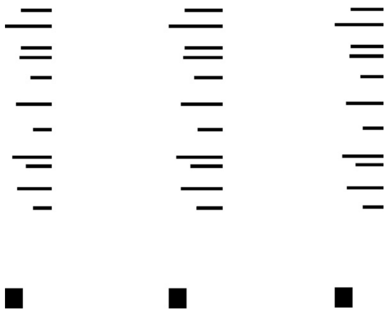

Figure 3.25 Cross-fuse left pair for valid occlusion with a phantom occluder, and cross-fuse right pair for invalid occlusion. Vice versa for uncrossed fusion.

eyes. Importantly, the latter observation shows that disparity-based stereo was available as a response in either the valid or the invalid case. In the invalid case, seeing local stereo slants was the only ecologically valid response. In the valid case, however, the global resolution of seeing an occluder represented a single solution for all lines and was preferred to a series of different local resolutions consistent with conventional stereopsis. This indicates that global considerations are powerful in stereopsis and that conventional disparity-based stereopsis is not necessarily the paramount depth response.

Figure 3.26 shows some even more remarkable examples of perceived phantom occlusion when conventional stereopsis was available on a local basis (as shown by the response to the invalid cases). In Figure 3.26a, crossed fusion of the left pair demonstrates a phantom occluder sloping in depth. Crossed fusion of the right pair (invalid for occlusion) shows lines at different local slants. Figure 3.26b (left pair, crossed fusion) shows a smoothly curving occluder in depth. The invalid case again shows local slants.

3.5 Conclusions

Consideration of the binocular layout of overlapping surfaces and of the variety of ways monocular regions contribute to perceiving this layout seems to require a new approach to binocular vision. Certainly, a division of binocular spatial-layout perception into regular stereopsis based on the disparity of matched images on the one hand and depth from unpaired (monocular) regions on the other is not a tenable position, for the following reasons:

(1) Global context may cause a given horizontal disparity to be treated as a uniocular occlusion, with this response replacing the normal stereo response to horizontal disparity. In the von Szily stereograms (von Szily,

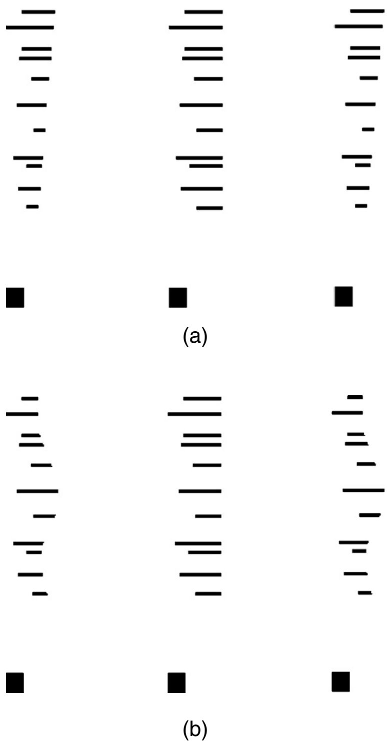

Figure 3.26 In (a), a diagonal occluder sloping in depth is perceived. In (b), the occluder is perceived to curve in depth. Cross-fuse left pair in each case for valid occlusion, and cross-fuse right pair for the invalid case. (See text for details.)

1921), the Cook and Gillam (2004) intrusion stereograms, and the occlusion stimulus of Häkkinen and Nyman (1997), the context favoring an occlusion interpretation seems to consist of cyclopean T-junctions. In ambiguous stereopsis (Gillam and Grove, 2004), the context consists of multiple disparate lines, all consistent with a single global occlusion resolution. When the eyes are switched, making the occlusion interpretation invalid, the same disparities are resolved locally according to regular stereoscopic principles.

(2) Disparity-based stereopsis can cooperate with monocular details to determine depth magnitude (monocular-gap stereopsis). This cooperation results in highly metric depth (at a location without matched features), with detection thresholds similar to those for fully disparity-defined depth, and cross-adaptation with it. The presence of a monocular gap is critical to obtaining these depth effects.

(3) The phantom rectangle, a binocular/monocular stimulus which has no disparity at all, elicits depth that closely resembles that of disparity-based stereopsis, facilitating search and showing the same depth scaling and capture.

The various forms of binocular depth perception we have considered vary from one another in several ways. They vary in the constraints present or imposed in each case. These constraints are not always understood. What is the basis of the imposition of the minimum-depth constraint or the minimum-slant constraint? Why, for example, does the phantom rectangle have a greater depth than the minimum-depth constraint? Why do separated bars in monocular occlusion zones not follow the constraint? We have argued that this latter finding is related to a lack of contextual support from cyclopean T-junctions. Such support can also come from other monocular regions supporting the same occluding surface (the phantom rectangle) or from multiple disparities all consistent with the same uniocular occlusion (ambiguous stereopsis). Support can also come from binocular disparity elsewhere in the image (monocular-gap stereopsis).

Despite their differences, we regard all the phenomena we have considered here to be aspects of a complex binocular surface recovery process. We would argue further that disparity-based stereopsis is not qualitatively different but part of the same process, differing in being more highly constrained and less in need of contextual support. The processes underlying the surprising range of binocular information we can respond to constitute fertile ground for further research, modeling, and physiological exploration.

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