Monocular occlusions determine the perceived shape and depth of occluding surfaces

Inna Tsirlin　　　Center for Vision Research, York University, Toronto, ON, Canada

Laurie M. Wilcox　　　Center for Vision Research, York University, Toronto, ON, Canada

Robert S. Allison　　　Center for Vision Research, York University, Toronto, ON, Canada

Recent experiments have established that monocular areas arising due to occlusion of one object by another contribute to stereoscopic depth perception. It has been suggested that the primary role of monocular occlusions is to define depth discontinuities and object boundaries in depth. Here we use a carefully designed stimulus to demonstrate empirically that monocular occlusions play an important role in localizing depth edges and defining the shape of the occluding surfaces in depth. We show that the depth perceived via occlusion in our stimuli is not due to the presence of binocular disparity at the boundary and discuss the quantitative nature of depth perception in our stimuli. Our data suggest that the visual system can use monocular information to estimate not only the sign of the depth of the occluding surface but also its magnitude. We also provide preliminary evidence that perceived depth of illusory occluders derived from monocular information can be biased by binocular features.

Introduction

Occlusion of one object by another gives rise to monocular areas in the two eyes' images (see Figure 1A). Until recently, little empirical attention has been paid to the implications of this fact, since research in stereopsis has primarily focused on the detection and extraction of depth from binocular disparity. In the last few decades, experiments and demonstrations have highlighted the potential importance of these monocular occlusion cues in stereoscopic depth perception (Harris & Wilcox, 2009). For example, it has been shown that the presence of monocular occlusions textured similarly to the surrounding binocular surface yields faster depth processing in random dot stereograms (RDSs) and in natural stimuli (Gillam & Borsting, 1988; Grove & Ono, 1999; Wilcox & Lakra, 2007). On the other hand, the presence of occluded areas textured differently from the surrounding binocular surface can hinder depth perception (Grove, Gillam, & Ono, 2002; Grove & Ono, 1999). Ecologically "invalid" occlusions (i.e., monocular region in the right eye to the left of the occluder in Figure 1A), which cannot be interpreted as being camouflaged against the binocular object, can be subject to rivalry and suppression (Shimojo & Nakayama, 1990). Monocular occlusions have also

been shown to affect the perceived depth order in ambiguous stimuli such as wallpaper patterns (Anderson & Nakayama, 1994; Hakkinen & Nyman, 2001). The presence of occluded regions can also create illusory contours that account for these regions (Anderson, 1994; Ehrenstein & Gillam, 1998; Gillam & Nakayama, 1999; Liu, Stevenson, & Schor, 1994).

The pioneering investigators of monocular occlusions, Anderson (1994), Gillam and Borsting (1988), and Nakayama and Shimojo (1990), have suggested that the primary function of monocular regions in stereoscopic depth perception is to define depth discontinuities and the boundaries of the occluding objects in depth. Nakayama and Shimojo (1990) provided a demonstration that supports this hypothesis. They showed that introducing a monocularly occluded region in a sparse random dot stereogram created a smooth illusory edge instead of a jagged edge perceived in the absence of occlusion. However, the difference between the percepts was not very salient since many of the subjects in their experiment did not spontaneously see the difference and some did not see it even after the percepts have been described to them.

We have designed a stimulus, shown in Figure 2, to evaluate empirically the role of monocular occlusions in localizing depth discontinuities and defining the shape of
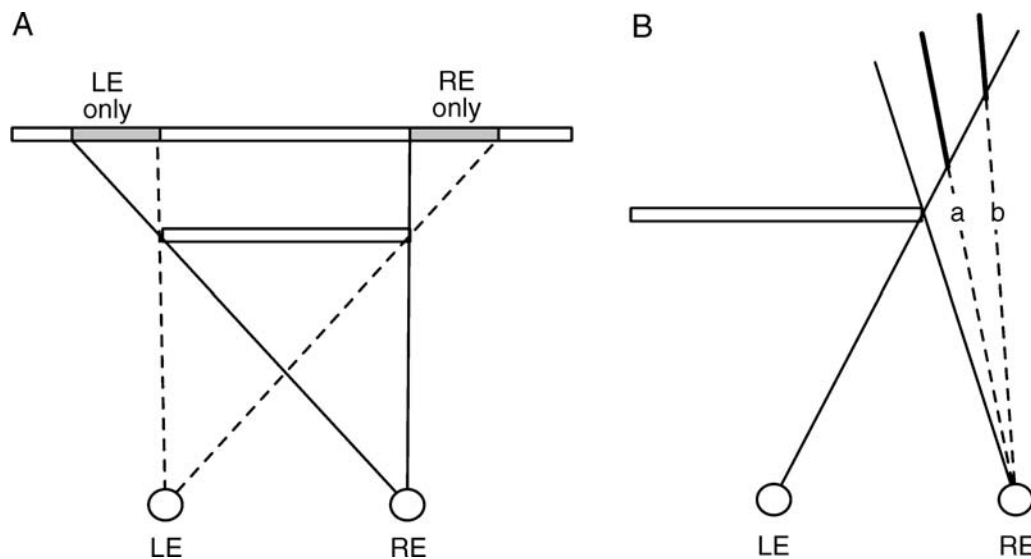
Figure 1. Occlusion geometry. (A) A foreground surface occludes regions of the background in each eye on the contralateral side. (B) According to the viewing geometry, the minimum possible depth of the occluded objects is determined by the lateral separation between them and the occluder. Here, the bold lines indicate the zones of possible depth for objects a and b, which are visible only in the right eye. While the maximum depth of the occluded object is unconstrained, its minimum depth is constrained by the occlusion geometry. In this case, if the near surface fully occludes the far object from the left eye, the occluded object must lie to the left of the line of sight tangent to the edge of the occluder.

the occluding surface in depth. In this stimulus, monocular occlusions drastically alter the perceived shape of the occluding surface. In the absence of a monocular region in this stimulus, the foreground surface is perceived as a textured square. Adding a monocular occlusion to the stimulus changes the perceived configuration. Now, the shape of the foreground surface is rectangular and it is composed out of a textured square and a blank region. In the first experiment, we demonstrate this phenomenon empirically with naïve observers.

Our stimulus also allows us to examine the quantitative properties of depth percepts from monocular occlusions. This aspect has received attention in the literature, but it requires further investigation (Cook & Gillam, 2004; Gillam, 1995; Gillam, Blackburn, & Nakayama, 1999; Gillam, Cook, & Blackburn, 2003; Gillam & Nakayama, 1999; Liu et al., 1994; Liu, Stevenson, & Schor, 1995, 1997; Nakayama & Shimojo, 1990). Since monocular occlusions are only present in one eye, binocular disparities cannot be used to precisely localize monocularly occluded areas or illusory occluders induced by monocular occlusions in depth. However, in some cases depth magnitude from monocular occlusions could be deduced from the constraints imposed by the viewing geometry. For example, in Figure 1B the minimum possible depth of the monocular object is constrained by the line of sight from the eye that does not see the monocular object, and hence, the minimum depth depends on the object's lateral separation from the occluding surface. However, the maximum depth is unconstrained in this configuration; multiple solutions are possible.

Consequently, in this case, to place the monocular object at an exact location in depth, the visual system might be expected to adopt the minimum depth constraint. Liu et al. (1994) and Nakayama and Shimojo (1990) were the first to demonstrate that manipulating the horizontal distance of the monocular object from the occluder or the width of the monocular region can influence the amount of perceived depth between the occluding and the monocular objects. However, in both cases, it was subsequently argued that depth percepts in these stimuli were at least in part attributable to binocular disparity (Gillam, 1995; Gillam et al., 2003; Liu et al., 1995, 1997). Later, Cook and Gillam (2004), Gillam and Nakayama (1999), and Pianta and Gillam (2003b) have presented other instances of quantitative depth perceived from monocular occlusions. However, in Gillam and Nakayama's (1999) stimulus the perceived depth was larger than that predicted by the minimum depth constraint, in Pianta and Gillam's (2003b) stimulus perceived depth was partially dependant on edge disparity (Pianta & Gillam, 2003a) and in Cook and Gillam's (2004) stimulus quantitative depth was not perceived in all conditions (bar vs. intrusion).

Although it seems that the visual system relies on the geometric constraints in some cases, clearly we do not have a complete understanding of the conditions for quantitative depth perception from monocular occlusions. In our stimuli, we can manipulate the viewing geometry to generate uni- or bi-directional constraints on the possible depth of the illusory occluder. Hence we can investigate under which conditions (if at all) the visual system uses
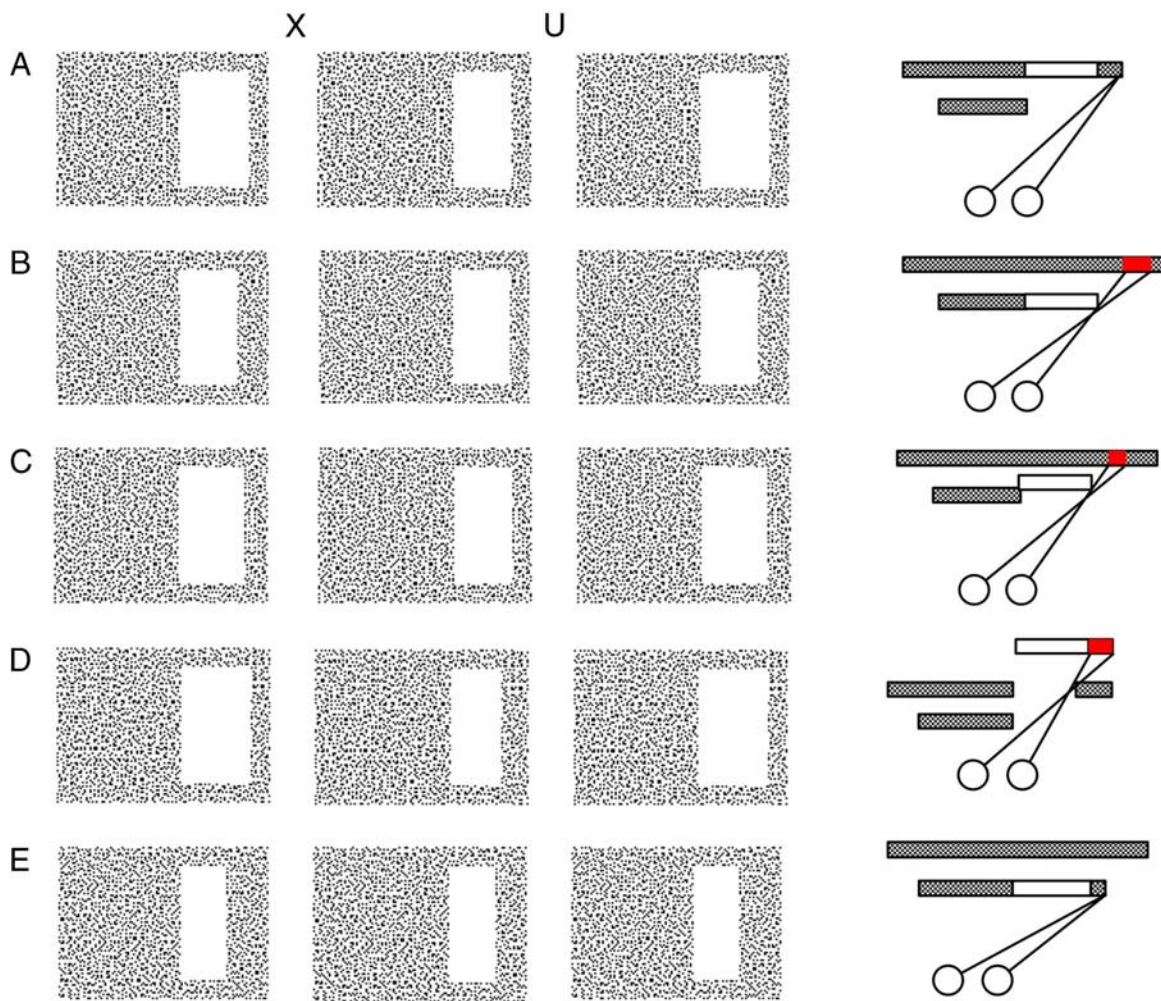
Figure 2. Stimuli used in Experiments 1 and 2. RDS in the left and center columns are arranged for crossed fusion and in the center and right columns for uncrossed fusion. The rightmost column illustrates the typical corresponding cyclopean percepts where the random dot texture is shown in gray, blank region in white, and occluded regions in red. (A) No Occlusion condition—there is no monocular region to the right of the blank area. The blank area is perceived as part of the background. (B, C) Occlusion condition—there is an occluded region in the right eye's image to the right of the blank area. When the size of the monocular region is equal to the disparity of the central random dot square (as in (B)), the blank area is perceived as part of the foreground. When the size of the monocular region is smaller than the disparity of the random dot square (as in (C)), the blank area is perceived in between the background and the foreground. (D) Reverse Occlusion condition—the monocular region is located in the left eye's image and the blank area is perceived as lying behind the background. (E) Binocular Strip condition—there is a binocular random dot strip to the right of the blank area, which has a disparity equal to that of the central random dot square. In this case, the blank area is perceived as part of the foreground.

these constraints to assign a precise depth to the illusory occluder. In Experiment 2, we manipulate the geometric constraints by varying the location (eye) and the width of the occluded region and ask our observers to estimate the perceived depth of the illusory occluder. In Experiments 3 and 4, we evaluate the role binocular disparity plays in the qualitative and quantitative depth percepts observed in Experiments 1 and 2.

Our data show that the qualitative change in the shape and depth of the occluding surface in our stimuli does not depend on binocular disparity and is caused solely by the monocular occlusion information. The data also suggest that quantitative depth perception is possible on the basis of monocular occlusions alone but also that these percepts can be biased by neighboring binocular features with an unambiguous disparity signal.

Experiment 1

Methods

Observers

Five observers naïve to the purpose of the experiments participated in the study (DS, AS, SL, MV, and MR). All
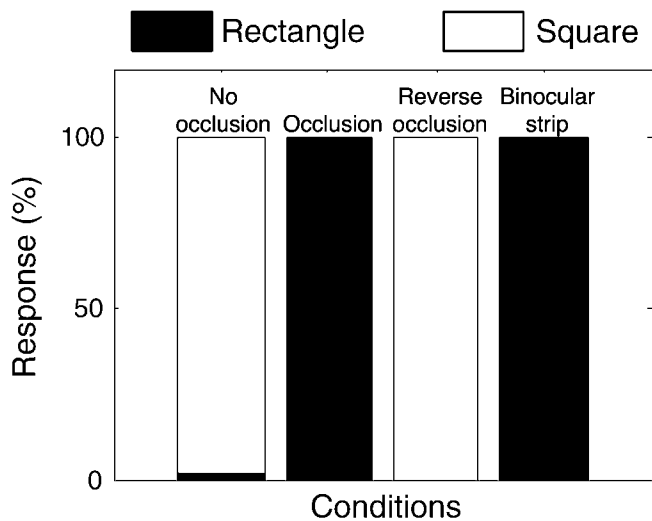
Figure 3. Results of Experiment 1 for all observers. The different types of stimuli are plotted on the abscissa. The ordinate shows the proportion of subject' responses—"square" (in white) and "rectangle" (in black)—for each stimulus.

observers had normal or corrected-to-normal visual acuity and good stereoacuity as measured with Randot stereoacuity test.

Apparatus

Scripts for stimulus presentation were executed on a G5 Power Macintosh using Python 2.5. Stimuli were presented on a pair of CRT monitors (ViewSonic G225f) arranged in a mirror stereoscope with a viewing distance of 0.45 m. The resolution of the monitors was set to 1280 × 960 pixels and the refresh rate to 75 Hz. At this resolution and viewing distance, each pixel subtended 2.24′ of visual angle. Observers used a chin rest to stabilize head position during testing.

Stimuli

We used an RDS (see Figure 2), consisting of a random dot frame (background) 22.4′ wide, which was positioned at zero disparity, surrounding a central region (foreground) composed of two parts. The left side of the central region was a square patch of random dot texture subtending 2.24° × 2.24° with crossed disparity of 4.48′, so it appeared shifted toward the observer in depth. The remainder of the central region was blank and contained no disparity information. The element density of the random dot regions was 25% and each element was 2.24′ × 2.24′. The whole stimulus subtended 4.2° × 3.2°.

Four variants of the stimulus were presented to the observers in Experiment 1:

1. No Occlusion—In the first condition, there was no monocular region on the border between the blank region and the random dot frame (Figure 2A).

2. Occlusion—In the second condition, we added a monocular random dot region in the right eye's image on the border between the blank region and the frame. The width of the region was 4.48′, equal to the disparity of the textured foreground square. This stimulus corresponded to a depth arrangement where the blank region appears in front of the background (Figure 2B).

3. Reverse Occlusion—This stimulus was the same as the Occlusion stimulus, but the monocular random dot region was added to the left eye image. This stimulus corresponded to a depth arrangement where the blank region appears behind the background (Figure 2D).

4. Binocular Strip—Instead of the monocular region used in occlusion and reverse-occlusion stimuli, a binocular random dot strip was added on the border between the blank area and the background. The disparity of this strip was 4.48′, equal to the disparity of the textured foreground square (Figure 2E).

Note that when the monocular region is introduced normal binocular matching is not possible between the dots of the monocular region in one eye and the dots of the right-hand edge of the blank area in the other eye since these dots are uncorrelated. Consequently, the perceived depth of the illusory surface cannot result from conventional stereoscopic matching.

Procedure

At the beginning of each trial, the observers fixated on a white square (31′ × 31′) for 1 s after which the fixation mark was replaced by the stimulus. The stimulus presentation time was unlimited and observers could move their eyes freely. We asked the observers to specify the perceived shape of the foreground of the RDS in a forced-choice judgment by pressing buttons on a gamepad. The two choices were "square" or "rectangle". The instructions were presented in a written form for consistency. The presentation order was randomized. Observers completed 10 trials for each condition.

Results

The results (Figure 3) showed that when the occluded region was absent (Figure 2A), the blank area was perceived at the depth of the background frame and the foreground region appeared square and limited to the random dot texture. The presence of an occluded region along the vertical border of the blank area and the background (Figure 2B) created a dramatic change in percept; all observers now perceived the blank area at the depth of the random dot square, so the foreground was a continuous opaque rectangle that was colored white on one side and textured on the other. This suggests that the

monocular region determined the location of a depth discontinuity and triggered the interpolation of a 3D surface.

When the monocular region was added to the left half-image, instead of the right (Figure 2D), all observers again reported that the foreground was square. In this case, the white area appeared to be shifted behind the background frame elements.

For comparison, we also tested a condition in which we replaced the monocular region with a binocular strip of texture with disparity equal to that of the foreground random dot square (Figure 2E). As expected, all observers perceived a rectangular surface, similar to that perceived in stimuli with monocular regions (Figure 2B).

Experiment 2

In Experiment 2, we evaluated the quantitative nature of apparent depth from monocular occlusions in our stimuli. We manipulated the size of the occluded region and the eye in which the occluded region was located and asked the observers to match a disparity probe to the depth of the blank area in the center of the stimulus. As shown in Figure 4A, in the Occlusion condition, where the blank area is seen in front of the random dot frame, both the minimum and maximum possible depths are constrained (for more detailed diagrams of the viewing geometry, see Supplementary Figures 1 and 2). If the visual system uses geometric constraints from monocular occlusions, then it should be able to localize the illusory region in depth with fairly high precision since the possible depth is constrained on both sides. The exact location of the occluder in depth will then depend on the width of the monocular region. In the Reverse Occlusion condition, where the blank region is perceived beyond the random dot frame, only the minimum depth is constrained (see Figure 4C). Hence, in this condition, if the visual system adapts the minimum constraint, the perceived depth of the illusory occluder should also depend on the size of the monocular region. However, since the possible depth here is constrained only in one direction, the perceived location of the illusory occluder in depth might not be as precise as in the Occlusion condition. In both conditions, if quantitative depth can be perceived from monocular occlusions in our stimuli, then depth estimates should increase linearly with the width of the monocular regions in accordance with the geometric constraints.

Methods

The observers and apparatus were the same as in Experiment 1. We used the same stimulus as in Experiment 1 except that the central random dot square had a crossed disparity of 13.44′ and the width of the occluded region was one of 0, 4.48′, 8.96′, or 13.44′. The monocular region was added either to the images of the left or the right eye resulting in 7 different conditions (2 eyes × 3 widths + 0 width). The observers were asked to adjust a disparity probe (black circle with radius 13.44′) to match the depth of the white portion of the central area of the RDS. The probe was presented to the left of the RDS and its initial disparity was chosen at random. The disparity of the depth probe was adjusted in steps of 1.12 min (1/2 a pixel). Anti-aliasing was used to achieve disparities smaller than a pixel. The observers used a gamepad to adjust the disparity of the probe and to indicate their decision.

Results

The results of Experiment 2 are shown in Figure 5. In the Occlusion condition, when monocular occlusions of variable width were added to the right half-image, the blank area appeared positioned at intermediate depths, between the random dot square and the background (e.g., compare the depth of the blank region perceived in stimuli B and C in Figure 2). Observers' depth estimates increased linearly with the increase in the size of the monocular region. In the Reverse Occlusion condition, the blank region appeared to lie at different depths behind the surround depending on the width of the monocular region. Similarly, perceived depth increased with the width of the monocular region. One of the observers (SL) could not see depth in this condition. Consequently, we have removed her from the sample when we combined the data to create Figure 5. Her data and the combined data for all five observers can be seen in Supplementary Figures 3 and 4. Note that the standard errors are slightly larger in the Reverse Occlusion condition (especially for the largest width) indicating that the depth estimates were not quite as precise in this condition as in the Occlusion condition. This could occur since in the Reverse Occlusion conditions the possible depth of the illusory occluder is only constrained in one direction and consequently is harder to estimate precisely.

Experiment 3

The results of Experiment 2 suggest that quantitative depth can be perceived from monocular occlusions in our stimuli. However, in light of the findings of Gillam et al. (2003) and Liu et al. (1997), it is important to rule out any possibility of binocular matching. One possible scenario is that size disparity between the blank regions in the two eyes resulting from the addition of the occluded region created a percept of slant in the blank region, which could
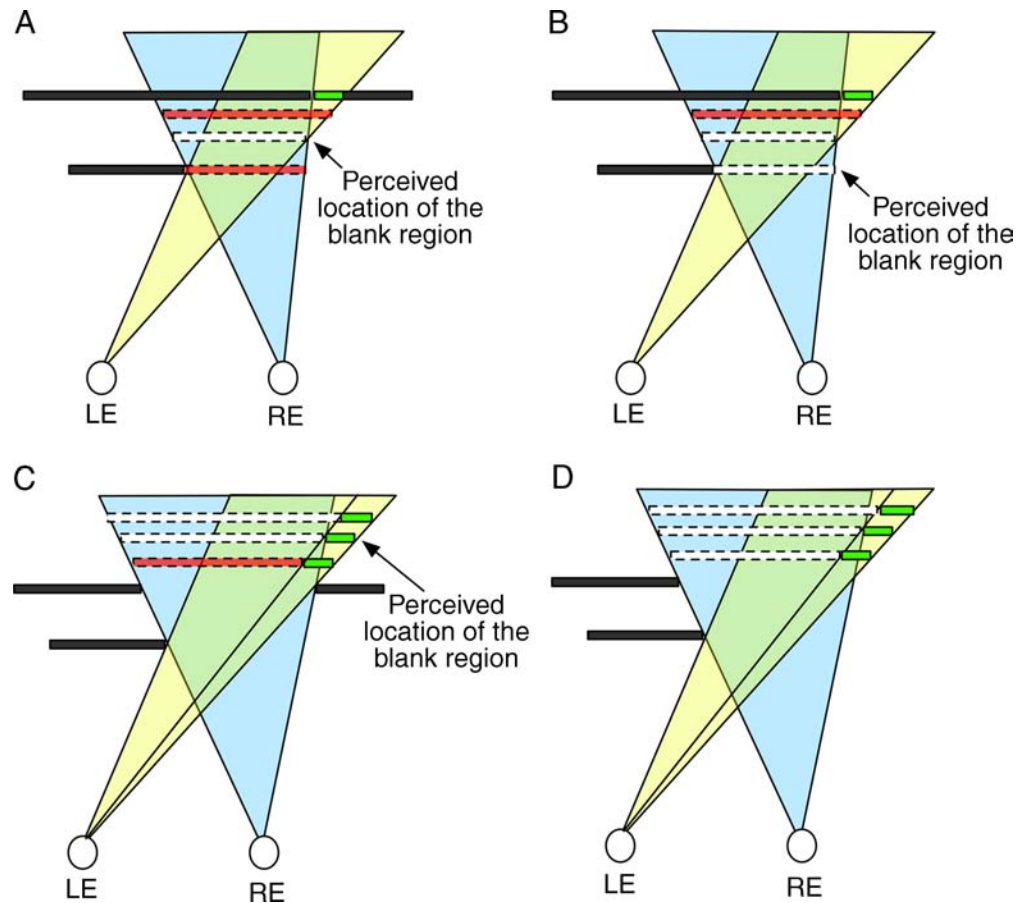
Figure 4. The viewing geometry of the stimuli in Experiments 2 and 3. Blue and yellow areas show the lines of sight of the right and left eyes, respectively. Monocularly occluded regions are shown as green bars. Black bars represent the random dot texture and white bars with a dashed outline represent the blank region. Red bars with dashed outlines show possible positions of the illusory surface in depth that violate the viewing geometry. In the Occlusion stimuli of Experiments 1 and 2 when the monocular occlusion is placed in the right eye, the depth of the blank region is constrained on both sides as shown in (A). In (B), when the right portion of the random dot surround is removed, geometric constraints are weakened as the maximum depth becomes unconstrained. (C) In the Reverse Occlusion stimulus, only the minimum possible depth of the blank region is constrained. As shown in (D), in this configuration, the depth of the illusory surface becomes unconstrained in both directions when the right portion of the random dot surround is removed. For more detailed diagrams of the viewing geometry, see Supplementary Figures 1 and 2.

have caused the change in percept of depth of the blank region. However, this explanation can be rejected since neither slant nor depth is perceived in our stimuli in the No Occlusion condition. In this condition, due to the disparity shift of the random dot square, there is also size disparity between the blank regions in the left and right images (see Figure 2A). However, the blank region is seen as coplanar with the background, lying at zero disparity as shown in the 0 width condition of Experiment 2. Moreover, when asked, our observers did not report slant percepts in the stimuli of Experiments 1 and 2.

Another possible explanation of our results involves binocular disparity. When our stimuli contain monocular occlusions, the random dot textures defining the right-hand edges of the blank area in the right and left half-images are uncorrelated. Consequently, these random dots cannot be matched by the stereoscopic system. However, the texture-defined edges could potentially be matched rather than the individual texture elements. Importantly, the disparity between these edges would be equal to the width of the monocular region and would predict the same depth percepts.

There are several reasons why this scenario is not very likely. First, note that in this scenario double matching on two different scales would have to take place. On the fine scale, the binocular dots of the right-hand part of the random dot frame would be matched in the two eyes. Then the texture edge formed by these same dots in one
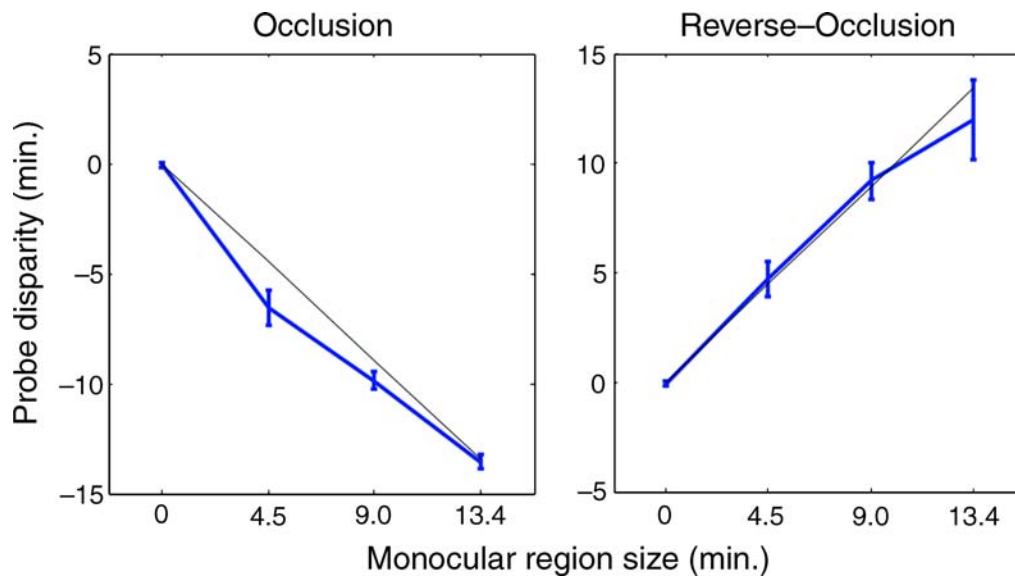
Figure 5. Results of Experiment 2 for all observers except for SL. The ordinate shows the disparity of the probe and the abscissa shows the size of the monocular region. Negative disparity values are assigned to crossed depth. The error bars show ±1 standard error of the mean. The thin black line indicates the predicted depth.

eye would have to be matched to the edge formed by the monocular region in the other eye. It is not clear why the visual system would choose to resort to this complicated solution instead of relying on viewing geometry.

Second, one of the observers (SL) could not see depth very well in the Reverse Occlusion stimuli although she had no problem seeing depth in the Occlusion condition (her data is shown in Supplementary Figure 3). This is an experienced stereoscopic observer who can see both crossed and uncrossed depths. Consequently, if quantitative depth in our stimuli was indeed based upon stereoscopic

matching, then this observer should have seen depth in both conditions. Individual differences in perception of quantitative depth from occlusions have been reported before in the literature (Cook & Gillam, 2004).

The third argument concerns the element density in the stimuli. Matching texture borders requires these borders to be well defined. In our original stimulus, the dot density was set to 25%; consequently, the texture borders were well defined. Figure 6 shows an example of our stimuli with density of 2.7%. In Figure 6A, the width of the occluded region is equal to the disparity of the random dot
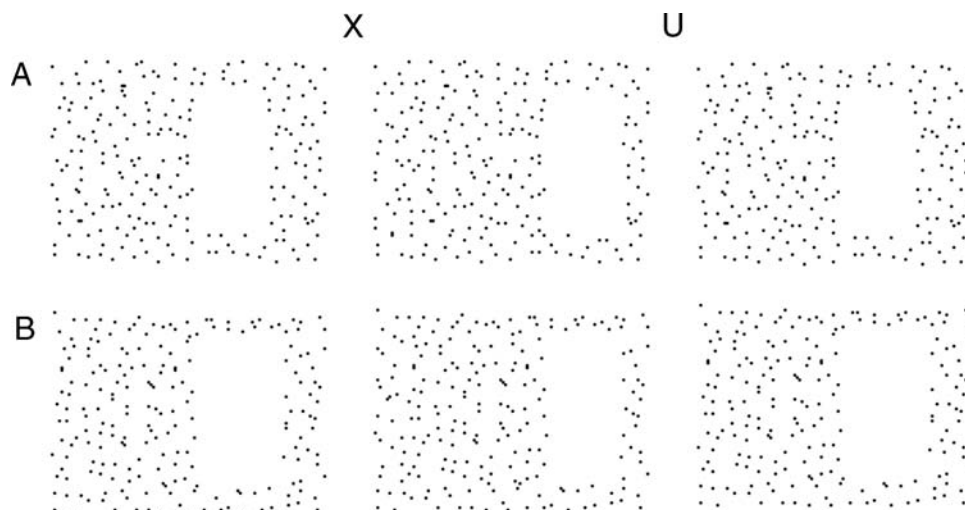

Figure 6. An example of our stimuli with 2.7% density (actual stimuli had 25% density), both panels showing the Occlusion condition. In (A), the size of the occluded region is equal to the disparity of the random dot square, and in (B), it is smaller than the disparity of the random dot square. Left and center columns are arranged for crossed fusion and center and right columns for uncrossed fusion.
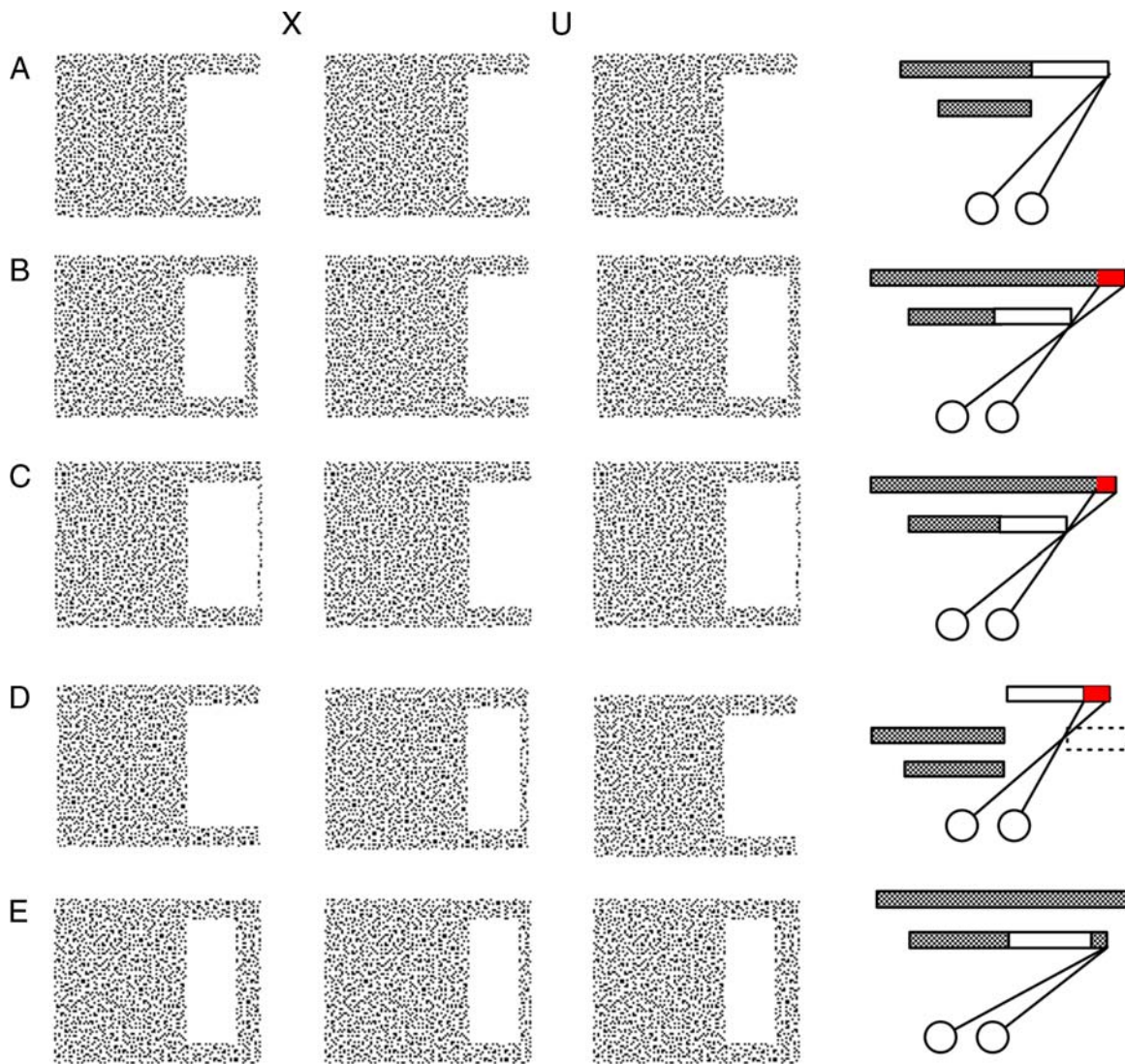
Figure 7. Stimuli used in Experiment 3. RDS in the left and center columns are arranged for crossed fusion and in the center and right columns for uncrossed fusion. The rightmost column illustrates the typical corresponding cyclopean percepts where the random dot texture is shown in gray, blank region in white and occluded regions in red. The stimuli are identical to those used in Experiments 1 and 2 except that we have removed the rightmost portion of the background (see legend for Figure 2).

square, and in Figure 6B, it is smaller. The texture borders in these stimuli are not very well defined due to low density; however, the illusory occluder is still seen at different depths in Figures 6A and 6B.

However, even when a sparse texture is used a border contour can still be perceived. Consequently, to evaluate the possible role that binocular disparity played in Experiments 1 and 2, we completely removed the right portion of the random dot surround from our stimuli (see Figure 7) and repeated the experiments using these modified stimuli. In these stimuli, the right-hand texture border created by the monocular occlusion in one eye cannot be matched to anything in the other eye, thus excluding the possibility of the involvement of binocular disparity.

Methods

The observers, apparatus, and procedure used in Experiment 3 were the same as in Experiments 1 and 2, respectively. The stimulus was modified by removing the rightmost portion of the random dot background (see Figure 7) so it subtended $3.74° \times 3.2°$.

Results

The results of Experiment 3 for the qualitative task (rectangle vs. square) shown in Figure 8 were virtually identical to those of Experiment 1 (Figure 3). The presence of the occluded region created a depth edge, which triggered
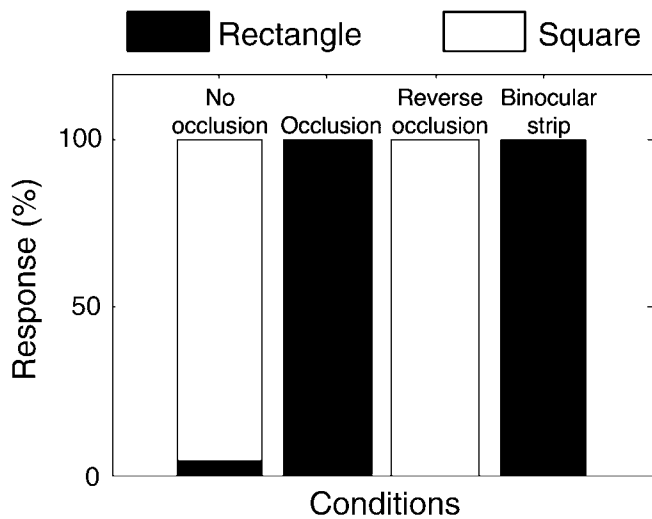
Figure 8. Results of the qualitative task of Experiment 3 for all observers. The different types of stimuli are plotted on the abscissa. The ordinate shows the proportion of subject' responses—"square" (in white) and "rectangle" (in black)—for each stimulus.

depth interpolation across the blank area, while in the absence of monocular occlusions the blank area was perceived as part of the background. Consequently, this effect does not depend on binocular matching and is based solely on monocular information present in the stimulus.

However, the results of the disparity matching task shown in green in Figure 9 were different from those of Experiment 2 (shown in blue). Regardless of the width of the monocular occlusion, the presence of monocular

occlusions in the right half-image (Occlusion condition) yielded a percept of the blank area at the same depth as the random dot square. When the occlusions were introduced in the left half-image (Reverse Occlusion condition), the blank area was perceived to lie at the same short distance behind the surround regardless of the width of the monocular occlusion.

Two important points are raised by these data. First, these data offer additional evidence that monocular occlusions influence the perceived depth of the illusory occluding surface. In the Occlusion conditions, the presence of monocular occlusions, regardless of their size, creates a percept of an illusory occluder seen in depth. Second, these results suggest that binocular matching of the texture edges may have been responsible for the quantitative depth percepts in Experiment 2.

However, note that in the modified stimuli the geometric constraints are weaker than in the original stimuli. As shown in Figures 4A and 4C, for both occlusion configurations in our original stimuli, the minimum depth, or both minimum and maximum depths were constrained. Hence, the visual system could have relied on this information to localize the blank region. In the modified Reverse Occlusion stimuli, the magnitude of the depth from occlusions was not constrained at all after the removal of the right-hand border (Figure 4D). This could explain the absence of quantitative depth in these stimuli in Experiment 3. In the Occlusion stimuli, after the removal of the right-hand border, only the minimum depth remained constrained (Figure 4B). Although the visual system could have used this constraint to precisely localize the illusory occluder in depth, the occluder was
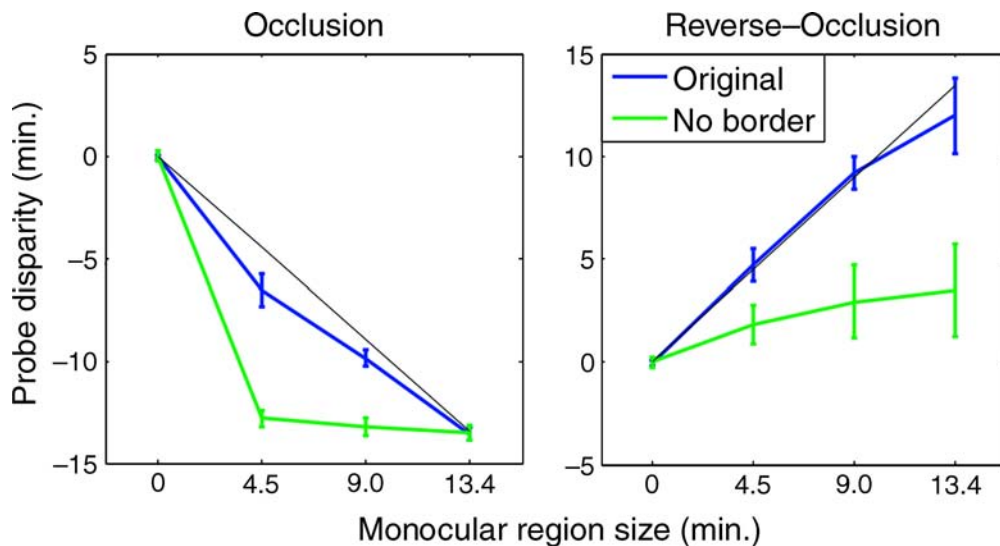

Figure 9. Results of the disparity matching task of Experiment 3 for all observers except SL. The ordinate shows the disparity of the probe and the abscissa shows the size of the monocular region. The blue line shows the depth estimates with the stimuli used in Experiment 2 (original) and the green line shows the depth estimates with the modified stimuli with the right-hand border removed (no border). Negative disparity values are assigned to crossed depth. The error bars show ±1 standard error of the mean. The thin black line indicates the predicted depth.
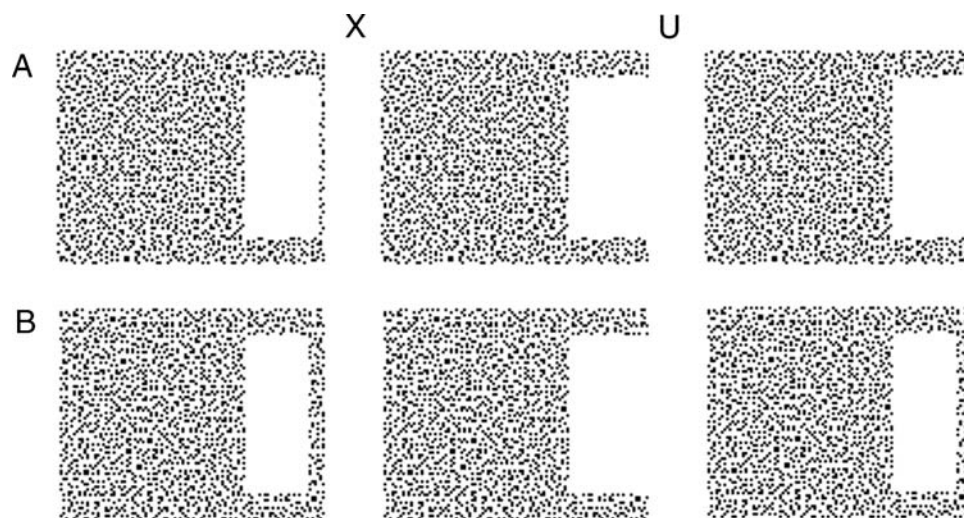
Figure 10. Stimuli used in Experiment 4. The stimuli from Experiment 3 were modified by placing the random dot square at zero disparity. In (A), the width of the monocular region is smaller than in (B). Left and center columns are arranged for crossed fusion and center and right columns for uncrossed fusion.

always perceived at the depth of the binocular square. It is possible that the illusory occluder was captured by the strong disparity signal of the adjacent random dot square. Since the depth of the illusory surface was restricted in only one direction (minimum), the capture effect could have taken place in the unrestricted direction, toward the uncrossed depth of the binocular square. We have tested this possibility in Experiment 4.

Experiment 4

To examine the effect of the disparity of the random dot square on the perceived depth of the illusory occluder, we set the disparity of the binocular square to zero in the stimuli with no right-hand border. We then repeated the disparity matching experiment (Experiment 2). In these stimuli, binocular matching of texture-defined edges cannot take place since the right-hand border is removed. Binocular capture should not affect the depth of the illusory occluder perceived in the presence of the monocular region since the binocular square has zero disparity and cannot pull the illusory occluder in the unrestricted direction. Consequently, increase of the perceived depth of the illusory surface with the increase in the width of the monocular region in this case would suggest that quantitative depth can be seen purely on the basis of monocular information.

The modified stimuli are shown in Figure 10. Note that now the illusory surface looks slanted. Its left edge is at zero disparity, alongside the random dot texture, and its right edge is elevated due to the presence of monocular occlusions. This slant is not likely to occur due to size disparity between the images of the two eyes since the

right-hand border of the frame is removed so there is no clear indication where the blank region ends in the eye that does not see the occluded region. Instead, the slant occurs due to the interpretation of the occluded region as part of the binocular frame located at the fixation plane. The blank area on the side of the occlusion is then interpreted as an occluding surface with crossed depth.

Methods

Three naïve observers participated in this experiment. Two from the original sample (MV and DS) and a new observer (MT). The new observer had to complete the disparity matching task with stimuli from Experiments 2 and 3 before participating in Experiment 4. The stimuli were the same as in Experiment 3, except that the random dot square had a zero disparity (see Figure 10).

We asked the observers to set the disparity probe to the perceived depth of the *right edge* of the illusory occluder as we varied the width of the monocular region. Only the Occlusion condition, with the monocular occlusion in the right eye, was tested (see Results section of Experiment 3). The procedure for this experiment was exactly the same as in Experiment 2.

Results

All observers perceived the slanted surface in depth and could make veridical depth judgments. As shown in Figure 11, the perceived depth of the illusory occluder increased with the increase in the width of the monocular region. Perceived depth for the first three widths of the monocular region was very similar to that in the original
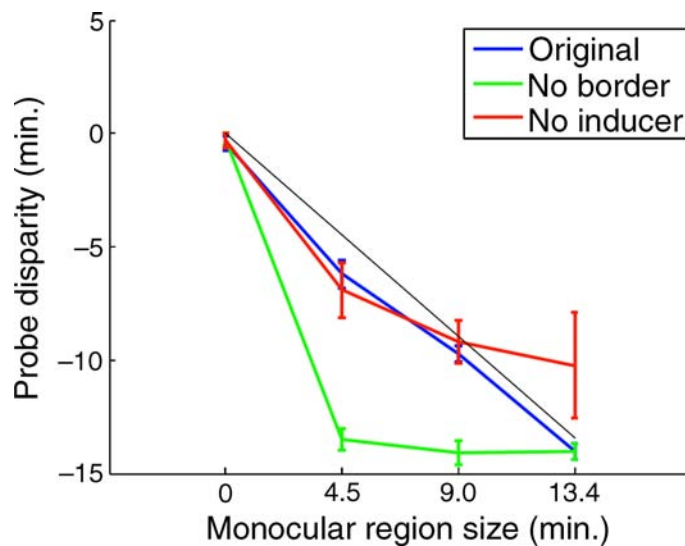
Figure 11. Results of Experiment 4. The ordinate shows the disparity of the probe and the abscissa shows the size of the monocular region. The blue line shows the depth estimates with the original stimuli in Experiment 2 (original) and the green line shows the depth estimates with stimuli of Experiment 3, which had no right-hand border (no border). The red line shows the depth estimates with the stimuli where the random dot square had a zero disparity (no inducer). The error bars show ±1 standard error of the mean. The thin black line shows the predicted depth.

experiment, while for the largest width the depth in the current stimuli was underestimated on average. These data suggest that quantitative depth could be perceived in our stimulus on the basis of monocular occlusions alone.

Discussion

Monocular occlusions are abundant in natural scenes, and the work presented here demonstrates that the visual system puts this information to good use. Our experiments provide direct evidence that the visual system uses monocular occlusions to localize depth discontinuities and to define the shape and depth of the occluding surfaces. In our stimuli, in the absence of a monocular occlusion on the border of the blank region and the background, the blank region was perceived as part of the background and the foreground had a square shape. The presence of a monocular occlusion on the border in the right eye (Occlusion condition) signaled a depth edge and triggered depth interpolation across the blank region creating a percept of an occluding surface composed out of blank and textured parts. When the monocular occlusion was placed in the corresponding location in the other eye (Reversed Occlusion condition), it signaled to the visual system that the blank region was positioned behind the textured surround creating an aperture through which the

occluded region and the blank region were seen. The occluder in this case was the background frame. Interestingly, when the right portion of the background frame was removed, an illusory intruding edge was perceived in its place to account for the monocular occlusion (see Figure 7D).

Experiment 2 showed that the magnitude of the perceived depth of the illusory occluder increased with increase in the width of the monocular region in both Occlusion and Reverse Occlusion configurations. This result is consistent with the restrictions imposed by the viewing geometry and it is likely that the visual system used these constraints to assign precise depth to the illusory surface. When the experiment was repeated with the right-hand border removed, the illusory surface was always perceived at the depth of the random dot square in the Occlusion condition, and at some distance behind the random dot frame at the Reversed Occlusion condition. It is possible that binocular matching between the texture-defined edges of the random dot frame and the occluded region took place in Experiment 2 and the removal of the edge prevented this matching. On the other hand, the geometric constraints, which the visual system would have to rely on to extract depth from occlusions, were weakened with the removal of the right-hand border. In the Reversed Occlusion condition, the position of the illusory surface was not restricted at all (except in sign) after the removal of the border, while in the Occlusion condition only the minimum depth remained restricted. We proposed that in the Occlusion condition, the illusory occluder was perceived at the depth of the random dot square at all monocular region widths since the strong disparity signal of the square pulled the illusory surface in the direction unrestricted by the geometry. Indeed, when the square was given a zero disparity, quantitative depth perception was restored, although depth was underestimated at the largest width of the monocular region. Taken together, these experiments reveal that the visual system is able to utilize the geometric constraints imposed by monocular occlusions to localize occluding surfaces in depth with higher precision. However, quantitative depth signal from monocular occlusions seems to be a relatively weak cue. The presence of an unambiguous disparity signal in the proximity of an illusory occluder can alter the perceived depth of the occluder when this depth is not completely restricted by the viewing geometry. A related effect has been described previously in da Vinci type of arrangements (Hakkinen & Nyman, 1996). Hakkinen and Nyman (1996) found that the perceived depth of a monocularly occluded object was biased in the direction of the disparity of a proximate binocular object.

Our results demonstrate clearly that the visual system uses monocular occlusions to identify the location and direction of depth discontinuities and object boundaries in a scene. Further, for ambiguous surfaces the occluded regions help define object shape and estimate the object's position in depth. Thus, monocular occlusions are not

simply a byproduct of stereoscopic matching but an important stage in the identification of depth discontinuities in a complex visual environment.

Acknowledgments

Commercial relationships: none.
Corresponding author: Inna Tsirlin.
Email: itsirlin@yorku.ca.
Address: Centre for Vision Research, CSE, York University, 4700 Keele St., Toronto, ON, Canada.

References

Anderson, B. L. (1994). The role of partial occlusion in stereopsis. *Nature, 367,* 365–368.

Anderson, B. L., & Nakayama, K. (1994). Toward a general theory of stereopsis: Binocular matching, occluding contours, and fusion. *Psychological Review, 101,* 414–445.

Cook, M., & Gillam, B. (2004). Depth of monocular elements in a binocular scene: The conditions for da Vinci stereopsis. *Journal of Experimental Psychology, 30,* 92–103.

Ehrenstein, W. H., & Gillam, B. (1998). Early demonstrations of subjective contours, amodal completion, and depth from half-occlusions: "Stereoscopic experiments with silhouettes" by Adolf von Szily (1921). *Perception, 27,* 1407–1416.

Gillam, B. (1995). Matching needed for stereopsis. *Nature, 373,* 202.

Gillam, B., Blackburn, S., & Nakayama, K. (1999). Stereopsis based on monocular gaps: Metrical encoding of depth and slant without matching contours. *Vision Research, 39,* 493–502.

Gillam, B., & Borsting, E. (1988). The role of monocular regions in stereoscopic displays. *Perception, 17,* 603–608.

Gillam, B., Cook, M., & Blackburn, S. (2003). Monocular discs in the occlusion zones of binocular surfaces do not have quantitative depth: A comparison with Panum's limiting case. *Perception, 32,* 1009–1019.

Gillam, B., & Nakayama, K. (1999). Quantitative depth for a phantom surface can be based on cyclopean occlusion cues alone. *Vision Research, 39,* 109–112.

Grove, P. M., Gillam, B., & Ono, H. (2002). Content and context of monocular regions determine perceived depth in random dot, unpaired background and phantom stereograms. *Vision Research, 42,* 1859–1870.

Grove, P. M., & Ono, H. (1999). Ecologically invalid monocular texture leads to longer perceptual latencies in random-dot stereograms. *Perception, 28,* 627–639.

Hakkinen, J., & Nyman, G. (1996). Depth asymmetry in daVinci stereopsis. *Vision Research, 36,* 3815–3819.

Hakkinen, J., & Nyman, G. (2001). Phantom surface captures stereopsis. *Vision Research, 41,* 187–199.

Harris, J. M., & Wilcox, L. M. (2009). The role of monocularly visible regions in depth and surface perception. *Vision Research, 49,* 2666–2685.

Liu, L., Stevenson, S. B., & Schor, C. M. (1994). Quantitative stereoscopic depth without binocular correspondence. *Nature, 367,* 66–68.

Liu, L., Stevenson, S. B., & Schor, C. M. (1995). Matching needed for stereopsis. *Nature, 373,* 203.

Liu, L., Stevenson, S. B., & Schor, C. M. (1997). Binocular matching of dissimilar features in phantom stereopsis. *Vision Research, 37,* 633–644.

Nakayama, K., & Shimojo, S. (1990). Da Vinci stereopsis: Depth and subjective occluding contours from unpaired image points. *Vision Research, 30,* 1811–1825.

Pianta, M., & Gillam, B. (2003a). Monocular gap stereopsis: Manipulation of the outer edge disparity and the shape of the gap. *Vision Research, 43,* 1937–1950.

Pianta, M., & Gillam, B. (2003b). Paired and unpaired features can be equally effective in human depth perception. *Vision Research, 43,* 1–6.

Shimojo, S., & Nakayama, K. (1990). Real world occlusion constraints and binocular rivalry. *Vision Research, 30,* 69–80.

Wilcox, L. M., & Lakra, D. C. (2007). Depth from binocular half-occlusions in stereoscopic images of natural scenes. *Perception, 36,* 830–839.