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Disparity biasing in depth from monocular occlusions

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ABSTRACT

Monocular occlusions have been shown to play an important role in stereopsis. Among other contributions to binocular depth perception, monocular occlusions can create percepts of illusory occluding surfaces. It has been argued that the precise location in depth of these illusory occluders is based on the constraints imposed by occlusion geometry. Tsirlin et al. (2010) proposed that when these constraints are weak, the depth of the illusory occluder can be biased by a neighboring disparity-defined feature. In the present work we test this hypothesis using a variety of stimuli. We show that when monocular occlusions provide only partial constraints on the magnitude of depth of the illusory occluders, the perceived depth of the occluders can be biased by disparity-defined features in the direction unrestricted by the occlusion geometry. Using this disparity bias phenomenon we also show that in illusory occluder stimuli where disparity information is present, but weak, most observers rely on disparity while some use occlusion information instead to specify the depth of the illusory occluder. Taken together our experiments demonstrate that in binocular depth perception disparity and monocular occlusion cues interact in complex ways to resolve perceptual ambiguity.

1. Introduction

The importance of monocular occlusions in binocular depth perception has been demonstrated convincingly in the psychophysical literature (for review see Harris and Wilcox (2009)). The presence of monocular occlusions, which are consistent with the scene geometry and texture, can decrease depth perception latency in natural and artificial stimuli (Gillam & Borsting, 1988; Grove & Ono, 1999; Wilcox & Lakra, 2007). Monocular areas that are inconsistent with the scene geometry or have different texture than the surfaces they are perceptually attributed to, can hinder depth perception (Grove, Gillam, & Ono, 2002; Grove & Ono, 1999; Shimojo & Nakayama, 1990). In ambiguous disparity stimuli, such as wallpaper patterns, the presence of monocular occlusions induces a form of "disparity-capture" (Hakkinen & Nyman, 2001). In certain configurations monocular occlusions can also produce illusory occluding contours and occluding surfaces (Anderson, 1994; Ehrenstein & Gillam, 1998; Gillam & Grove, 2004; Gillam & Nakayama, 1999; Tsirlin, Wilcox, & Allison, 2010).

It has been argued that the visual system can infer the amount of depth between an occluder and a monocular object or an occluded background and an illusory occluder, based on the constraints imposed by occlusion geometry (Gillam, Blackburn, & Nakayama, 1999; Gillam & Grove, 2004; Gillam & Nakayama, 1999; Liu, Stevenson, & Schor, 1994; Malik, Anderson, & Charowhas, 1999; Nakayama & Shimojo, 1990; Pianta & Gillam, 2003; Tsirlin et al., 2010).

To illustrate this point, in Fig. 1 we provide an example of the geometric constraints in stimuli used by Gillam and Nakayama (1999). This stimulus is composed of two vertical bars positioned in close proximity. In the left eye, a central part of the right bar is removed and in the right eye the central part of the left bar is removed. When the two half-images are fused, the visual system interprets the gaps in the bars as monocularly occluded areas and creates the percept of an illusory occluding surface floating in front of the bars. The lines of sight from each eye to the edges of the bars provide the geometric constraints on the minimum possible depth of the illusory occluder, as shown in Fig. 1B, but the maximum depth is unconstrained. The thickness of the bars dictates the magnitude of the minimum depth. Accordingly, Gillam and Nakayama (1999) showed that as the width of the bars increases the perceived depth of the illusory occluder increases as well.

From this and other examples in the literature (Gillam & Grove, 2004; Gillam & Nakayama, 1999; Gillam et al., 1999; Malik et al., 1999; Tsirlin et al., 2010) it is clear that occlusion geometry provides constraints that the visual system can use to localize monocular features or illusory occluders. However, when the occlusion geometry restricts the depth in only one direction (or not at all) monocular occlusions provide an ambiguous cue to depth (as illustrated in Fig. 1).

Tsirlin et al. (2010) studied the role of geometric constraints in the perception of quantitative depth from monocular occlusions

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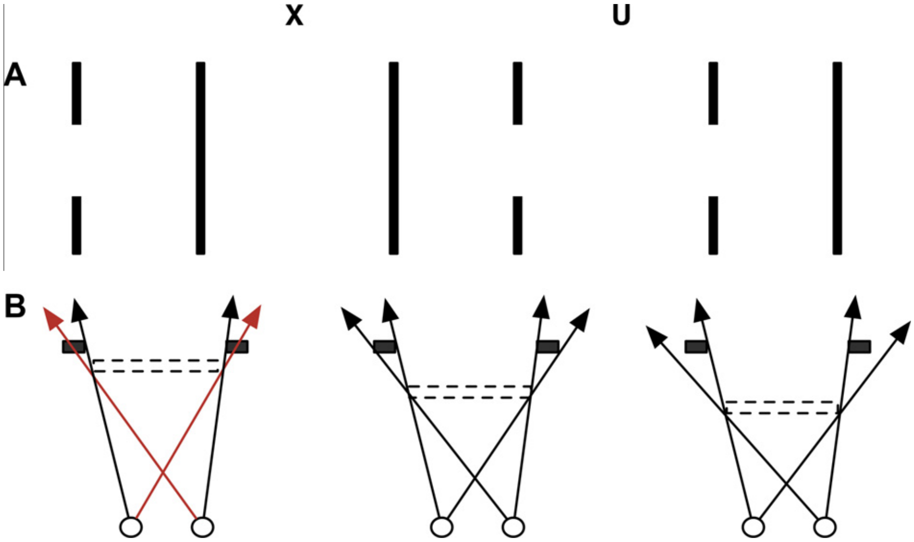

Fig. 1. Illustration of the geometric constraints in occlusion stimuli. (A) Shows the stimulus used by Gillam and Nakayama (1999). (B) Shows the corresponding geometry (view from above). The lines of sight are indicated with arrows, red for arrangements that violate geometric constraints. Dashed lines indicate the illusory occluder. The central diagram in (B) shows the minimum possible depth for the monocular bar (or the illusory occluder). The left diagram shows the violation of the constraints when the depth is smaller than the minimum. The right diagram shows that the depth can be larger than that specified by the minimum constraint. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

using a stimulus in which the presence of occlusions triggered the percept of an illusory occluder. The stimulus was composed of a random-dot frame at zero disparity and a bipartite central region. One side of the central area was a random-dot square with a crossed disparity.[1] The rest of the central region was blank (same color as the background) and in its original form was perceived to lie at the depth of the surrounding frame (see Fig. 2A). When a narrow strip of random dots was added to the image in the right eye between the blank area and the frame, the blank area appeared to lie in front of the frame, forming an illusory occluder (compare Fig. 2A and B). The perceived depth of the illusory occluder increased as the width of the monocular strip was increased (compare Fig. 2B and C). In this case both the minimum and maximum depth of the illusory occluder were constrained (see Tsirlin et al. (2010) for details).

However, when the geometric constraints were weakened by removing the right-hand portion of the random-dot frame (Fig. 2D), an interesting phenomenon was observed. The perceived depth of the illusory occluder no longer scaled with the width of the monocular strip, instead it was always perceived at or near to the depth of the binocular random-dot square (compare Fig. 2C and D). Since in this case only the minimum possible depth of the illusory occluder was constrained (similar to the case shown in Fig. 1), Tsirlin et al. proposed that the random-dot square biased the perceived depth of the illusory occluder in the direction unrestricted by the occlusion geometry. Indeed when the binocular square was assigned zero disparity, quantitative depth localization of the illusory occluder (on the occluded region side) was largely restored.

A biasing of depth from monocular occlusions by a binocular object was demonstrated previously in da Vinci arrangements (Hakkinen & Nyman, 1996). In these displays a monocular dot was placed a certain distance from a binocular rectangle, which was perceived as occluding the dot. Another binocular rectangle (inducer) was placed above the occluder. The perceived depth of the monocular dot increased as the inducer moved farther behind the occluder. Interestingly, in the original article on da Vinci stereopsis, Nakayama and Shimojo (1990) informally reported a similar phenomenon as that demonstrated by Hakkinen and Nyman. They used a disparity probe in their experiment to estimate perceived depth and found that "as the observer moves the binocular probe so it appears as farther and farther away, the monocular target also can appear to move back" (p. 1815). Neither of the articles linked the bias to occlusion geometry.

In the present manuscript we conduct a general test of the hypothesis proposed by Tsirlin et al. (2010) that the perceived depth of an illusory occluder can be biased by disparity in the direction unrestricted by occlusion geometry. To this end, in Experiment 1, we provide additional evidence for the biasing effect of binocular disparity in stimuli first presented by Tsirlin et al. (2010). In Experiment 2 we demonstrate how this phenomenon generalizes to other stimuli. We show that binocular disparity can bias the perceived depth of illusory occluders in the direction unrestricted by the viewing geometry. In Experiment 3 we demonstrate that, in a stimulus where the illusory occluder is localized by both occlusion and some disparity information, most observers rely on the disparity cue and thus exhibit little bias. However, we also show that the visual system may rely on monocular occlusion information in this stimulus. Finally, in Experiment 4 we show that the biasing effect does not take place in stimuli where the depth of occluding surfaces is defined by a reliable disparity signal rather than monocular occlusions.

2. Experiment 1

In this experiment we provide additional evidence for disparity biasing in the stimuli introduced by Tsirlin et al. (2010). We show that when the disparity of the inducing random-dot square increases, the perceived depth of the illusory occluder increases as well, despite the fact that the width of the monocular region remains constant.

2.1. Methods

2.1.1. Observers

Five observers participated in the study. One of them (IT) is one of the experimenters and the rest were naïve as to the purpose of

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[1] The terms 'crossed' and 'uncrossed' in this manuscript describe the disparity of a surface in a scenario when the eyes are fixated on the plane of the screen unless otherwise specified.

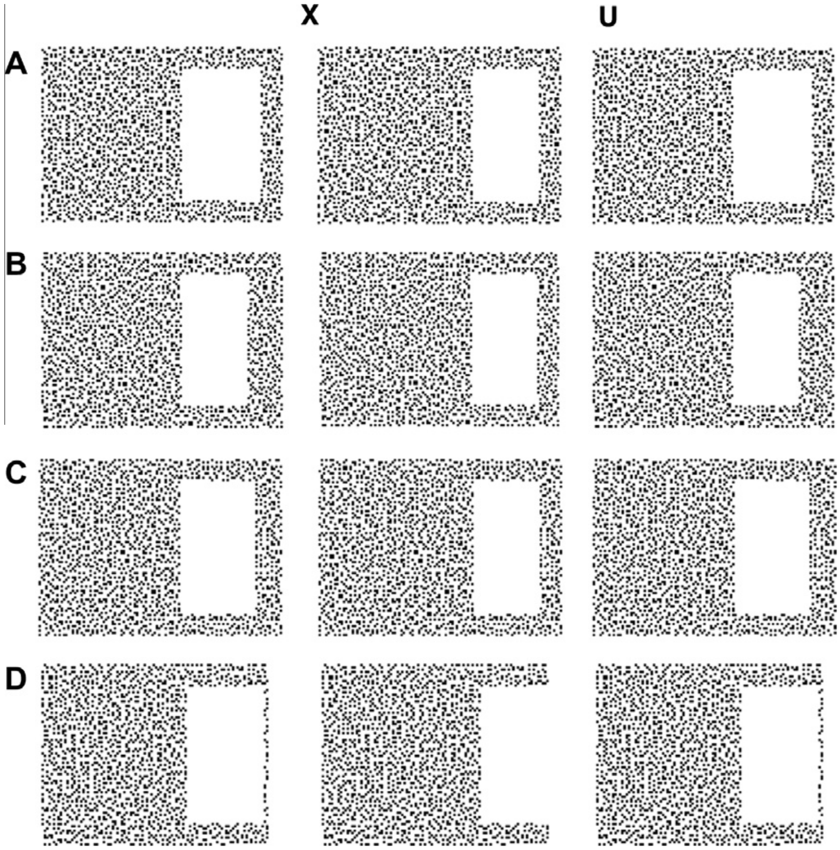

Fig. 2. Examples of stimuli used in Tsirlin et al. (2010). (A) There is no monocular region to the right of the blank area. The blank area is perceived as part of the background. (B and C) There is an occluded region in the right-eye's image to the right of the blank area. When the size of the monocular 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. In (D) the right hand side of the random-dot frame was removed. Although the width of the monocular region in (C) and (D) is the same, in (D) the black area is perceived at the depth of the binocular square by most observers. The left and the central columns are arranged for crossed fusion and the central and the right columns for divergent fusion.

the study. All observers had normal or corrected-to-normal visual acuity and good stereoacuity as measured with the Randot™ stereoacuity test (all observers achieved the criterion of 20 s of arc).

2.1.2. 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 at a viewing distance of 0.6 m. The resolution of the monitors was 1280 × 960 pixels and the refresh rate was 75 Hz. At this resolution and viewing distance, each pixel subtended 1.77 min of visual angle. The monitors were linearized and matched using a photometer to measure the gamma function. Observers used a chin rest to stabilize head position during testing and a gamepad to indicate their responses.

2.1.3. Stimuli

We used the stimulus from Experiments 3 and 4 in Tsirlin et al. (2010) which consisted of a three-sided random-dot frame (background) 22.4 arc min wide, positioned at zero disparity, surrounding a bipartite central region (foreground) as illustrated in Fig. 3. The left side of the central region was a square patch of random-dot texture subtending $1.77 \times 1.77^\circ$ with crossed disparity relative to the background (see values below) so that it appeared to be shifted towards the observer in depth. The remainder of the central region subtended $0.88 \times 1.77^\circ$ and was blank so it contained no disparity information. The element density of the random-dot regions was 25% and each element was 1.77 × 1.77 arc min (1 pixel). The complete stimulus subtended $2.8 \times 2.0^\circ$. A strip of random dots was added to the right of the blank region in the right eye, to simulate a monocular occlusion. The width of the monocular strip was either 3.5 or 7.08 arc min. The disparity of the square was set to 1, 2 or 3 times the width of the monocular strip. For stimuli with a monocular strip width of 3.5 arc min the disparity of the binocular square was set to 3.5, 7.08 or 10.62 arc min. When the monocular region was 7.08 arc min wide the disparity of the binocular square was set to 7.08, 10.62 or 14.8 arc min. In all stimuli the textured region consisted of black dots on a gray background. The blank portion of the central region of the stimulus had the same color as the background of the random-dot patterns. In total there were six different stimuli types (three square disparities × two monocular region widths).

2.1.4. Procedure

Observers were asked to adjust a disparity probe (a black circle with radius 13.44 arc min) to match the depth of the blank region in the central area of the RDS. The probe was presented 2.7° to the right of the center of the RDS. The disparity of the depth probe was adjusted in steps of 0.88 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. Each stimulus condition was presented 20 times in random order with 120 trials in total (20 times × 6 conditions). The experiment was completed in one session. Before the beginning of the experiment the observers were given a short training session to familiarize them with the task.

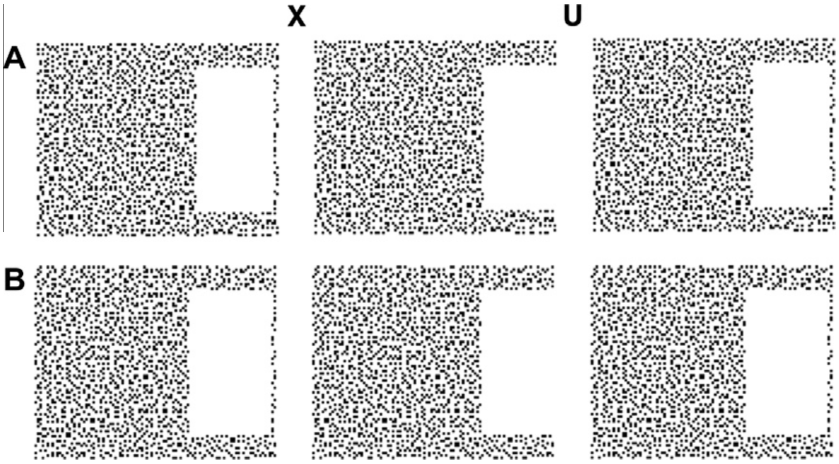

Fig. 3. Example of stimuli used in Experiment 1. In (A) and (B) the monocular region has the same width. In (B) the binocular textured square has a larger disparity than in (A) and hence the perceived depth of the blank region in this case is larger. The left and the central columns are arranged for crossed fusion and the central and the right columns for divergent fusion.

2.1.5. Statistical analysis

We used a non-parametric one-way repeated measures ANOVA (Friedman test) to analyze our data. Data for each monocular occlusion width was analyzed separately using an alpha level of 0.01.

2.2. Results and discussion

Fig. 4 shows the results of Experiment 1. The estimated disparity of the blank region is shown as a function of the disparity of the textured square and monocular region width. The dashed blue and the dotted red lines show the theoretical minimum disparity specified by the occlusion constraints corresponding to each monocular region width. If the textured square had no effect on the perceived depth of the blank region then observers' estimates should follow these lines (perceived depth of the blank region should remain constant). However, it is clear from the figure that the perceived depth of the blank region followed the disparity of the textured square regardless of the size of the occluded region. As the disparity of the textured square increased so did the estimated disparity of the blank region, as if the textured binocular square 'pulled' the blank region towards itself. Statistical analysis showed a highly significant effect of the disparity of the random-dot square on the perceived depth of the occluder for both occlusion widths ($\chi^2 = 10$, $p = 0.0067$ for both widths), consistent with the bias hypothesis proposed by Tsirlin et al. (2010).

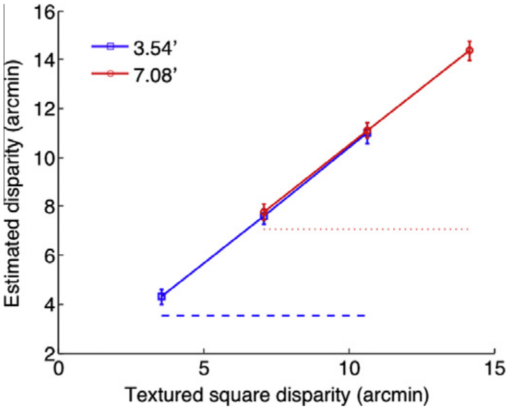

Fig. 4. Results of Experiment 1 for five observers. Inducer (textured square) disparity is plotted on the abscissa and the estimated disparity of the blank region on the ordinate. Blue line with square markers shows the data for stimuli with occluded region of width 3.54 arc min and the red line with circular markers the data for occluded region of width 7.08 arc min. Dashed red and dotted blue lines show the theoretical depth of the blank region if the depth of square would have no effect on the depth of the blank region (dashed line for stimuli with occluded region of width 3.54 arc min and dotted for stimuli with occluded region of width 7.08 arc min). Error bars show ±1 standard error of the mean. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

It is possible that the blank region is perceived as slanted since its depth is defined by monocular occlusions on the right side only. Since only one disparity probe was used in Experiment 1, slant was not assessed. To verify that the blank region was perceived as a frontoparallel surface we repeated a subset of conditions in Experiment 1 with a slightly different task. Only the monocular area width of 3.54 arc min was used, with the same three inducer disparities as in the original experiment (3.54, 7.08 or 10.62 arc min). Two disparity probes were used; one was centered above the right edge of the blank region and the other above its left edge. Only one probe appeared on each trial in order not to bias observers' responses. The probes and the stimuli were presented in random order. Two observers, naïve as to the purpose of the experiment participated in the study. These were new observers, who did not participate in Experiment 1, therefore they did not have expectations regarding the probe settings. The observers were asked to align the probes to the perceived depth of the appropriate edges of the blank region. The depth settings of the two probes for both observers were virtually identical for each type of stimuli as would be expected if the blank region was perceived as a fronto-parallel surface.

3. Experiment 2

In this experiment, we examined whether disparity biasing generalizes to stimuli other than that used by Tsirlin et al. (2010). We chose the stimulus designed by Gillam and Nakayama (1999), since depth from binocular matching is highly improbable in this stimulus. The stimulus, shown in Figs. 1 and 5, was described in detail in the Introduction. Gillam and Nakayama (1999) found that as the thickness of the bars increased, the perceived depth of the illusory occluder increased (see Fig. 5A and B). We tested whether a disparity-defined inducer could bias the depth magnitude of the illusory occluder to the point that its perceived location was determined by the inducer disparity. We used a binocular inducer in the form of a

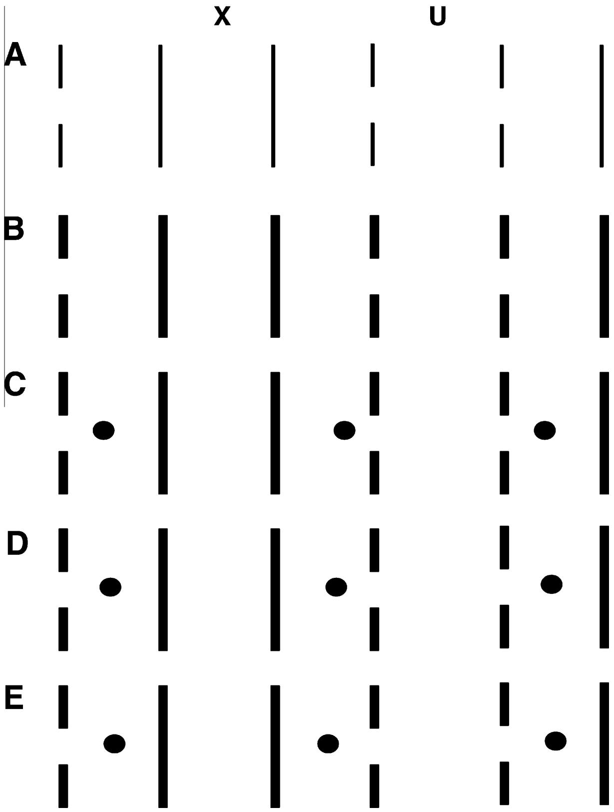

Fig. 5. An Illustration of the stimuli used in Experiment 2. The visual system interprets the gaps in the bars as monocular occlusions and creates a percept of an illusory occluding surface floating in front of the bars. In (B) the defining bars are thicker than in (A) and hence the illusory occluder appears to have more depth. In (C) and (D) a binocular disk (the inducer) with crossed disparity is placed with cyclopean direction midway between the two bars. In (C) the disparity of the inducer is larger than in (D) and the illusory occluder is seen further from the defining bars even though the bars have the same thickness. In (E) the inducer has a smaller crossed disparity than that specified by the geometric constraints. The edges of the occluder in this case are still seen in front of the bars, but its center appears concave. In the actual stimulus, the background was gray and the inducer disk was white. The left and the central columns are arranged for crossed fusion and the central and the right columns for divergent fusion.

small disk positioned in the center of the illusory surface between the two lines, as described below.

3.1. Methods

3.1.1. Observers

Six observers participated in the study. Two of them (IT and LW) are authors and the rest were naïve as to the purpose of the study. All observers had normal or corrected-to-normal visual acuity and good stereoacuity as measured with Randot™ stereoacuity test (all observers acheived a criterion discrimination level of 20 s of arc).

3.1.2. Apparatus

The apparatus was the same as used in Experiment 1 except that the scripts for stimulus presentation were executed using the Psychtoolbox package (v. 3.0.8) for MATLAB (v. 7.4).

3.1.3. Procedure

Experiment 2 consisted of three parts:

3.1.3.1. Occluder-Only. In the first part we replicated the original experiment of Gillam and Nakayama (1999). We used their stimulus with three different bar widths and asked the observers to estimate the depth of the illusory occluder using a disparity probe. In pilot experiments, we followed Gillam and Nakayama's protocol by displaying the probe and the stimulus simultaneously and allowing unlimited viewing time. However, the less experienced observers found it difficult to estimate the depth of the illusory occluder under unrestricted viewing conditions. Consequently, in the experiments reported here we limited the presentation time to 150 ms. The observers first fixated the zero-disparity nonius lines and, when they were well aligned, observers pressed a button to initiate a trial. After the stimulus was presented the disparity probe appeared and observers adjusted its depth to match the remembered depth of the illusory occluder (initially the probe had zero disparity). They were instructed to judge the depth at the vertical edges of the illusory occluder. We chose to evaluate the depth of the occluder at the edges since monocularly occluded areas define the shape and the depth of the vertical edges in this stimulus, and the depth signal is then interpolated between them. Thus depth at the edges of illusory occluders is most suitable to assess the effects of occlusion constraints and their interaction with disparity. Each of 3 bar widths was presented 20 times in random order for a total of 60 trials. Observers completed this part in one session.

3.1.3.2. Inducer-Only. In the second part of the experiment, we asked the observers to estimate the perceived depth of the binocular inducer only. This allowed us to directly compare the perceived depth of the inducer with the perceived depth of the illusory occluder in the subsequent Inducer + Occluder condition. The procedure was the same as in part one. Each of the six inducer disparities was presented 20 times in random order for a total of 120 trials. Observers completed this part in two sessions of 60 trials each.

3.1.3.3. Inducer + Occluder. The third part of this experiment was designed to reveal any biasing from the binocular inducer on the perceived depth of the illusory occluder. The stimulus used here was the original Gillam and Nakayama stimulus with a binocular inducer (disk) placed in the center between the stimulus lines (see Fig. 5C and D). The procedure used here was the same as that used in the other two parts. There were 18 different conditions (six inducer disparities × three widths) repeated 20 times for 360 trials in total. Observers completed this part in four sessions of 60 trials each.

The three parts of this study were completed in the same order by all observers. First, observers completed the Occluder-Only trials, then the Inducer-Only and finally the Inducer + Occluder condition. This order was chosen to familiarize the observers with the two component stimuli before they were tested with the combined stimulus. Before the first session of each part, observers were first shown the stimulus with an extended presentation time to familiarize them with the stimulus and then given a short training session with the relatively short exposure duration used in subsequent testing.

3.1.4. Stimuli

3.1.4.1. Occluder-Only. The stimuli used in this part replicated those used by Gillam and Nakayama (1999). The bar length was 2.5°. The horizontal separation between the bars was 1.5° and the vertical gap in one of the bars was 44 arc min. The width of the bars was either 1.77, 3.54 or 5.31 arc min. The selected range of bar widths was similar to that used in the original study (0.77–3.87 arc min). The bars were black on a gray background and had zero disparity. Examples of stimuli with different bar widths are shown in Fig. 5A and B.

The subsequently presented disparity probe consisted of two bars identical to the stimulus bar but with the monocular gap filled so that there was no percept of an illusory occluder. A black disk, 17.7 arc min in diameter, was positioned at the center of the bar configuration. The black disk could be moved in depth in 1.77 arc min steps. The two bars had zero disparity with respect to the plane of the screen and served as a reference for the moving disk. The disk was antialiased to allow for subpixel shifts. Both the stimulus and the probe were positioned in the center of the display.

3.1.4.2. Inducer-Only. This stimulus consisted of two bars with the same parameters as the stimulus in the Occluder-Only condition (width 3.54 arc min), but the monocular gap was filled so that there was no percept of an illusory occluder. The inducer was a white disk, 10.6 arc min in diameter, positioned at the center of the line configuration. The inducer disparity was either 3.54, 0, −3.54, −10.62, −14.16 or −17.7 arc min. The choice of disparity values is discussed in detail below. The disparity probe in this part was the same as in the Occluder-Only condition.

3.1.4.3. Inducer + Occluder. This stimulus was a combination of those used in the preceding two conditions. The inducer disk was placed in the center of the illusory occluder stimulus (see Fig. 5C–E). We used three bar widths for the illusory occluder stimulus as in the Occluder-Only condition and six inducer disparities as in the Inducer-Only condition. We used both crossed and uncrossed disparities for the inducer, although according to the geometric constraints the illusory surface must always be positioned some distance in front of the stimulus lines (the minimum crossed disparity in this stimulus is indicated by the width of the bars – −1.77, −3.54 or −5.31 arc min). Uncrossed (and small crossed) disparities were included to verify that the disparity biasing is indeed constrained by occlusion geometry as proposed by Tsirlin et al. (2010) and that the observers were estimating the depth of the illusory surface, and not the depth of the inducer. The disparity probe in this part was the same as in the Occluder-Only part.

3.1.5. Statistical analysis

3.1.5.1. Occluder-Only/Inducer-Only. As in Experiment 1 we used a non-parametric one-way repeated measures ANOVA (Friedman test) to test for the main effects of bar width or inducer disparity. The alpha level was set to 1%.

3.1.5.2. Inducer + Occluder. Due to inter-observer variability, data obtained in this condition were analyzed separately for each observer. We used a linear regression analysis with perceived depth as the dependent and inducer disparity as the independent variables. The slopes of the regression lines showed the relationship between inducer disparity and perceived depth of the occluder; the larger the slope, the stronger the relationship. We used a randomization procedure to generate an empirical distribution for the *F* statistic corresponding to each regression model. This is a non-parametric technique that avoids making explicit assumptions about the underlying distribution of the data. The data corresponding to each bar width were analyzed separately. To assess the role of geometric constraints on depth perception in our stimuli we computed two regression models for each bar width. In the first model we used data corresponding to inducer disparities that did not violate the geometric constraints (different for each line width). In the second model we used the data corresponding to the rest of the disparities. The alpha level was 1%.

3.2. Results and discussion

3.2.1. Occluder-Only

The results for this part of the experiment are shown in Fig. 6A. Since all observers had the same pattern of results we combined the data. There was a clear increase in estimated disparity with increasing bar width. This observation was confirmed by the statistical analysis; bar width had a significant effect on estimated disparity ($\chi^2 = 12$, $p = 0.0025$). These data confirmed the results reported in Gillam and Nakayama's (1999) original study including their observation that depth estimates were larger than those predicted by the minimum constraint.

3.2.2. Inducer-Only

The results for this experiment are shown in Fig. 6B (blue line with square markers). As in the Occluder-Only condition, the data were consistent across all observers so we combined them in the figure. As expected, observers' estimates of the inducer disk disparity increased with increasing disparity. This observation was confirmed by the statistical analysis; there was a significant main effect of inducer disparity ($\chi^2 = 25$, $p = 0.00014$). At larger inducer disparities observers underestimated the disparity. Since the probe appeared after the presentation of the stimulus it is possible that the time delay reduced the accuracy of observers' judgments, more so for larger inducer disparities. To verify this we repeated this experiment for two observers (IT and DS) with unlimited presentation time and the probe presented simultaneously with the

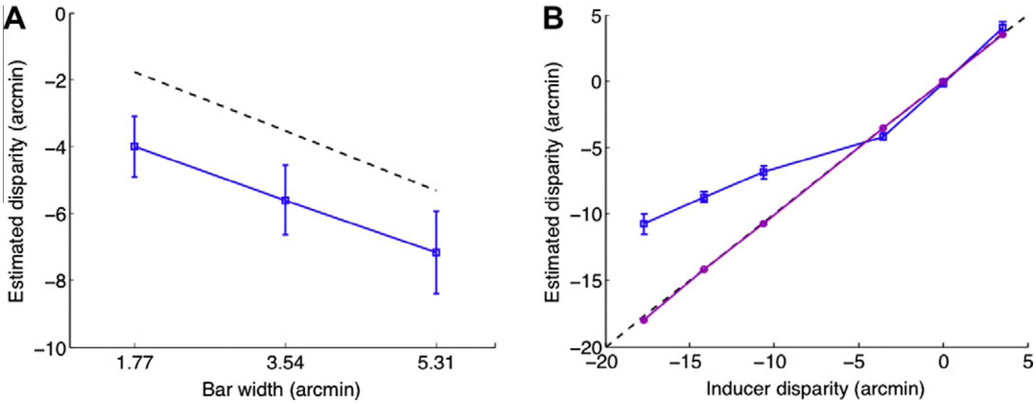

Fig. 6. Results of parts 1 and 2 of Experiment 2. (A) Results of the Occluder-Only condition. The bar width is plotted on the abscissa and the estimated disparity on the ordinate. The blue solid line shows the mean data for six observers and the black dashed line shows the theoretical disparity. Error bars show ±standard error of the mean. (B) Results of the Inducer-Only condition. Inducer disparity is plotted on the abscissa and the estimated disparity on the ordinate. The blue line with square markers shows the mean data for six observers and the black dashed line shows the correct disparity. The purple line with circular markers shows the mean data for observers IT and DS for the control experiment, where the stimulus and the disparity probe were presented simultaneously (see text for details). Error bars show ±1 standard error of the mean. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

stimulus (the probe was a small disk positioned to the right of the stimulus). The depth estimates in this case, as shown in Fig. 6B (purple line with circular markers), were veridical.

3.2.3. Inducer + Occluder

Data for this condition are shown in Fig. 7. For comparison we also replotted the data from the Inducer-Only part. The black line with no markers shows the results of the Inducer-Only task, the estimated disparity of the inducer in the absence of the illusory surface. The colored lines with different markers show the estimated disparity of the illusory surface in the presence of the inducer for different line widths. If the perceived depth of the illusory occluder was not affected by the inducer, we should have seen little change in the estimated disparity of the illusory occluder as the disparity of the inducer changed. The estimated disparity of the illusory occluder should have remained constant. This clearly was not the case for five of the six observers. Three observers (DS, IT and AS) showed a strong bias; when the inducer disparity increased in the crossed direction beyond the disparity specified by the minimum constraint, the disparity estimates became biased in the crossed direction. A similar trend can be seen for observers LT and LW, although the biasing effect was weaker. Observer FZ showed almost no effect of the inducer on the perceived depth of the illusory occluder.

These observations were confirmed by the statistical analysis shown in Table 1. Data from all observers except for FZ showed a significant dependence of estimated disparity of the occluder on inducer disparity for all bar widths when the inducer had a larger crossed disparity than the minimum crossed disparity specified by the occlusion constraints (column 'Slope CD' in Table 1). This minimum disparity for each line width was equal to the line width itself (−1.77, −3.54 and −5.31 arc min accordingly). When the inducer had an uncrossed or a crossed disparity smaller than the minimum, the relationship between the perceived depth and inducer disparity was not significant except in two cases, observers IT (width 5.31′) and AS (width 1.77′). FZ showed no significant relationship between estimated occluder disparity and inducer disparity for any of the conditions.

The configurations in which the occluder had an uncrossed or a smaller crossed disparity than the minimum specified by the geometric constraints created a very distinctive percept. That is, the illusory surface appeared to warp so that its edges sat toward the observer and its center was at the depth of the inducer (see Fig. 5E). The edges of the occluder were perceived to lie in front of the stimulus bars consistent with occlusion geometry. As indicated in the Methods section, observers were instructed to judge the depth of the illusory surface at its edges. As the data show, when the inducer had a small crossed or an uncrossed disparity observers still indicated that the illusory surface was in front of the stimulus lines (probe settings were always at crossed disparity). The lack of a significant effect of inducer disparity on the perceived depth of the occluder edges in these conditions allows us to draw two conclusions. First, the observers were performing the task correctly, estimating the depth of the illusory occluder at its edge, and not the depth of the inducer. Second, that the constraints imposed by the viewing geometry restrict the biasing effect of the binocular feature on the edges of the illusory occluder.

4. Experiment 3

Liu et al. (1994) also presented an example of illusory surface perception from monocular occlusions, using a different stimulus configuration. Their stimulus consisted of a thick black bracket on a white background, with the gap pointing to the left and to the right in the right and the left half-images respectively as shown in Fig. 8. In the cyclopean image an illusory white rectangle was perceived as floating in front of the black rectangle. Liu et al. (1994) found that perceived depth magnitude of the illusory rectangle was proportional to the width of the visible side-bars of the black bracket. They suggested that quantitative depth in their stimuli was perceived purely on the basis of monocular occlusions in accordance with the minimum depth constraint. However,

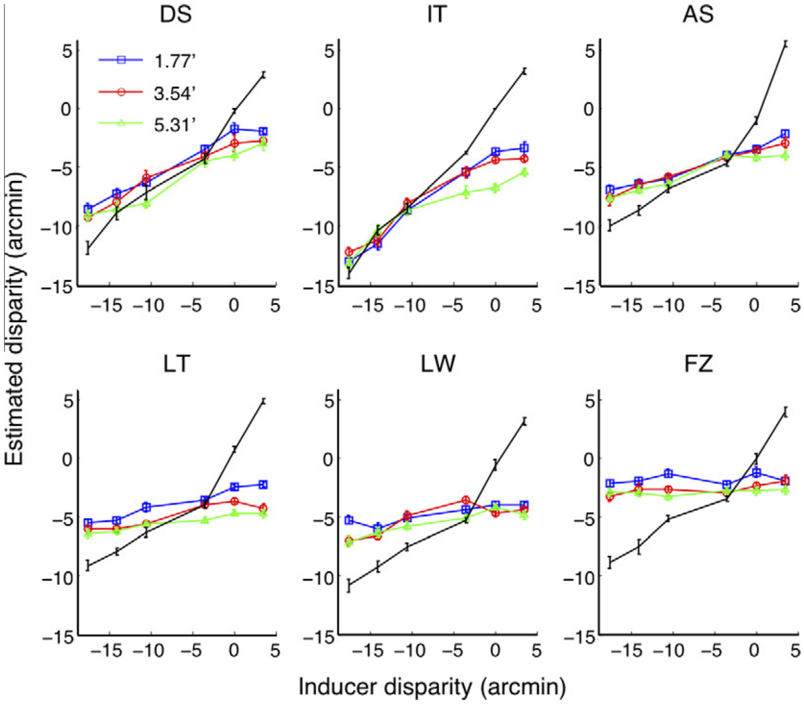

Fig. 7. Results of Experiment 2 for six observers. Inducer disparity is plotted on the abscissa and the estimated disparity on the ordinate. The solid colored lines with different markers show the data for different line widths from the Occluder + Inducer part. The black line with no markers shows data from the Inducer-Only part. Error bars show ±standard error of the mean. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Results of statistical analysis of Inducer + Occluder part of Experiment 2. The third column (Slope CD) shows the regression slopes corresponding to inducer disparities that are larger than the minimum crossed disparity specified by the occlusion constraint. The fourth column (UD) shows the regression slopes corresponding to inducer disparities that are smaller than the minimum disparity. Asterisks indicate a statistically significant results:

Observer	Width	Slope CD	Slope UD
DS	1.77	0.381^{***}	−0.067
	3.54	0.372^{***}	0.183
	5.31	0.329^{***}	0.217
FZ	1.77	0.027	−0.225
	3.54	0.014	0.15
	5.31	0.005	0.013
LT	1.77	0.169^{***}	0.050
	3.54	0.151^{***}	−0.038
	5.31	0.086^{**}	0.075
IT	1.77	0.537^{***}	0.075
	3.54	0.503^{***}	0.163
	5.31	0.407^{***}	0.238^{**}
AS	1.77	0.204^{***}	0.380^{**}
	3.54	0.238^{***}	0.18
	5.31	0.260^{***}	−0.010
LW	1.77	0.096^{***}	0.000
	3.54	0.259^{***}	−0.113
	5.31	0.139^{***}	0.038

** $p < 0.01$.
*** $p < 0.001$.

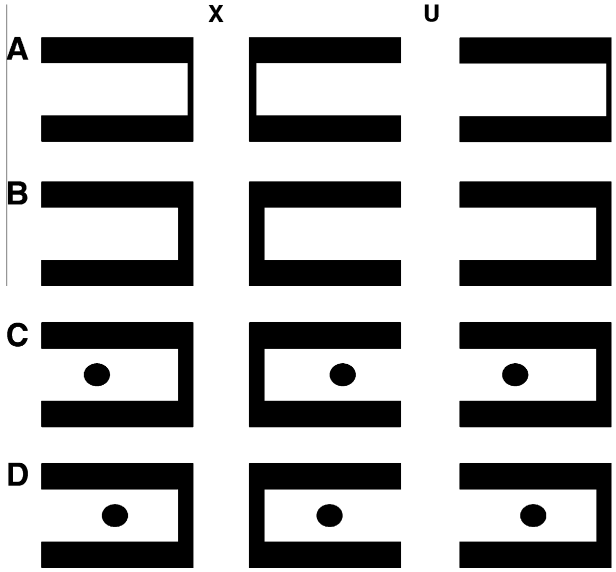

Fig. 8. Examples of stimuli used in Experiment 3. The visual system interprets the absence of one of the side-bars as a monocular occlusion and creates a percept of an illusory occluding surface floating in front of a black rectangle. In (B) the side-bar is thicker than in (A) and hence the illusory occluder has more depth. In (C) a binocular disk (the inducer) with crossed disparity is placed in the center of the bracket. Most observers perceive the disk at a different depth than the illusory occluder. In (D) the inducer has a more uncrossed disparity than that specified by the geometric constraints. The edges of the occluder in this case are still seen in front of the bars, but its center appears concave. In the actual stimulus, the background was gray and the inducer disk was white. The left and the central columns are arranged for crossed fusion and the central and the right columns for divergent fusion.

Gillam (1995) argued that while there were no matching vertical luminance edges, the visual system could match the horizontal luminance edges with disparities given by their endpoints. Liu, Stevenson, and Schor (1995, 1997) pointed out that the terminations of the horizontal edges in their stimulus have opposite contrast polarity and hence are not an optimal binocular matching primitive. They suggested instead that the bracket corners could be matched and they demonstrated this phenomenon using computational modeling.

This stimulus represents a good case to test the limitations of the disparity bias demonstrated in Experiments 1 and 2. If our visual system relies only on the disparity cues in this stimulus, the perceived depth of the illusory occluder should not be strongly affected by a nearby binocular feature. On the other hand, if depth is perceived primarily on the basis of monocular occlusions we should observe a depth biasing effect similar to that seen in Experiment 2. We have argued that when monocular occlusion geometry provides only weak constraints on depth, disparity represents a more reliable cue than monocular occlusions (Tsirlin et al., 2010). In the Liu et al. stimulus the occlusion geometry provides a constraint only on the minimum depth between the occluded rectangle and the illusory occluder similarly to Gillam and Nakayama (1999) stimulus (see Fig. 1). Consequently, we predict that observers will be more prone to rely on disparity in this case and a binocular inducer will have no effect on the perceived depth of the illusory occluder.

4.1. Methods

4.1.1. Observers

Six observers participated in the study. One of them (IT) is one of the experimenters and the rest were naïve as to the purpose of the study. All observers had normal or corrected-to-normal visual acuity and good stereoacuity as measured with Randot™ stereoacuity test (all observers acheived a criterion discrimination of 20 s of arc).

4.1.2. Apparatus

The apparatus was the same as in Experiment 2.

4.1.3. Procedure

The experiment consisted of the same three parts as Experiment 2. The procedure was also the same, except that in this case observers viewed the probe and test stimulus simultaneously (preliminary experiments showed that observers performed well under such conditions) as was the case in Liu et al's study. The presentation time was unlimited and observers indicated with a button press when they completed each trial. Observers completed the three conditions as outlined in Experiment 2.

4.1.3.1. Occluder-Only. In this part of the experiment we replicated the original experiment of Liu et al. (1994). We displayed their stimulus with three different side-bar widths and asked the observers to estimate the depth of the illusory occluder using a disparity probe. Each of 3 side-bar widths was presented 20 times in random order for a total of 60 trials. Observers completed this part in one session.

4.1.3.2. Inducer-Only. In the second part of the experiment, we asked observers to estimate the perceived depth of the binocular inducer only. Each of the seven disparities was presented 20 times in random order for a total of 140 trials. Observers completed this part in two sessions of 70 trials each.

4.1.3.3. Inducer + Occluder. The third part of the experiment was designed to reveal any depth biasing from the binocular inducer on the perceived depth of the illusory occluder. The stimulus used in this condition was a combination of the original stimulus and a binocular inducer. The procedure for this part was the same as for the previous two parts. Each stimulus condition was presented 20 times at random. There were 21 different conditions (seven inducer disparities × three side-bar widths) and 420 trials in total which were completed in four sessions of 105 trials each.

4.1.4. Stimuli

4.1.4.1. Occluder-Only. The stimuli used in this part of the experiment replicated the stimulus of Liu et al. (1994). The width of the side-bars (the vertical portion of the bracket) was one of 1.77, 7.08 or 12.39 arc min. These widths were close to the range of approximately 5–25 arc min used by Liu et al. (1994). The total size of the bracket was 2.06 × 1.47° and the height of the gap inside the bracket was 1°. The bracket was black on gray background and was presented with zero disparity in the center of the screen. Examples of the stimulus with two different side-bar widths can be seen in Fig. 8.

The disparity probe was a black disk, 17.7 arc min in diameter positioned to the right of the stimulus (it was presented simultaneously with the stimulus). The probe could be moved in depth in 1.77 arc min steps. It was antialiased to allow for subpixel shifts.

4.1.4.2. Inducer-Only. In this part of the experiment the bracket had the same parameters as in the Occluder-Only condition (side-bar width 7.08 arc min), but the monocular gap was filled in such that no illusory occluder was perceived. The inducer was a white disk, 10.6 arc min in diameter, positioned vertically in the center of the bracket. The inducer disparity was one of 3.54, 0, −1.77, −7.08, −14.16, −17.7 or −21.24 arc min. The choice of disparity values was governed by the same considerations as in Experiment 2. The disparity probe was the same as in the Occluder-Only condition.

4.1.4.3. Inducer + Occluder. This experiment combined the stimuli from the other two conditions. The inducer disk was placed in the center of the illusory occluder stimulus (see Fig. 8C and D). We used three side-bar widths for the illusory occluder stimulus as in the Occluder-Only condition and seven inducer disparities as in the Inducer-Only condition. The disparity probe was the same as in the other two conditions.

4.1.5. Statistical analysis

Statistical analysis for each of the conditions was the same as in Experiment 2.

4.2. Results and discussion

4.2.1. Occluder-Only

Since all observers showed the same pattern of results we have combined the data in Fig. 9A. As can be seen in the figure, there was a clear increase in estimated disparity as the width of the side-bars was increased. This observation was confirmed by the statistical analysis; the Friedman test showed a highly significant effect of width on perceived depth ($\chi^2 = 12$, $p = 0.0024$). These data confirm the results reported in the original experiment by Liu et al. (1994). However, in our case the disparity was overestimated on average as it was in Experiment 2. In Liu et al.'s original experiment disparity estimates were closer to the theoretical prediction (the minimum constraint), although one of their three observers (PB) seemed to underestimate and another (LM) to overestimate the perceived depth.

4.2.2. Inducer-Only

As in the first part, the data were consistent across all observers so we have combined them in Fig. 9B. As expected, observers' estimates increased as the disparity of the inducer was increased. Statistical analysis showed a highly significant effect of inducer disparity on perceived depth ($\chi^2 = 12$, $p = 2.757\text{e}-06$). Here the estimates were more accurate than in Experiment 2 since the probe was presented concurrently with the stimulus.

4.2.3. Inducer + Occluder

Data for this condition are shown in Fig. 10. For comparison we also plotted the data from the Inducer-Only condition. The black line without markers shows the results of the Inducer-Only task, that is, the estimated disparity of the inducer in the absence of the illusory surface. The solid colored lines with different markers show the estimated disparity of the illusory surface in the presence of the inducer for different side-bar widths. If the inducer did not affect the perceived depth of the illusory occluder, we should see no change in the estimated disparity of the illusory occluder as the disparity of the inducer changes. Indeed, most of the observers showed little effect of the inducer on the perceived depth of the occluder. However, observer DS showed a markedly different pattern of results. In her data there is a clear bias in the perceived depth of the illusory occluder in the presence of the inducer, when the inducer has a larger crossed disparity than the minimum crossed disparity specified by the viewing geometry (this disparity for each side-bar width is equal to the width itself). These observations

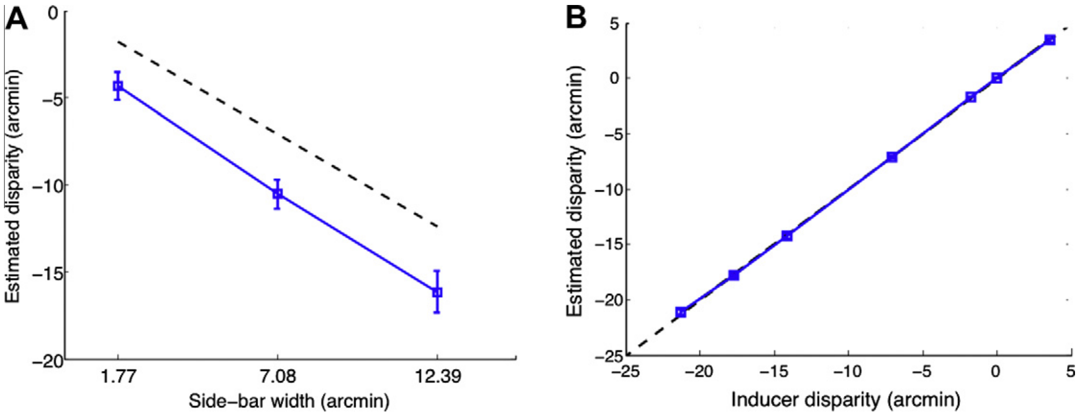

Fig. 9. Results of parts 1 and 2 of Experiment 3. (A) Results of Occluder-Only part. The side-bar width is plotted on the abscissa and the estimated disparity on the ordinate. The solid blue line shows the mean data for six observers and the dashed black line shows the theoretical disparity. Error bars show ±standard error of the mean. (B) Results of Inducer-Only part. Inducer disparity is plotted on the abscissa and the estimated disparity on the ordinate. The solid blue line shows the mean data for six observers and the dashed black line shows the theoretical disparity. Error bars show ±standard error of the mean. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

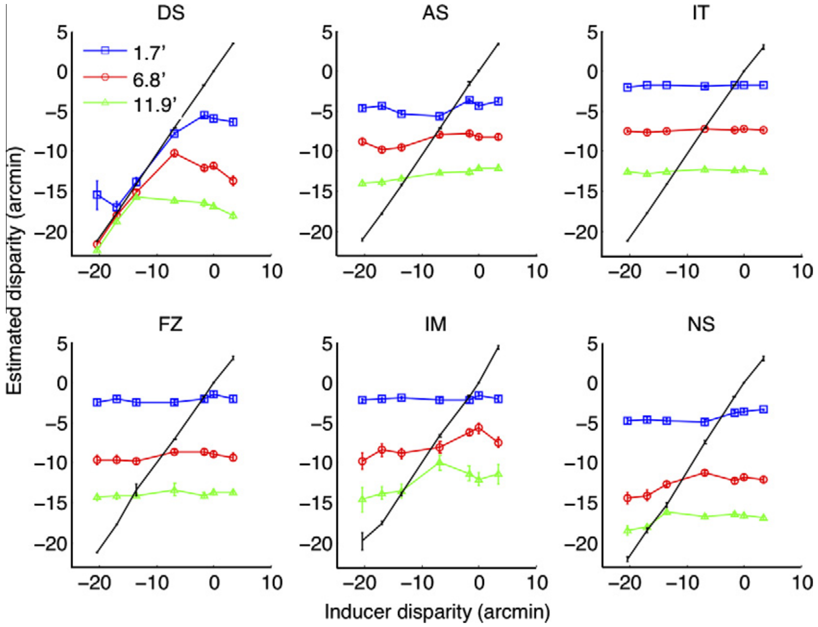

Fig. 10. Results of Experiment 3 for six observers. Inducer disparity is plotted on the abscissa and the estimated disparity on the ordinate. The solid colored lines with different markers show the data from the Occluder + Inducer part for different side-bar widths. The black line without markers shows data from the Inducer-Only part. Error bars show ±standard error of the mean. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

are confirmed by the statistical analysis shown in Table 2. Observer DS showed a highly significant relationship between the inducer disparity and occluder depth for all side-bar widths when inducer had a larger crossed disparity than the minimum crossed disparity specified by occlusion constraints. In contrast, the data from observers IT and FZ showed no effect of inducer disparity on perceived occluder depth. Observers AS, IM and NS showed a significant effect of inducer disparity for the larger side-bar widths; AS and IM for width 12.39′ and NS for widths 7.08′ and 12.39′. For all other side-bar widths these observers showed no significant effect of inducer disparity.

Table 2
Results of statistical analysis of Inducer + Occluder condition in Experiment 3. The third column (Slope CD) shows the regression slopes corresponding to inducer disparities that are larger than the minimum crossed disparity specified by the occlusion constraint. The fourth column (UD) shows the regression slopes corresponding to inducer disparities that are smaller than the minimum disparity. Asterisks indicate a statistically significant results.

Observer	Width	Slope CD	Slope UD
DS	1.77	0.611***	−0.161
	7.08	0.787***	−0.307***
	12.39	0.411***	−0.159***
AS	1.77	0.018	0.007
	7.08	0.076	−0.029
	12.39	0.099***	0.063
IT	1.77	0.004	0.000
	7.08	0.023	−0.013
	12.39	0.021	−0.014
FZ	1.77	0.006	−0.007
	7.08	0.076	−0.067
	12.39	0.069	−0.023
IM	1.77	−0.003	0.011
	7.08	0.102	0.091
	12.39	0.324**	−0.153
NS	1.77	0.037	0.064
	7.08	0.237***	−0.077
	12.39	0.135***	−0.007

** $p < 0.01$.
*** $p < 0.001$.

The relatively small effect of the binocular inducer in the Liu et al. (1994) stimulus for 5 of the 6 observers suggests that these observers primarily relied on binocular disparity in this stimulus. However, DS's data show that it is *possible* for the visual system to use monocular occlusion information to define the depth of the illusory surface under these conditions.

5. Experiment 4

In Experiments 1–3 we made the implicit assumption that the perceived depth of surfaces defined by disparity would not be biased in the presence of a binocular feature placed in the center of the surface. Although this assumption makes intuitive sense, it must be verified empirically. Moreover, it is important that we confirm that the disparity biasing exhibited by observer DS in Experiment 3 was indeed due to her reliance on depth from occlusions. It is possible that, for this observer, even surfaces defined by unambiguous disparity could have had their depth biased by proximate features with different disparity. We modified the Liu et al. (1994) stimulus by filling the monocular gaps, such that the smaller inner rectangle had well defined vertical luminance edges on both sides. The smaller rectangle had crossed disparity with respect to the big rectangle and was perceived in front of the big rectangle in depth (see Fig. 11). We then repeated the Occluder + Inducer condition of Experiment 3 with this modified stimulus.

5.1. Methods

Observers and apparatus were the same as in Experiment 3.

5.1.1. Stimulus

The stimulus was composed of a black rectangle subtending 2.06 × 1.47° and a gray rectangle (same color as the background) subtending 1.6 × 1°. The disparity of the gray rectangle was one of 1.77, 7.08 or 12.39 arc min (the same as the widths of the side-bars in Experiment 3). The black rectangle was presented with zero disparity at the center of the screen. The inducer

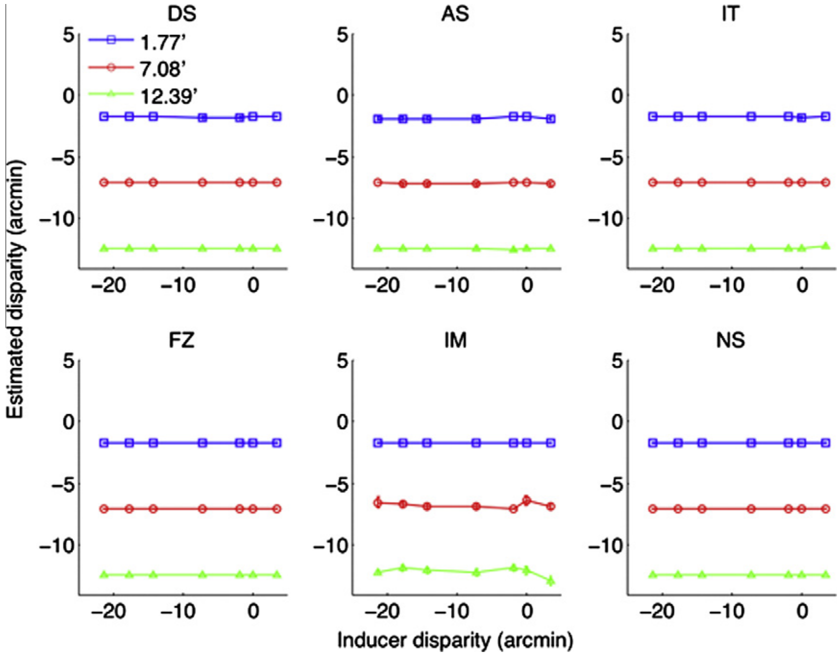

Fig. 11. Example of stimuli in Experiment 4. When fused the stimulus is perceived as a small, white rectangle in front of a bigger black rectangle (in the actual experiment the background and the small rectangle were gray). In (B) a binocular disk (the inducer) with crossed disparity is placed in the center of the small rectangle. In (C) the inducer has a smaller crossed disparity than that of the small rectangle. The left and the central columns are arranged for crossed fusion and the central and the right columns for divergent fusion.

was a white disk, 10.6 arc min in diameter, positioned vertically in the center of the gray square. The inducer disparity was one of 3.54, 0, −1.77, −7.08, −14.16, −17.7 or −21.24 arc min (same as in Experiment 3). The disparity probe was the same as in Experiment 3. Examples of the stimulus with two different side-bar widths can be seen in Fig. 11.

5.1.2. Procedure

The observers were asked to adjust the disparity probe to the depth of the gray rectangle which appeared to lie in front of the black rectangle. As before they were told to ignore the white disk. The disparity probe was presented simultaneously with the stimulus and the presentation time was not limited. Each stimulus

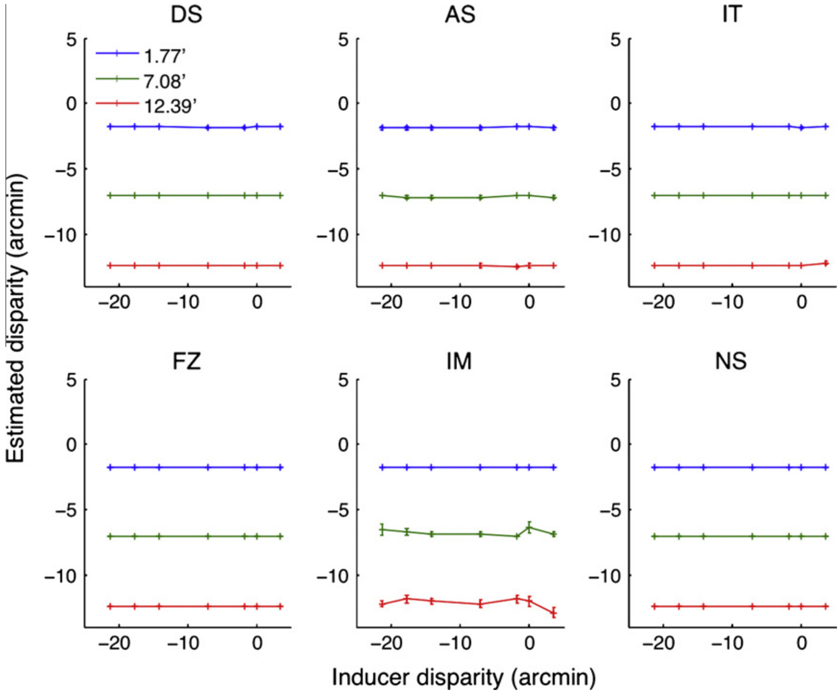

Fig. 12. Results of Experiment 4 for six observers. Inducer disparity is plotted on the abscissa and the estimated disparity on the ordinate. Differently colored lines with different markers represent the disparity of the gray square. Error bars show ±standard error of the mean. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

condition was presented 20 times at random. There were 21 different conditions (seven inducer disparities × three occluder disparities) and 420 trials in total. Observers completed this part in four sessions of 105 trials each.

5.1.3. Statistical analysis

Since the results of all observers were virtually identical, we pooled their data for this analysis. We fit three regression models, one for each surface disparity and assessed the significance of the slopes using a randomization technique (see Experiment 2).

5.2. Results and discussion

Fig. 12 shows the results of Experiment 4. It is clear that the perceived depth of the small, gray rectangle was not affected by the inducer disparity for any of the observers, including DS. Statistical analysis showed no significant relationship between the inducer disparity and estimated disparity of the rectangle. These results show that depth from disparity in the configuration used in Experiment 4 is not subject to the biasing effect demonstrated for depth from monocular occlusions in Experiments 1–3. The results also confirm that the pattern of results shown by observer DS in Experiment 3 was due to her reliance on monocular information when viewing the Liu et al. (1994) stimulus.

6. General discussion

We have shown that the perceived depth of illusory occluders, induced by monocular occlusions, can be biased by a binocularly-defined feature. The effect was demonstrated in several different stimuli where the presence of monocularly occluded features created a percept of an illusory occluding surface.

This disparity-induced biasing was limited by the constraints specified by occlusion geometry. That is, a binocular inducer that had an uncrossed or a smaller crossed disparity than the minimum crossed disparity specified by the occlusion geometry, could not ‘pull’ the perceived depth of the edges of the illusory occluder in the uncrossed direction. However, when the inducer had a larger crossed disparity than the minimum crossed disparity, then the perceived depth of the (whole) illusory occluder was biased toward the inducer. Previously (with stimuli similar to those in Experiment 1), we showed that when the depth of the illusory occluder was constrained in both directions, the binocular inducer had no effect on the perceived depth of the occluder (Tsirlin et al., 2010). Taken together these findings show that the visual system is guided by geometric constraints in estimating qualitative and quantitative depth from monocular occlusions.

The disparity biasing demonstrated in the present experiments is also likely to be modulated by the size of the binocular inducer and the strength of its disparity signal. The bias created by the stimuli used in Experiment 1 was greater than that seen in Experiment 2. In Experiment 1 the perceived depth of the illusory occluder was almost identical to that of the inducer for all observers, while in Experiment 2 there was a large effect for three observers, a smaller effect for two other observers and no effect for one observer. This difference could be explained by the differences in binocular inducers used in the two experiments. In Experiment 1, the inducer was a (relatively) large surface—larger than the adjacent illusory occluder—and its disparity was defined by multiple elements. In Experiment 2, the inducer was a single small disk – smaller than the illusory occluder – and its disparity was defined by the vertical components of the circular contour. Consequently, this inducer’s disparity signal was weaker than the signal of the inducer in Experiment 1. It is possible that intensifying the disparity signal of an inducer by increasing its extent, number and/or the length of its vertical edges might result in a stronger biasing effect.

Investigation of the biasing phenomenon in Experiment 3 revealed an interesting tradeoff between monocular occlusion and disparity cues. The Liu et al. (1994) stimulus, used in Experiment 3, contains both monocular occlusion and binocular disparity cues to the depth of the illusory occluder (Gillam, 1995; Liu et al., 1995, 1997). Since monocular occlusions provide an ambiguous cue to depth in this stimulus (only the minimum possible depth of the illusory occluder is restricted), the observers were expected to rely on the binocular disparity signal to establish the depth of the illusory occluder. Grove et al. (2002) provided evidence to support this hypothesis when they examined the effect of the content of monocular zones on depth perception from occlusions in stimuli including those of Gillam and Nakayama (1999) and Liu et al. (1994). Although perceived depth in the former stimulus was reduced when the monocular regions were textured differently from the background, the depth in the Liu et al. stimulus was not. Accordingly, we hypothesized that, in the Liu et al. (1994) stimulus, the inducing binocular feature would have little effect on the perceived depth of the occluder. This was indeed the case for five of the six observers. However, one observer showed a strong bias, similar to her results in Experiment 2. Experiment 4 showed that the bias was not present for this or any other observer in stimuli where the occluding surface had luminance defined edges on both sides. The stimuli used in Experiment 4 had a strong disparity signal, while in Liu et al. (1994) stimulus the disparity signal was weak in comparison to a conventional stimulus, such as that of Experiment 4.[2] The relative weakness of the disparity cue might have caused observer DS to rely on the monocular occlusion information instead.

Another example of the selection of monocular occlusions as the primary cue to depth in stimuli with both cues present was provided by Hakkinen and Nyman (2001). They showed a disparity capture-like effect with Gillam & Nakayama’s (1999) stimuli overlaid on a wall-paper pattern. The binocular pattern was captured by the depth induced by monocular occlusions so that it was perceived at the depth of the illusory occluder. Taken together with the results of Experiment 3, these findings suggest that some observers rely on monocular occlusions to determine the location in depth of a surface in stimuli where disparity information is present but is ambiguous or weak. Thus, monocular occlusions can serve as the primary quantitative depth even in the presence of a disparity signal.

The possible mechanisms behind the bias phenomenon shown here most likely involve disparity interpolation and extrapolation. In disparity interpolation the disparity signal propagates from the source of the disparity signal (e.g. a luminance edge) across the surface towards the next source of disparity. One could imagine a similar depth interpolation process taking place in illusory occluder stimuli. The depth signal generated by the visual system based on occlusion geometry at the edges propagates across the blank regions. Due to the weak constraints on the magnitude of depth in the illusory occluder stimuli the propagating depth signal is relatively weak. The unambiguous disparity signal in the inducer, such as the disk in Experiment 2 and the RD surface in Experiment 1, could interfere and bias the perceived depth of the occluder.

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[2] Gillam (1995) proposed that the endpoints of the horizontal luminance edges were matched in the Liu et al. stimulus. However, as was noted by Liu et al. (1995), these endpoints have different contrast polarity and hence cannot be considered as optimal matching primitives. Liu et al. (1995, 1997) proposed disparity-tuned corner detectors that could match the corners in their stimulus to extract the disparity of the illusory occluder. However, the corners in their stimulus did not provide the optimal stimulation (eliciting the maximal response) for the proposed detectors. Whether such detectors are indeed involved in depth perception in Liu et al. stimulus, or horizontal contours are matched instead as was proposed by Gillam, the disparity signal in this stimulus is weak, causing some observers to base their depth percepts on monocular occlusions.

This hypothesis is supported by the phenomenology of the case where the inducer has a disparity that is less crossed than that specified by the occlusion constraints; the illusory occluder appears to bend inwards at the center where the inducer is positioned, while its edges are seen at the depth specified by the viewing geometry. This indicates that depth from disparity of the inducer is interpolated across the blank area to meet the depth signal generated by the occlusions. Similar spreading of the disparity signal across a uniform area of up to several degrees was reported by Takeichi, Watanabe, and Shimojo (1992). In their case, as in Experiments 2 and 3, the source of the disparity signal was small and positioned at the center of the uniform region. However, in their case the disparity signal spread from the source to the luminance defined edges that had crossed disparity with respect to the disparity of the inducer.

There have been several cases in the literature in which depth percepts were initially assumed to be based on monocular information, but were later attributed at least in part to binocular disparity (Gillam, 1995; Gillam, Cook, & Blackburn, 2003; Liu et al., 1997; Pianta & Gillam, 2003). One such stimulus was used in Experiment 3. Our results, based on a range of stimulus configurations, suggest that the presence or absence of the biasing phenomenon might be useful as a general "litmus" test to determine whether depth magnitude in a given stimulus configuration is perceived primarily via monocular occlusions or binocular disparity. At least for horizontal occlusion/disparity configurations[3] the degree to which a disparity-defined inducer can bias the perceived depth of a monocular feature or an illusory occluder in the unconstrained direction can reveal the extent to which the visual system relies on monocular geometry to specify depth magnitude.

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[3] Interestingly, there is little or no bias of perceived depth in a stimulus in which an illusory surface was created via vertical occlusions like that used by Malik et al. (1999) (Anderson, personal communication). It is possible that the biasing effect we have observed is contingent on the involvement of horizontal occlusions, as was the case in all stimuli we have tested, but this hypothesis remains to be tested.