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Occlusion constraints and stereoscopic slant

Jukka Häkkinen, Göte Nyman
Department of Psychology, General Psychology Division, University of Helsinki, PO Box 13 (Meritullinkatu 1B), FIN-00014 Helsinki, Finland; e-mail: jukka.hakkinen@helsinki.fi
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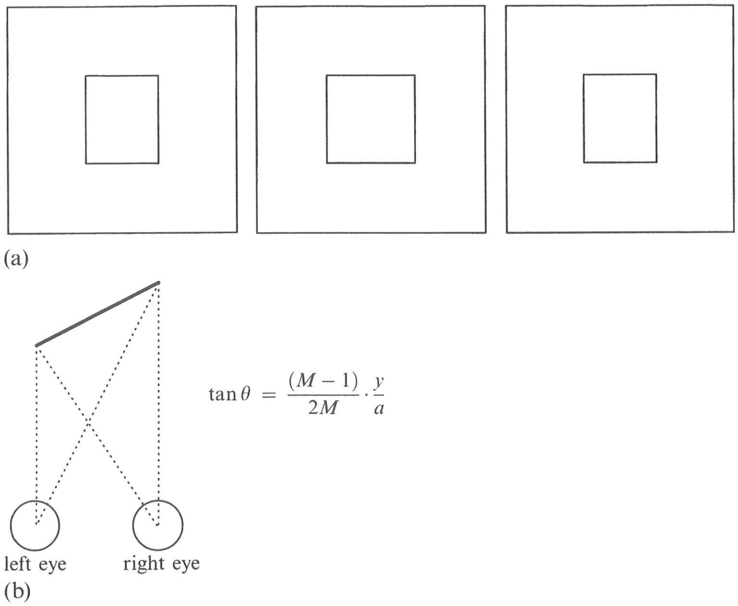
Abstract. In binocular vision horizontal magnification of one retinal image leads to a percept of three-dimensional slant around a vertical axis. It is demonstrated that the perception of slant is diminished when an occlusion interpretation is possible. A frontoparallel plane located in the immediate vicinity of a slanted surface in a location which allows a perception of occlusion reduces the magnitude of perceived slant significantly. When the same plane is placed on the other side, the slant perception is normal because there is no alternative occlusion interpretation. The results indicate that a common border between the occluder and a slanted surface is not a necessary condition for the reduction effect. If the edges are displaced and the edge of the slanted surface is placed in a location in which it could be occluded, the effect still appears.

1 Introduction

It appears natural to think that in binocular vision horizontal magnification of the image in one eye should lead to perception of a vertically slanted surface (figure 1) (Ogle 1962; Gillam et al 1988). However, it is known that perception of slant around the vertical axis is ambiguous. For example, the magnitude of slant is diminished when contradictory perspective cues are present (Gillam 1968). Similarly, it has been shown



$$\tan\theta = \frac{(M-1)}{2M}\cdot\frac{y}{a}$$

Figure 1. Stereoscopic slant around a vertical axis. (a) Three-dimensional slant around a vertical axis is perceived if the picture of one eye is horizontally magnified. In this and all subsequent stereograms a crossed fuser should fuse the left and centre images and an uncrossed fuser should fuse the centre and right pairs. All descriptions of stereograms refer to the right and centre half images. (b) The slant angle, θ, in degrees can be calculated by the equation above where M is the magnification in percent, y is the observation distance, and a is half the interocular distance.

that recognition of a slant around a vertical axis takes more time than recognition of a slant around a horizontal axis (Rogers and Graham 1983; Gillam et al 1988). In the present experiment we investigate a new kind of slant ambiguity, which is related to three-dimensional-occlusion processing in the visual system. The ambiguity is demonstrated in figure 2b, where small slanted surfaces are localised adjacent to a large frontoparallel rectangle. It is evident from figure 2a that the surfaces are similarly

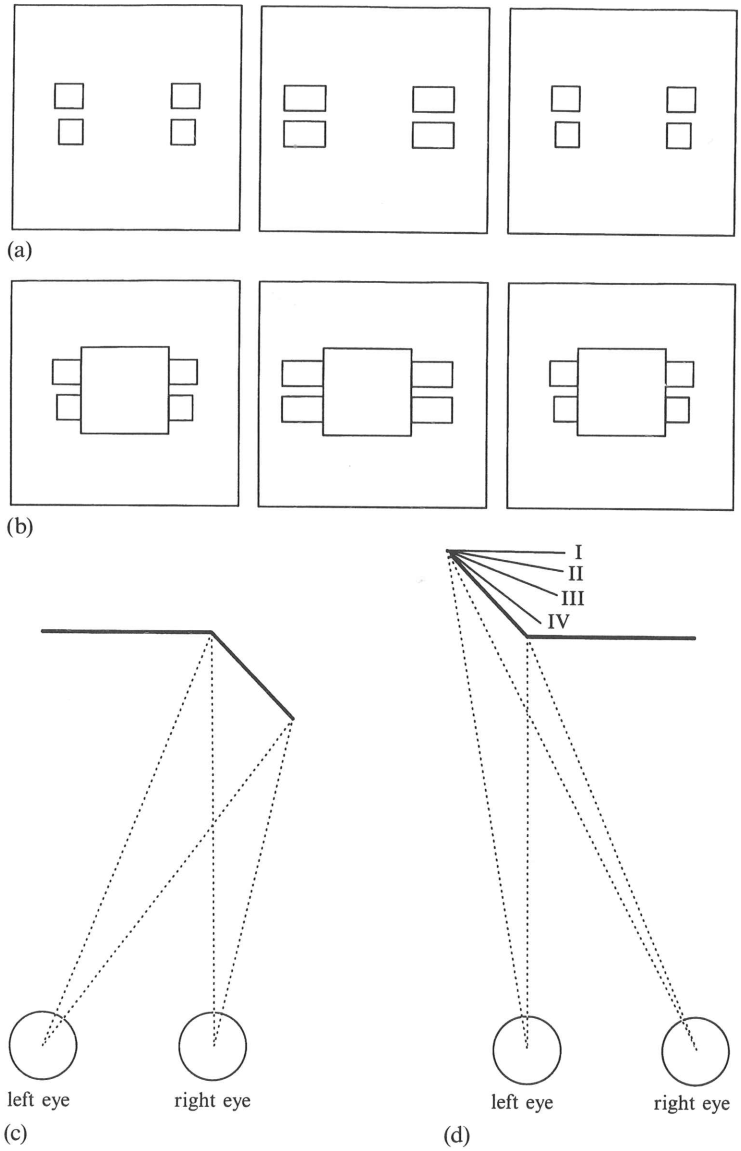


Figure 2. Stereoscopic slant around the vertical axis is diminished if an occlusion interpretation is possible. (a) In normal conditions the horizontally different sizes of the rectangles produce perception of slanted surfaces. (b) If an occluding rectangle is added to a scene, the perception is significantly different. The surfaces on the right are still slanted but on the left side they appear occluded and the perceived slant is reduced. (c) A schematic figure of the surfaces on the right side of the frontoparallel surface. (d) Alternative occlusion interpretations for the left side. The thick line represents the slant interpretation and the thin lines I, II, III, and IV are some of the alternative interpretations in which the perceived slant is reduced. The purpose of experiment 2 was to measure the perceived slant of a surface when an occluding surface is added to the scene.

slanted because the magnification relationships between the small rectangles are the same. Still, when the stereogram in figure 2b is fused, only the rectangles on the right side appear clearly slanted. On the left side of the frontoparallel surface the perceived slant is reduced.

The difference is visible because magnification of the image in one eye allows two interpretations. The classical interpretation (Ogle 1962) is grounded in the fact that, when a plane is slanted around the vertical axis, more of it is seen by one eye than the other (figure 1). But there is another three-dimensional structure where the same binocular view is presented: an occlusion configuration where one plane occludes another plane. In a world full of opaque objects it is quite common that near objects may occlude more-distant objects to some degree. If an object is partially occluded, one eye sees a horizontally larger object than the other. In the daily visual world there are rich texture cues which are used to differentiate between occlusion and slant interpretations, but if there is no texture, the interocular differences produced by an occlusion and a slant around vertical axis are similar.

Shimojo and Nakayama (1990; Nakayama and Shimojo 1990) have demonstrated that the eye of origin is a critical variable when three-dimensional occlusion is perceived. If an object is partially occluded by a near surface, the right eye sees a monocular segment on the right side of the occluder and the left eye one on the left side. By using artificial depth configurations it has been noticed that monocular areas which are visible to an opto-geometrically invalid eye (ie to an eye which could not see the occluded area in natural conditions) are either suppressed (Shimojo and Nakayama 1990) or, if there is no clearly defined background, became equidistant to the occluding plane (Nakayama and Shimojo 1990). We propose that the perception of slant around the vertical axis is also affected by similar constraints. For example, if a binocular object is placed in the immediate horizontal vicinity of a slanted surface, the possibility of an occlusion interpretation should diminish the perceived slant significantly. The hypothesis is represented schematically in figures 2c and 2d. When a slanted surface is adjacent to an opaque surface, the relation between the slanted surface and frontoparallel surface determines whether the slant is perceived. The slant on the right side (figure 2c) cannot be interpreted as an occlusion, so the perceived slant should not be diminished significantly. On the left side (figure 2d) there are many alternative interpretations which would produce exactly similar retinal images. Consequently, the alternative slant interpretations I, II, III, and IV of figure 2d are equally probable. The purpose of the present experiment was to determine how much these alternative interpretations affect the perceived slant.

We created three experiments to test the effects of an available occlusion interpretation to the perception of slant around a vertical axis. In the first experiment the experimental subjects viewed a single slanted plane. In the second experiment we tested the effect of alternative slant interpretations by placing the rectangle alternatively in a position which supported an occlusion interpretation and in a position which did not. In the third experiment we tested the significance of a common border between the occluding and occluded object.

2 General method

The stimuli were presented on a 20 inch Eizo Flexscan 9500 screen. The stereoscopic effect was created by dividing the screen into two areas, which were seen by left and right eye separately. The two views were separated by a sheet of cardboard perpendicular to the screen and a pair of prisms was attached to the other side of the cardboard in order to ease the fusion of the stimuli. The viewing distance was 100 cm and mean luminance of the display was 14 cd m^{-2}.

The subject saw first a fixation stimulus in the middle of the screen and after that an experimental stimulus (figure 3). The former was a binocular cross whose parts were a horizontal line 26.1 min arc × 1.7 min arc horizontal and a vertical line 1.3 min arc × 10.2 min arc. Two dichoptic nonius lines 1.3 min arc × 17.0 min arc were placed at the upper and lower sides of the cross. The presentation time of the fixation cross was unlimited and the minimum viewing time was 2 s. The end of the fixation was signalled to the subject by enhancing the brightness of the binocular cross slightly. When viewing the fixation stimulus the task of the subject was to fixate at the binocular cross and at the same time to monitor the lateral movement of the nonius lines. When the lines appeared aligned the subject pressed a button to view the target stimulus. This procedure was used to ensure that the vergence position would be the same before every target stimulus.

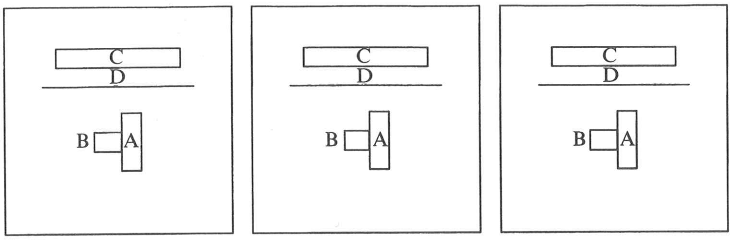


Figure 3. The experimental stimulus. The components of the stimulus are indicated by letters: A, occluding plane; B, slanted plane; C, comparison plane which the subject could slant in depth; and D, intermediate line.

The experimental stimulus consisted of four objects: an occluding surface (object A in figure 3; 68 min arc × 136 min arc), a slanted target figure (object B in figure 3), an adjustable comparison plane (object C in figure 3; 145 min arc × 13 min arc), and an intermediate line (object D in figure 3; 182 min arc × 2.6 min arc). Subjects estimated the surface slant by adjusting the slant of the comparison plane. It rotated around the vertical axis when appropriate buttons on a computer keyboard were pressed. The three-dimensional rotation of the comparison plane was accomplished by changing the size of the binocular half images according to the laws of three-dimensional geometry. The intermediate line was added because it is known that slant around the vertical axis is difficult to perceive without a reference. The viewing time was unlimited and the subjects were instructed to be as accurate as possible. The subjects practised the adjusting procedure until their slant adjustments were sufficiently accurate.

Four volunteers and the first author acted as subjects. The volunteers did not know the purpose of the experiment. Their stereoscopic acuity was tested before the experiment.

3 Experiment 1

The purpose of the first experiment was to measure subjects' ability to estimate stereoscopic slant around the vertical axis. It served also as a preliminary test: one subject was excluded from the main experiment because she had difficulties in perceiving three-dimensional slant.

3.1 *Method*

Each subject was shown a total of 140 rectangular stimuli (object B in figure 3). The occluding surface (object A in figure 3) was not present in this experiment. The size of the rectangle was 98 min arc × 49 min arc and it could appear in five different slants (0°, 12°, 23°, 34°, and 45°). Each angle was repeated twenty-eight times. The task of the subject was to estimate the slant of each stimulus by rotating the comparison plane.

3.2 *Results*
The perceived slants are plotted in figure 4 as a function of geometric slant. It is evident that the perception of slant was very accurate. Some subjects had initially a tendency to underestimate the slant when the angle was large but this tendency diminished during practice.

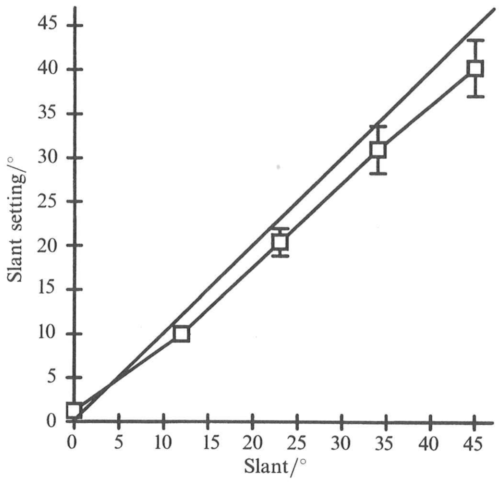


Figure 4. Slant settings as a function of geometric slant from experiment 1. The diagonal line is a prediction based on picture geometry. Averaged data for five subjects are plotted and the vertical lines represent ±1 standard error of the data points.

4 Experiment 2
4.1 *Method*
The slanted surfaces were presented as in the previous experiment. There was an additional frontoparallel surface (object A in figure 3; 68 min arc × 136 min arc), which could be on the left or right side of the slanted surface in such a way that the frontoparallel and occluded surface had a common border. There were three alternative conditions: (1) frontoparallel surface on the side that creates a possibility of an occlusion interpretation (figure 2d), (2) surface on the side that could not be interpreted as an occlusion interpretation (figure 2c), and (3) no occluding rectangle. Each slant was repeated twelve times which resulted in a total of 180 stimuli (five slants × three conditions × twelve times). The task of the subject was to estimate the slant of each stimulus by rotating the comparison plane.

4.2 *Results*
Perceived magnitude of slant decreased when an occlusion interpretation was possible (figure 5). The perception of slant did not disappear completely, but its magnitude was clearly smaller. An analysis of variance for repeated measures showed that the slopes of the curves in figure 5 were significantly different ($F_{2,8} = 54.706$, $p < 0.0001$). A Newman–Keuls a posteriori analysis revealed that the occluding condition differed from other two conditions at the 0.01 level.

5 Experiment 3
It is possible that the reduced slant is related to the theory presented by Nakayama et al (1989). According to Nakayama et al a border can be perceived either as intrinsic or extrinsic relative to an object. In the former case the border is seen normally as a part of the object but in the latter case the border is attributed to an occluding object and it is not taken into account in the pattern-recognition processes of the

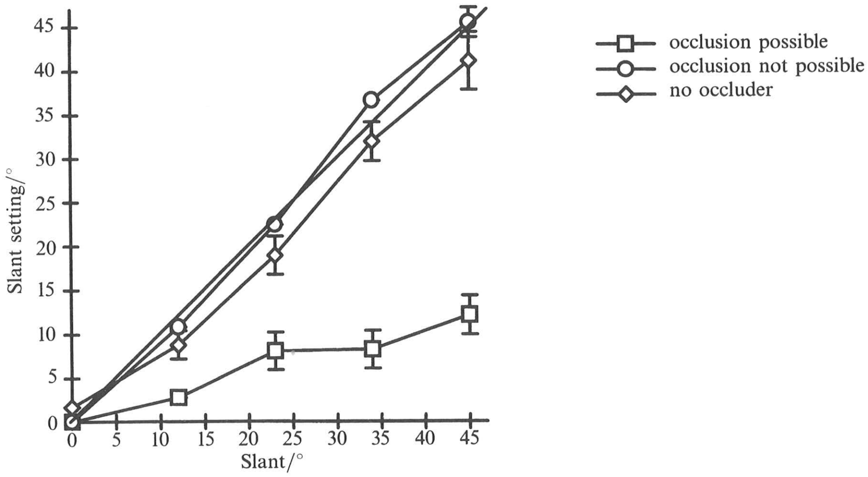


Figure 5. Results of experiment 2. Slant settings from three occlusion configurations are plotted as a function of geometrical slant. The diagonal line is a prediction based on figure geometry. Each graph is a plot of averaged data for five subjects and the vertical lines represent ±1 standard error of the data points.

occluded object. Nakayama et al have demonstrated that occlusion signalled by binocular disparity affects the recognition and groupings of occluded objects when they have partially common borders with the occluder. Grossberg (1994) has suggested that the phenomenon is based on a process where the disparity of the occluded object is inhibited in the common border area. The same process might affect the common border between the occluding and slanted surface in our experiment. If a common border is always attributed to a nearer surface, the slant is diminished in experiment 2 because the common border no longer belongs to the slanted surface.

Also, more-complex depth processes related to depth discontinuity have been suggested. Nakayama and Shimojo (1990) have demonstrated that typical occlusion relations of the visual world are taken into account when depth discontinuities are processed in the visual system. In the immediate horizontal vicinity of every binocular surface there is an area where monocular objects visible to only one eye can lie (figure 6a). The size of this zone is defined by the visibility lines between which the dots in the real world must be. According to Nakayama and Shimojo (1990) a monocular object localises to the leading edge of the depth constraint zone if an occlusion interpretation is possible. If the depth constraint zone is used in the processing of stereoscopic slant, it might be possible that an edge which is inside the depth constraint zone also produces a perception of reduced slant. In figure 6b the plane adjacent to the occluding plane (O) can be interpreted for example as a slanted plane (I) or as an occluded plane (II) which does not continue under the occluding plane O. Because the right eye sees that the slanted plane does not continue under the occluding plane O, the probability of slant perception might increase. It is also possible that the common border between the occluder and slanted surface is necessary in order for the slant perception to be disrupted. In figure 6c the stereoscopic configuration is presented as a stereogram. The figure is ambiguous but most observers perceived it as slightly slanted. Some observers initially reported a perception of occlusion but the percept transformed to a moderate slant after a short while.

To measure the effect of common borders we performed experiment 3, where the distance between the edges of the slanted and the occluding surface was varied in one eye and the innermost edge of the slanted plane was always within the depth constraint zone. The experimental configuration is presented schematically in figure 7

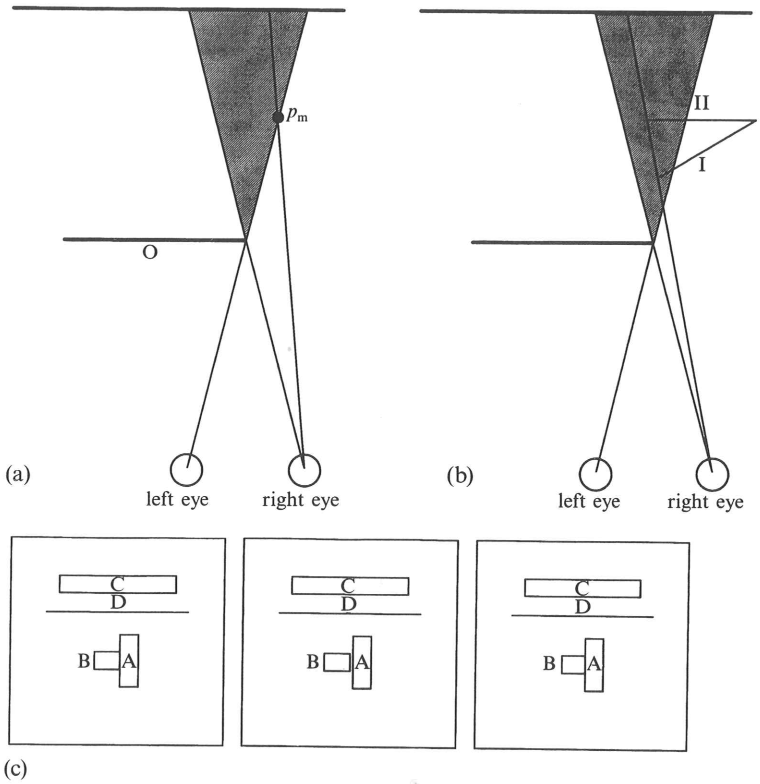


Figure 6. The depth constraint zone. (a) The monocular dot p_m which is visible only to the right eye can theoretically be anywhere on the visual axis. However, a binocularly visible plane (O) occludes the background to different extents in the two eyes. This interocularly unpaired area, the depth constraint zone (shaded region), represents an area between the visibility lines of the eyes in which monocular objects that are visible only to the right eye could lie ecologically validly. Nakayama and Shimojo (1990) have demonstrated that a monocular dot localises to the leading edge of the depth constraint zone. (b) A slanted plane which is partially displaced from the occluder (O) makes two interpretations possible. The plane can be perceived for example as slanted (I) or as an occluded frontoparallel plane (II) which does not continue under the occluder. (c) A stereogram that depicts the stimulus in experiment 3. The components of the stimulus are indicated by letters: A, occluding plane; B, slanted plane; C, comparison plane which the subject could slant in depth; and D, intermediate line.

where I, II, and III represent the variable distance between the frontoparallel and slanted plane.

5.1 *Method*

The experimental configuration was similar to that in previous experiments. A frontoparallel surface appeared at a position which always allowed an occlusion interpretation and its distance from the slanted surface was varied (figure 7; I, II, and III). The displacement could be 0, 3.6, or 5.2 min arc and the resulting percept was similar to that in figure 6c. The occluding edge shifted only in the eye that saw the wider rectangle in order that the occlusion interpretation was possible (centre half image in figure 6c). The smaller rectangle was always attached to the occluding border (right half image in figure 6c). The visual direction of a binocular object is a mean of the position of the half images, so the binocular lateral position of the binocular objects changed when the disparity was changed. Because the change in visual direction was half the displacement, the innermost border of the slanted plane was within the depth constraint zone. In the condition with 3.6 min arc the difference between the edges

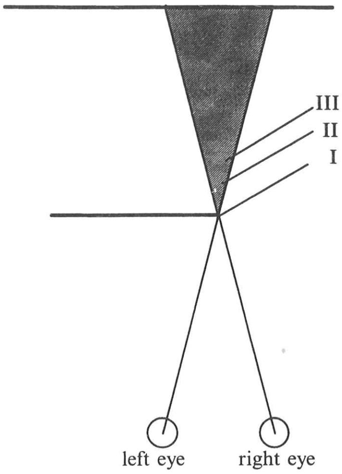


Figure 7. In experiment 3 we investigated whether a slant is diminished when the occluding and occluded object do not have a common border in one eye but the edge of the slanted surface is still within the depth constraint zone. The tilted lines (I, II, III) represent the three conditions in the experiment.

was barely visible and in the condition with 5.2 min arc the difference was clearly visible.

5.2 *Results*

The common border between occluding and occluded surface is not a necessary condition for the diminished slant. Figure 8 shows that the disruption of slant perception occurred in all experimental conditions. An analysis of variance for repeated measures showed that the slopes were significantly different ($F_{2,6} = 12.799$; $p < 0.0068$). The results indicate two things: first, the perceived depth of binocular corresponding points is affected by occlusion rules. In other words, the relationship between depth and binocular disparity is different inside the depth constraint zone. Second, the perception of slant becomes more veridical as the lateral distance between the edges of the occluding and slanted surface is increased.

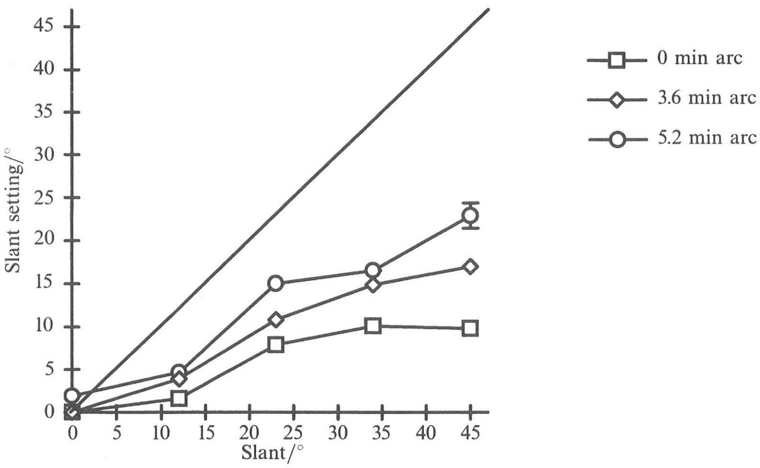


Figure 8. Results of experiment 3. Slant settings from three lateral distances are plotted as a function of geometrical slant. The diagonal line is a prediction based on figure geometry. Each graph is a plot of averaged data for five subjects and the vertical lines represent ±1 standard error of the data points.

6 Discussion

6.1 *Occlusion and three-dimensional slant*

The results demonstrate that occlusion constraints affect the perception of slant around a vertical axis. When a surface that is horizontally magnified in one eye is adjacent to a binocular plane, the possibility for an occlusion interpretation diminishes the perceived slant significantly. The process which is the reason for the diminished slant might be related to the common border between the occluding surface and the slanted plane. Nakayama et al (1989) (see also Grossberg 1994) have suggested that when two surfaces have a common border, the near surface inhibits the far surface, which leads to a depth interpretation where the border is attached to the near surface. This has been shown to affect different recognition and grouping processes for three-dimensional patterns (Nakayama et al 1989). We think that the edge of the slanted surface that is common with the occluding surface is similarly inhibited and thus it is not perceived as a part of the slanted surface. Because there are no additional texture cues, the occlusion percept becomes dominant.

In experiment 3 we demonstrated that a common binocular border between the occluding and occluded surface is not a necessary condition for the diminished slant. It seems that when an edge is inside the depth constraint zone, normal matching rules between binocular elements are no longer valid. Curiously, the depth configuration is more ambiguous in this case: in experiment 3 we show that when the distance between the occluding and occluded surface is increased, the slanted surface is seen more and more slanted. However, the slant still deviates strongly from the slant predicted by its binocular geometry.

Previous binocular-matching rules have been based on different sets of assumptions. It has been assumed, for example, that the edges of objects should be matched first, or that the visual world changes continuously (Marr 1982). We suggest that these assumptions should take the discontinuity structure of the visual world into account. Our results imply that the processing of stereoscopic slant is closely related to the processes that integrate binocular and monocular areas of the visual field.

6.2 *Temporal properties of binocular-matching processes*

We also observed an interesting temporal phenomenon related to our stereograms. Initially all the slanted surfaces appeared as occluded but after a while some of them started to appear as slightly slanted. This might be related to Gillam et al's (1988) results demonstrating a very long temporal latency for seeing stereoscopic slant. They also show that a stereogram which consists of a frontoparallel surface linked to a slanted surface ('vertical hinge') is significantly slower to process than other slanted stereograms. The vertical-hinge stereogram is similar to the stereogram in figure 3 so the longer latency could be caused by the possibility of occlusion interpretation, which complicates the processing of three-dimensional structure.

The long postfusional latency for slant is not the only important finding concerning temporal features of stereopsis. The findings of Mitchison and McKee (1985, 1987), who investigated interpolation effects in simple stereograms of periodic dots, are also significant. They noticed that initially the visual system interpolates between unambiguous edges but with longer presentation time a three-dimensional percept is determined by discrete matches. In our experiment 2 one edge of the slanted surface and two edges of the occluding surface are unambiguous. An interpolation between the unambiguous edges would be clearly slanted. If the visual system initially interpolates between unambiguous edges, the initial percept should be a slant. In the current experiment this did not happen; many subjects reported that they initially saw a discontinuity and perceived depth continuity increased gradually when discrete pairings are reached. This suggests that the concept of simple interpolation may not be sufficient when the differences between early and later binocular matching process are considered. At the current stage the temporal effects noticed in our experiment are preliminary and they have to be accurately quantified before strict conclusions are made.

6.3 *Conclusions*

All these phenomena suggest that the matching of binocularly visible edges is not a sufficient process for determining the three-dimensional structure of the visual world. There exist ambiguous situations which cannot be solved without additional depth cues. For example, texture gradients are probably used in everyday situations to differentiate between occlusion and slant. The three-dimensional processing in the visual system is a complex modular process which can not be reduced to a simple principle like stereopsis. Because of the complexity of the world, a large set of depth cues are used and the depth structure can be perceived unambiguously only after some integrative process which considers the possible depth structures indicated by each module. This leads to a situation where local cues become interpreted according to global context.

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References

Gillam B, 1968 "Perception of slant when perspective and stereopsis conflict: experiments with aniseikonic lenses" *Journal of Experimental Psychology* **72** 299 – 305

Gillam B, Chambers D, Russo T, 1988 "Postfusional latency in stereoscopic slant perception and the primitives of stereopsis" *Journal of Experimental Psychology: Human Perception and Performance* **14** 163 – 175

Grossberg S, 1994 "3-D vision and the figure – ground separation by visual cortex" *Perception & Psychophysics* **55** 48 – 120

Marr D, 1982 *Vision: A Computational Investigation into the Human Representation and Processing of Visual Information* (San Francisco, CA: W H Freeman)

Mitchison G J, McKee S P, 1985 "Interpolation in stereoscopic matching" *Nature (London)* **315** 402 – 404

Mitchison G J, McKee S P, 1987 "The resolution of ambiguous stereoscopic matches by interpolation" *Vision Research* **27** 285 – 294

Nakayama K, Shimojo S, 1990 "Da Vinci stereopsis: depth and subjective occluding contours from unpaired image points" *Vision Research* **30** 1811 – 1825

Nakayama K, Shimojo S, Silverman G H, 1989 "Stereoscopic depth: its relation to image segmentation, grouping, and the recognition of occluded objects" *Perception* **18** 55 – 68

Ogle K, 1962 "Special topics in binocular spatial localization", in *The Eye* Ed. H Davson (London: Academic Press) pp 350 – 407

Rogers B, Graham M, 1983 "Anisotropies in the perception of three-dimensional-surfaces" *Science* **221** 1409 – 1411

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