
Perceiving binocular depth with reference to a common surface

Zijiang J He

Department of Psychological and Brain Sciences, University of Louisville, Louisville, KY 40292, USA; e-mail: zjhe@louisville.edu

Teng Leng Ooi

Department of Biomedical Sciences, Southern College of Optometry, 1245 Madison Avenue, Memphis, TN 38104, USA; e-mail: tlooi@sco.edu

Received 14 June 1999, in revised form 15 May 2000

Abstract. A common surface is a spatial regularity of our terrestrial environment. For instance, we walk on the common ground surface, lay a variety of objects on the table top, and display our favorite paintings on the wall. It has been proposed that the visual system utilizes this regularity as a reference frame for coding objects' distances. Presumably, by treating the common surface as such—ie an anticipated constant—the visual system can reduce its coding redundancy, and divert its resources to representing other information. For intermediate-distance space perception, it has been found that absolute distance judgment is most accurate when a common ground surface is available. Here we explored if the common surface also serves as the reference frame for the processing of binocular-disparity information, which is a predominant cue for near-distance space perception. We capitalized on an established observation where the perceived slant of a surface with linear binocular-disparity gradient is underestimated. Clearly, if the visual system utilizes this incorrectly represented slant surface as a reference frame for coding the objects' locations, the perceived depth separation between the objects will be adversely affected. Our results confirm this, by showing that the depth judgment of objects (two laterally separated vertical lines) on, or in the vicinity of, the surface is underestimated. Furthermore, we show that the impact of the common surface on perceived depth separation most likely occurs at the surface-representation level where the visual surface has been explicitly delineated, rather than at the earlier disparity-processing level.

1 Introduction

In 1950 J J Gibson introduced the ground theory of space perception, which places a substantial emphasis on the significance of the ground surface in space perception. Essentially, the ground theory adopts the view that the large common ground surface acts as a perceptual reference frame for space perception and locomotion. The impetus for Gibson's theory was no doubt based in part on the observation that objects which we frequently interact with in the real world are often seen on a common ground surface. In this way, it would be beneficial for the visual system to embrace the prevalent ground surface as a reference frame for coding objects' locations, in order to enhance its coding efficiency. Since its conception, Gibson's ground theory of space perception has been developed considerably, both in its theoretical and empirical aspects (eg Gibson 1950, 1979; Sedgwick 1983, 1989; Sinai et al 1998).

Recently, a support for the ground theory was reported by Sinai et al (1998). They examined the role of the common ground surface in absolute distance judgment for performances in both perceptual (distance matching) and visually directed (blindfolded walking) action. They found that when an object was seen on a continuous, homogeneous texture ground surface, the observer was able to make accurate distance judgment. However, when similar surface information was unavailable, eg when the object was seen across a gap in the ground, or across distinct texture regions, distance judgment was impaired. Thus their study provides support for the important role of the ground

surface in space perception and visually directed action, for the intermediate distance range (3–9 m) on which their observers were tested.

Our goal in the current paper is to examine if the reliance on surfaces also applies to space perception at the nearer distance range (< 2–3 m), where other types of common surfaces besides the ground surface are more prominent. It should be noted at the outset that the visual system possibly utilizes multiple and different mechanisms for near- and intermediate-distance space perception. This is because, while we may stand or walk on the ground surface, most of our activities at near distances also involve interacting with objects that are above the ground surface, say on the table top or on the wall within our arm's reach. Furthermore, while the primary cues for intermediate-distance perception are monocular depth cues such as texture gradient, angle of declination, etc with respect to the ground surface, the primary cue that is both reliable and of high resolution for near-distance perception is binocular disparity (Cutting and Vishton 1995; Howard and Rogers 1995; Sedgwick 1986). Thus, such diversity in the utilization of available cues for intermediate- versus near-distance space perception suggests that the visual system might use different coding mechanisms at the intermediate- and near-distance ranges. Nevertheless, it is reasonable to ask whether these presumably different mechanisms observe the same general ecological constraint. Specifically, given the significance of the common surface at both intermediate and near distances, it is fitting to test the hypothesis that the visual system also uses the visual surface as a reference frame for coding binocular depth information which is prevalent at the near distance (ie the surface hypothesis).

In our experiments below, we reasoned that if the visual surface acts as a reference frame for coding stereoscopic location, the perceived relative depth between two objects will depend on the configuration of the nearby common surface which acts as the reference frame. We will show that, when the configuration (slant) of the common surface is underestimated (ie its depth is perceptually compressed), the observer will also underestimate the relative depth between objects that are located on, or near, the common surface. Conversely, when the configuration of the surface is more accurately estimated, relative-depth perception becomes more accurate. Part of this work has been presented in an abstract form elsewhere (He and Ooi 1997).

2 Experiment 1. Relative depth compression on a slanted surface

Our experiments capitalized on the well-known phenomenon where an observer often underestimates the slant of a stereoscopic figure that is rotated around its vertical axis (Gillam and Ryan 1992; McKee 1983; Mitchison and McKee 1990; Mitchison and Westheimer 1984; Youngs 1976). For example, McKee (1983) showed that the threshold for detecting depth separation between two vertical lines increases dramatically when the two vertical lines are connected by two horizontal lines, forming a rectangle. Figure 1 reproduces the stereograms used by McKee (1983). By free-fusing the left and middle half-images divergently, or the middle and right ones convergently in stereogram (a), one can see the left vertical line in front of the right vertical line. However, in stereogram (b) one sees much less depth separation between the two vertical lines, and can barely see the slant of the resultant rectangular surface. In other words, the depth of the slanted stereoscopic surface (rectangle) is underestimated or compressed.

In the present experiment, we used a slanted illusory rectangle as the common surface in the test display (figure 2a). By free-fusing the left and middle half-images divergently, or the middle and right half-images convergently, one will perceive a slanted illusory rectangle that is raised above its four inducing pacmen. On the illusory rectangular surface lie two vertical lines that are stereoscopically separated, with the left line in front of the right line. During the experiment, the observer is shown a test

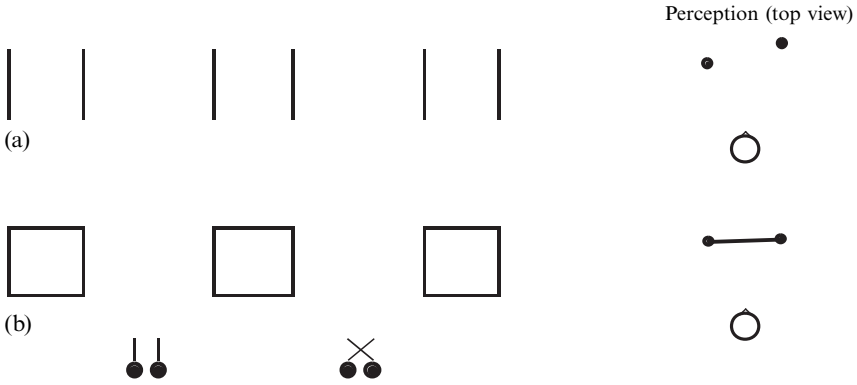


Figure 1. Stereoscopic displays similar to McKee (1983). For these and subsequent stereograms, uncrossed fusers should free-fuse the left and middle half-images, and crossed fusers the middle and right half-images. To the right of each stereogram, a top-view perception of the stimulus is shown. More depth separation between the two vertical lines is perceived in (a) than in (b), despite the fact that their horizontal disparity is the same.

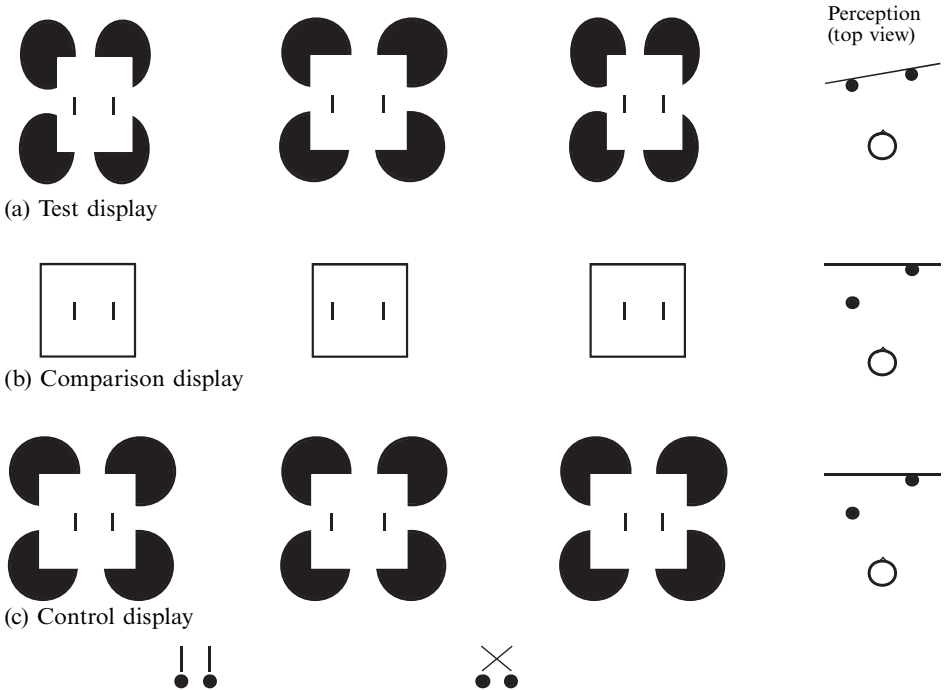


Figure 2. Stimulus for experiment 1. (a) Test display: When fused, the illusory rectangular surface and the inducing pacmen are perceived as slanted with their left sides closer to the reader. A pair of vertical test lines with a relative horizontal disparity is located on the surface of the illusory rectangle. (b) Comparison display: The same pair of vertical lines as in (a) is now seen against a frontoparallel rectangular surface. (c) Control display: Essentially the same as the comparison display, but with the rectangular background surface being subjectively formed. Notice that the perceived relative depth separation between the two vertical lines is smaller in (a) than in (b) and (c).

display similar to this, and is asked to subsequently compare his perception of the depth separation between the two vertical lines in the test display with another similar pair in a comparison display, which is shown in figure 2b. Now, if the reader free fuses the stereogram in figure 2b, it will be seen that the comparison display consists of a pair of stereoscopic vertical lines that are placed against a frontoparallel square

background surface. It can be readily noted that the perceived depth separation between the vertical lines is greater in the comparison display than in the test display, even though their binocular disparity is the same. Similarly, a greater depth separation is observed when the frontoparallel square of the comparison display is subjective (Kanizsa square; figure 2c). This qualitative observation is consistent with the prediction of the surface hypothesis, that the background surface acts as a reference frame for coding the depth separation between the two vertical lines. As such, the perceived relative depth separation between the two vertical lines on the slanted surface (figure 2a) is reduced since the slant of the illusory rectangular reference surface is underestimated.

2.1 General methods

2.1.1 Apparatus and stimuli. The stereoscopic displays were presented on a computer monitor driven by a Commodore computer (model A3000) for experiments 1–3, and a Power Macintosh computer (model 7500/100) for experiment 4. They were viewed through a pair of haploscopic prisms to allow for fusion. The viewing distance was 57 cm in experiments 1–3, and 100 cm in experiment 4. The stereograms illustrated in figure 2 for experiment 1 typify the general design of the stereoscopic stimuli used in the entire study. In the test display (figure 2a), the binocular disparity between the two vertical lines was fixed at 12.1 min.⁽¹⁾ Meanwhile, the binocular disparity between the two vertical lines in the comparison display (figure 2b) assumed one of seven binocular-disparity values (1.1, 3.3, 5.5, 7.7, 9.9, 12.1, and 15.3 min), as it randomly varied from trial to trial.

The dimension of the test display. The diameter of each circular pacman viewed by the right eye was 100.1 min, while the horizontal and vertical diameters of each elliptical pacman viewed by the left eye were 84.7 min and 100.1 min, respectively. This resulted in an illusory surface of 128.7 min \times 128.7 min in the right eye, and 110.0 min \times 128.7 min in the left eye, so that, when fused, a single illusory rectangle was perceived. Notably, this illusory rectangle was slanted and raised (cross disparity) by about 5.5 min above the inducing pacmen. On the surface of the illusory rectangle lay two vertical lines (1.1 min \times 83.6 min in size) with a horizontal separation of 66 min in the left eye, and 78.1 min in the right eye. Thus, with stereoscopic viewing, these two lines were separated by a horizontal binocular disparity of 12.1 min.

The dimension of the comparison display. The square stimulus was 128.7 min \times 128.7 min in each eye. Upon each square stimulus lay a pair of vertical lines. These vertical lines were similar to the ones in the test display, with the exception that the horizontal separation between the two lines in the left eye could be varied.

2.1.2 Observers. One author (S3) and five experienced psychophysical observers who were naïve to the purposes of the study participated in the experiments. They all had normal or corrected-to-normal visual acuity and at least 40 s of arc of stereoacuity. Informed consent was obtained from the naïve observers before commencing the experiments. The observers were given about 100 practice trials to familiarize them with the depth-judgment task before starting the proper data collection.

2.1.3 Procedure. In preparation for a trial, the observer fixated on a cross at the center of the field of view. He then pressed a computer mouse button to initiate the trial, which consisted of four sequentially presented frames. First, the test display (figure 2a) appeared on the screen for 1 s. Upon its removal, a mask made of random dots was presented for 0.2 s. This was followed by the presentation of the comparison display (figure 2b) for 1 s, and then the random-dot mask again for 0.2 s, terminating the trial. During the trial, the observer was asked to remember the relative depth separation between the two vertical lines in the test display (fixed binocular disparity) and then to compare it with

⁽¹⁾Here and subsequently 'min' stands for 'min of arc'.

that between the two lines in the comparison display (whose predetermined binocular disparity varied randomly from one trial to the next), to determine which pair had the larger perceived depth separation. The observer responded by pressing '1' on the computer keyboard if the perceived depth separation was larger in the test display, and '2' if the perceived depth separation was smaller in the test display. The entire experimental session consisted of 105 trials, with 15 trials for each of the seven binocular disparity values in the comparison display.

2.2 Results

The results for the three observers are shown individually in figure 3. In each graph, the x values represent the binocular disparity between the two vertical lines in the comparison display (figure 2b), and the y values show the percentage of seeing more depth separation between the two lines in the test display. As the binocular disparity between the two vertical lines in the test display was fixed at 12.1 min (figure 2a), the psychometric functions in figure 3 are expected to decrease with increasing binocular disparity of the lines in the comparison display. Further, for each graph, the binocular disparity at which the psychometric function intersects the 50% horizontal line can be taken as the equivalent perceived depth separation between the lines in the test display for the observer. Thus, if the common background surface has no effect on stereo depth perception, the equivalent perceived depth should occur at a binocular-disparity value of 12.1 min. Clearly, this is not the case, for all three observers demonstrated having equivalent perceived depth of less than 12.1 min, indicating a depth reduction in the test display (figure 2a).

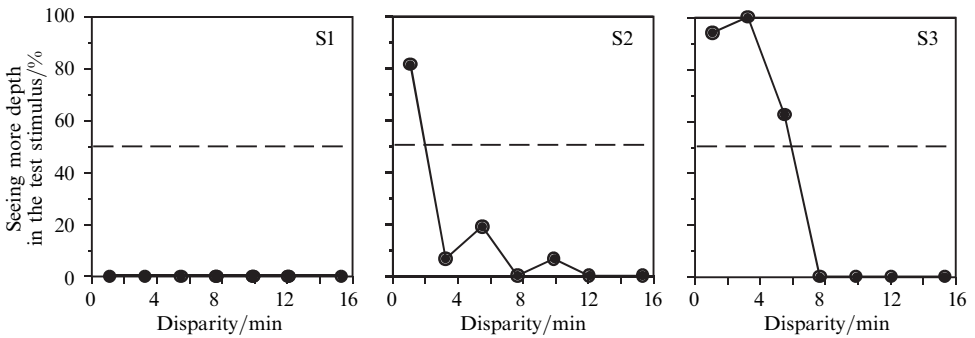


Figure 3. Results of experiment 1 from three observers. The percentage of seeing more depth between the two lines in the test display (figure 2a, disparity = 12.1 min) than that in the comparison display (figure 2b, variable disparity) is plotted against the disparity values assumed by the two vertical lines in the comparison display. The disparity value at which the psychometric function intersects the 50% horizontal line defines the equivalent perceived depth between the two lines in the test display. Clearly, for all observers, the equivalent depth is smaller than 12.1 min indicating that less depth is perceived in the test display.

Of particular interest are the data from observer S1 who repeatedly perceived the vertical lines in the test display to have reduced depth separation compared to their counterparts in the comparison display. This observer also reported not seeing the slant of the illusory rectangular surface, when questioned about the orientation (ie slanted or frontoparallel) of the surface after the experiment. Undoubtedly, this observer's responses further reinforce the prediction of the surface hypothesis that the depth separation between objects on a surface is underestimated when the slant of the surface itself is underestimated.

To further support the contention that the surface slant was underestimated, we conducted a control experiment below, in which the same three observers were asked to quantitatively demonstrate their perception of surface slant.

2.3 Control experiment

2.3.1 Method. The same three observers were presented with the slanted Kanizsa surface used in the main experiment, which deviated 56° from the frontoparallel plane. During the experiment, the observer viewed the Kanizsa surface through a pair of haploscopic prisms from a viewing distance of 57 cm, with the instruction to estimate and remember the slant of the Kanizsa surface. Thereafter the observer turned his head and body leftward 90° away from the computer setup to face a real physical surface (a $20\text{ cm} \times 26\text{ cm}$ in size piece of paper with a diagonal grid pattern). This real surface was pasted on a piece of steel bar which could be rotated around the vertical axis by the experimenter. The observer then instructed the experimenter to rotate the real surface to mimic the slant of the remembered Kanizsa surface, and subsequently to rotate the surface again until it appeared to be frontoparallel to the observer. The experimenter noted the angular subtense between these two positions (orientations), which was taken as the perceived slant of the Kanizsa surface in the main experiment. This procedure was repeated twice for each observer.

2.3.2 Results. The perceived slant measured in the three observers, S1, S2, and S3, was 9.5° , 17.25° , and 18.25° , respectively. Clearly, they all underestimated the stereoscopic slant of the Kanizsa surface from the main experiment. It can also be noticed that the degree of slant underestimation differs among the three observers. Recall that in the main experiment (figure 3), S1 did not report seeing any depth separation between the two test lines. Coincidentally, he also showed a much larger slant underestimation compared to S2 and S3.

Indeed, individual differences in perceiving the stereoscopic slant of a square have been reported by others in the past. For example, Mitchison and Westheimer (1984) noticed that one of their observers was unable to detect the depth of a slanted square frame, while the remaining three observers could perceive the depth reasonably well (see their figure 2).

2.4 Discussion

Our finding is consistent with the earlier report by Mitchison and Westheimer (1984) who used a slanted grid of dots as the background. They, too, found that the relative depth threshold between two test lines increased on viewing them on the slanted grid. Additionally, by employing a subjective surface for the background, we further the observation by showing that the background surface as a whole, rather than the local features on the background, affects the perceived depth between the two test lines. As previous studies (eg Nakayama et al 1995) have suggested that the subjective surface is formed at the surface-representation level, which is a level beyond the local filtering level, our finding implies that the observed depth effect occurs at the surface-representation level.

3 Experiment 2. Relative depth compression in the vicinity of a slanted surface

Experiment 1 shows that the perceived depth separation between two lines is reduced when they are located on a slanted surface. This led us to wonder if the depth-reduction effect can also be observed for line stimuli that are located near the surface, and not directly supported by the surface. To investigate this, in the current experiment we measured the perceived depth separation between two lines when they were raised above the illusory rectangular surface.

Figures 4b and 4c show examples of the stimuli employed in the experiment. Figure 4a is similar to the test display shown in experiment 1 (figure 2a), and has been included here for comparison. By free-fusing the left and middle half-images divergently, or the middle and right ones convergently, one will see a slanted illusory rectangle each in figure 4a and 4b, with a pair of vertical lines on each surface.

Of significance is the location of the vertical lines with respect to the slanted surface. In figure 4a, the lines lie directly on the slanted illusory surface. But in figure 4b the lines are raised above the slanted illusory surface. Noticeably, even though the binocular disparity between the pair of lines is the same in figures 4a and 4b, the perceived depth separation between these lines is larger in the latter figure than in the former one. But when compared to the comparison display (figure 4c), where a similar pair of vertical lines are seen against a frontoparallel square surface, it is quite obvious that the perceived depth separation between the lines raised above the slanted surface (figure 4b) is still smaller. Overall, these observations indicate that the perceived depth perception between the two lines can also be affected by a nearby slanted surface, even if the reduction in depth is not as great as when the lines are directly placed on the slanted surface.

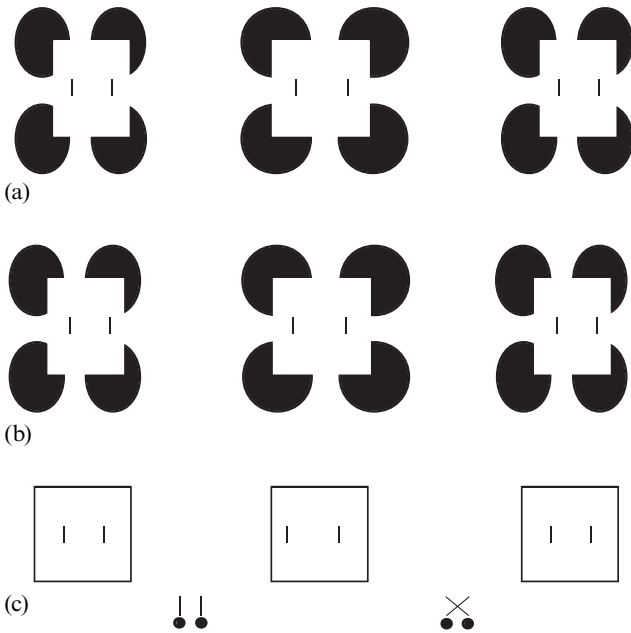


Figure 4. A sample of the stimuli used in experiment 2. Stereograms (a) and (c) are the same as the stereograms in figures 2a and 2b, respectively. Stereogram (b) is modified from (a), with the two vertical lines on the illusory rectangle raised from its surface, ie a lines–surface separation is added to the display. With fusion, notice that the perceived relative depth between the two vertical lines in (b) is smaller than in (c), but larger than that in (a).

3.1 Methods

3.1.1 Stimuli. Four test displays with pairs of vertical lines raised to different extents above the slanted illusory surface (ie lines–surface separation) were used. All other aspects of the test displays, including the binocular disparity of the lines (12.1 min), were similar to the ones used in experiment 1. The lines–surface separation values in the four test displays were 2.2, 4.4, 6.6, and 8.8 min. The comparison display employed in the present experiment was the same as the one used in experiment 1.

3.1.2 Procedures. By following the same procedure as in experiment 1, a psychometric function like that in figure 3 was obtained for each of the four lines–surface separation conditions. This enabled us to derive the equivalent depth of the lines on the slanted surface (ie the disparity at which the psychometric function intersects the 50% horizontal line, as in figure 3) for each lines–surface condition.

3.2 Results and discussion

The relationship between the equivalent depth and the lines–surface separation is plotted for each observer in figure 5. Also included in the curve of observers S2 and S3 are the equivalent depth values when the lines–surface separation was zero, ie the data from experiment 1. Notably, even though the equivalent depth increases with the lines–surface separation for all observers, it never quite reaches 12.1 min which was the physical binocular disparity between the two lines in the test displays. This indicates that depth reduction can also occur for line stimuli which are raised above the slant surface, ie coincidence with the reference surface is not a strict requirement. Rather, it includes objects that are located in the vicinity of (above) the reference surface as well.

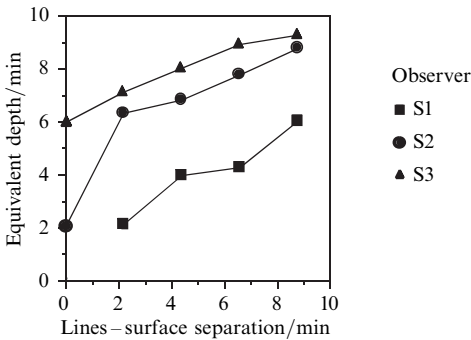


Figure 5. Results of experiment 2 from three observers. The equivalent perceived depth between the two vertical lines never quite reaches 12.1 min (the actual disparity of the lines) with increasing lines–surface separation, suggesting that objects near the surface are not immune to its influence. However, the influence of the surface decreases with increasing lines–surface separation. (Note: Observer S1 did not have an equivalent depth value when the lines–surface separation was zero, as he consistently perceived less depth in the test display.)

At the same time, it is interesting to note that, despite individual differences among our three observers, their equivalent depth percepts increase with increasing lines–surface separation. This finding is consistent with a recent report by Glennerster and McKee (1999) who used a slanted grid of dots as the background and measured depth threshold for detecting the separation of two vertical lines against the background. Their results showed that the slanted grid background caused an increase in depth threshold between the two lines when the lines were located close to the background. However, the impact of the slanted background decreased when the lines were located farther from the background. Furthermore, they revealed that their observations were largely independent of eye fixations; ie the impact of the slanted background occurred whether the eyes fixated on the background or the test lines.

While it is not known why larger depth compression occurs on or near the slanted surface, we can offer a speculation which is based on the cost–benefit of coding with respect to the surface. We know now that the visual system codes relative distances with respect to the common background surface for objects that rest on it, and objects that are located in its vicinity. Presumably, by adopting the common surface as a reference frame, the visual system can code the objects on it with less redundancy and more efficiency. This is because by referring the relative objects' locations to the common surface, the three-dimensional (3-D) coding of the objects can essentially be reduced to a two-dimensional (2-D) coding (see figure 13 later; this speculation will be further elaborated in section 6). As such, this would allow the visual system to commit its resources to coding other aspects of the objects' properties (Attneave 1954; Barlow 1961).

However, when objects are located quite far away from the common surface (eg increased lines–surface separation), the cost of using the common surface to code the objects' locations increases. This cost arises from having to extrapolate the images of the objects to the common surface. It is reasonable to assume that the extrapolation process will be plagued with increasing uncertainty or noise when the objects are located farther away from the surface, making it a very costly process. Thus, when this occurs, the visual system might just abandon the explicit surface-coding strategy, and resort to an alternative depth-coding strategy used for coding objects in the dark, or impoverished environment. With this alternative strategy, stereoscopic depth is possibly obtained according to the binocular disparity of the objects with respect to the horopter, or an implicit representation of the frontoparallel plane. No doubt, further experiments are needed to explore this speculation.

4 Experiment 3. Disparity-gradient hypothesis versus surface hypothesis

Our results so far have demonstrated that the perceived depth separation between two vertical lines is reduced when they are seen on, or in the vicinity of, a slanted surface. We have also assumed that the perceived depth reduction is due to an underestimation of the slant of the illusory rectangle, which acts as a reference frame for the space coding of the locations of the vertical lines (ie the surface hypothesis). However, there is an equally important, alternative explanation that should be considered. This alternative explanation assumes that the underestimation of slant is due to the linear disparity gradient of the slanted plane (Mitchison and Westheimer 1984). In this way, the reduction in perceived depth separation between the two vertical lines is directly caused by the linear disparity gradient of the plane. That is, the perceived depth reduction is due to the interaction between the vertical lines and slanted plane at the disparity-processing level, which is a level prior to the formation of an explicit representation of the surface (ie the disparity-gradient hypothesis). To test this disparity-gradient hypothesis, we employed in the current experiment the two types of stimuli illustrated in figure 6.

By free-fusing the left and middle half-images divergently or the middle and right ones convergently in figure 6, one can see a slanted rectangular surface in the slant-surface condition (a). In the frontoparallel condition (b), the stereoscopic impression is that of a vertical bar occluding a larger rectangular surface in the frontoparallel plane. This latter impression is remarkable, because the stimulus for the frontoparallel condition in each eye comprises essentially of the same basic rectangle from the slant-surface condition, with only some additions. What is added to each half-image is a vertical bar to the left of the basic rectangle, and another rectangle to the left of the vertical bar. Most critically, the vertical bar is carefully placed so that its T-junction just intersects the left border of the basic stimulus (right rectangle) from the slant-surface condition. Thus the linear-disparity-gradient information in the basic rectangle upon which the two vertical lines lie is the same in both the slant-surface and frontoparallel conditions. Consequently, when the half-images are fused in the frontoparallel condition, it is reasonable to assume that the basic rectangle would be perceived as slanted. That this is not so, can be attributed to the overriding influence of the T-junctions of the occluding vertical bar, which causes the visual system to interpret the two rectangles behind the vertical bar as a single continuous rectangle in the frontoparallel plane that is partially occluded in the middle (Anderson and Julesz 1995; Nakayama and Shimojo 1990).

Let us elaborate on this analysis by first referring the reader to figure 1, in which the depth separation between the two vertical lines [in condition (a)] is underestimated when they are joined by horizontal lines [in condition (b)] (McKee 1983). In the latter condition, the two vertical lines are presumed by the visual system to be owned by the two horizontal lines, as together they form a rectangular plane, whose slant happens to be underestimated owing to depth compression. In a similar manner, we can extend

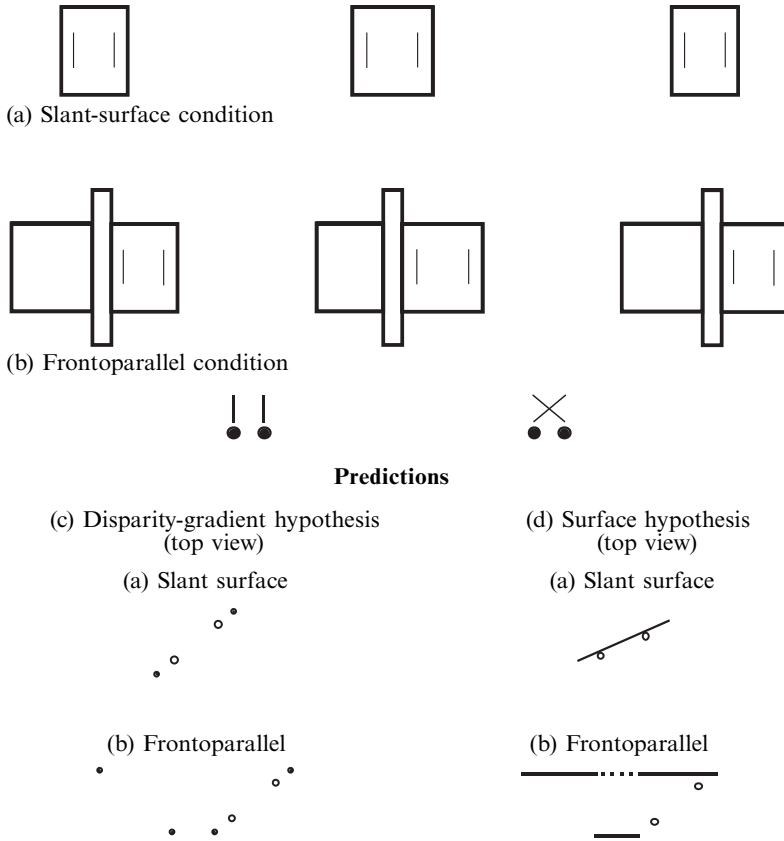


Figure 6. Stimuli and predictions of experiment 3. (a) Slant-surface condition: Two vertical lines are seen on a slanted rectangular surface. The depth separation between the two lines is underestimated owing to the underestimation of the slant of the rectangular surface. (b) Frontoparallel condition: Modified from (a), with the addition of a vertical rectangular bar to the left of the original stimulus, and another rectangle to the left of the bar. When fused, the rectangular bar is seen in front of the two rectangles beside it. Noticeably, even though the right rectangle has the same disparity information as in (a), it is seen as a frontoparallel surface, instead of a slanted one. This is due to the T-junction formed between the right and middle rectangles. Note also that the depth separation between the two vertical lines is larger here than in the condition above. (c) and (d) Predictions of the disparity-gradient hypothesis (c) where no difference in depth judgment is predicted between the two conditions; and the surface hypothesis (d) where less depth perception is predicted in the slant-surface condition.

the same consideration to the basic rectangular surface in figure 6a, ie the slant-surface condition. However, the same consideration appears to be disregarded by the visual system in the frontoparallel condition in figure 6b, causing the basic rectangle to be perceived more as part of a larger rectangular surface in the frontoparallel plane, behind the occluding vertical bar. This can be attributed to the fact that the visual system now regards the left border (vertical line) of the basic rectangle as belonging to the occluding vertical bar. In other words, the basic rectangle no longer exists since its left border is missing.

How will the observer perceive the depth separation between the two vertical lines (ie the objects on the basic rectangle) in the two conditions above? To aid in predicting the perceptual outcomes, we have schematically depicted the disparity-gradient distribution and surface configuration of the stimuli in both conditions, in figures 6c and 6d, respectively. Let us first consider the prediction of the disparity-gradient hypothesis.

As shown in figure 6c, the disparity-gradient distribution in the vicinity of the two vertical lines (open circles) is about the same in conditions (a) (slant-surface condition) and (b) (frontoparallel condition). Thus, the disparity-gradient hypothesis predicts that the observer will perceive the same depth separation between the two vertical lines in both conditions. Now, let us consider the prediction of the surface hypothesis. Figure 6d shows the surface configuration in the vicinity of the two vertical lines (open circles) in the slant-surface condition (a) and frontoparallel condition (b). Clearly, while a slanted rectangular surface is perceived in the slant-surface condition, a frontoparallel rectangular surface is perceived in the frontoparallel condition. Thus, the surface hypothesis predicts that the observer will perceive less depth separation between the two vertical lines in the slant-surface condition (a), as the slant of the rectangular surface will be underestimated. The reader can readily verify the prediction of the surface hypothesis.

4.1 Method

4.1.1 *The dimension of the stimulus in the slant-surface condition.* To create the slant impression of the rectangular surface under stereoscopic viewing, the half-images were given slightly different dimensions. Specifically, the size of the rectangle in the right eye was 80.3 min \times 82.5 min, and in the left eye was 67.1 min \times 82.5 min. The two vertical lines (1.1 min \times 25.3 min in size) that lay on the slanted rectangle had a binocular disparity of 8.8 min. This was produced by having the line separation in the half-images differ in the two eyes, with 44 min in the left eye and 52.8 min in the right eye.

4.1.2 *The dimension of the stimulus in the frontoparallel condition.* The size of the occluding vertical bar was 15.4 min \times 198 min in each half-image. The additional rectangle in the left eye's half-image was 80.3 min \times 82.5 min, and in the right eye's half-image was 67.1 min \times 82.5 min. The remaining aspects of the stimulus were similar to that in the slant-surface condition.

4.1.3 *The dimension of the comparison display.* The comparison display employed in the current experiment (not shown) was essentially similar to that in figure 2b, except for its size. Here, the rectangular surface was 80.3 min \times 82.5 min in each eye. The dimension of the two vertical lines on the rectangular surface was the same as that in the test conditions (figures 6a and 6b). The line separation between the two vertical lines was fixed at 52.8 min in the right eye, while it was randomly varied to assume one of six different binocular-disparity values (0, 2.2, 4.4, 6.6, 8.8, and 11.0 min) in the left eye.

4.1.4 *Procedures.* The same procedures as those used in experiment 1 were employed.

4.2 Result and discussion

The data from the three observers are shown in figure 7, and are plotted in a manner similar to that in experiment 1 (figure 3). Each graph represents the data from an observer. The curves with the triangular and circular symbols represent, respectively, the responses from the slant-surface condition and frontoparallel condition. For all observers, the curves for the frontoparallel condition are shifted to the right relative to the curves for the slant-surface condition, indicating that they saw more depth separation between the two vertical lines in the frontoparallel condition (b). This finding is inconsistent with the disparity-gradient hypothesis, which predicts equal depth perception in the two conditions. It, however, supports the prediction of the surface hypothesis that the perceived depth separation between the two vertical lines is larger in the frontoparallel condition. Thus, our finding suggests that the perceived depth separation between the two vertical lines is determined by the surface configuration of the background surface, and not directly by the disparity-gradient distribution on the surface.

Notably, our finding of reduced depth separation on a slant surface can be related to the depth-contrast effect, which has been reported by previous researchers (eg Gogel

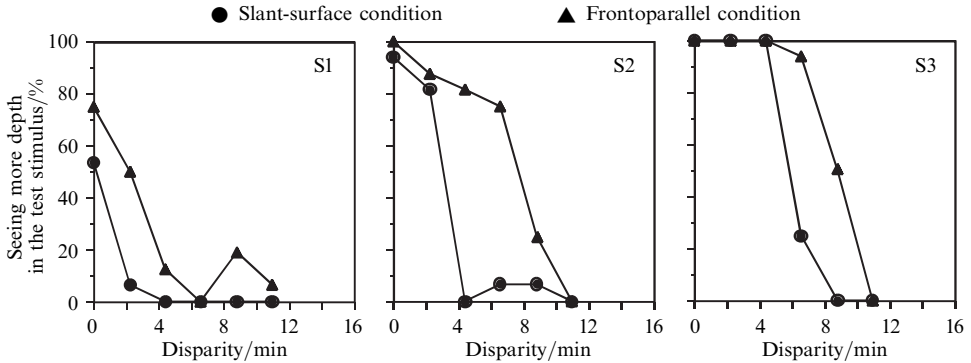


Figure 7. Results of experiment 3 from three observers. The percentage of seeing more depth between the two lines in the test displays from the two conditions in experiment 3 is plotted as a function of the disparity of the comparison display (not shown). For each graph, the curve from the slant-surface condition (circles) is shifted to the left relative to the curve from the frontoparallel condition (triangles). This indicates that less depth is seen in the slant-surface condition, supporting the surface hypothesis.

1954, 1977; Koffka 1935; Kumar and Glaser 1991; Mitchison and Westheimer 1984; Werner 1938). Mitchison and Westheimer (1984) provided an insightful explanation for the depth-contrast effect. Their basic idea was that the perceived depth of an object is related to its salience, which is defined by the weighted relative disparity between the object and its neighboring features. According to their reasoning, the weighting function is high for features that are near to one another and low for features that are far apart. Thus salience receives a larger contribution from the nearer features than from the farther features. Such approach to salience as a function of proximity is similar to Gogel's adjacency principle (Gogel 1970, 1972). Mitchison (1993) also noted that salience is a measure of the local difference in depth between an object and its surrounding features. This is a significant insight, as it implies that the depth perception of an object relies on its relation to its surrounding factors. Indeed, this is consistent with our working hypothesis that the depth separation between objects depends on their relationship with the reference surface.

However, our finding that perceived depth separation between objects is determined by the surface configuration rather than disparity gradient differs conceptually from the salience explanation of Mitchison and Westheimer (1984). Implicit in the salience explanation is the assumption that the locus of the mechanism underlying the depth-contrast effect is at the earlier disparity-processing level. On the other hand, our surface hypothesis places the locus of the mechanism at the later surface-representation level.

4.3 Additional control experiment

Nevertheless, it could be argued that the results reported above are still predictable by the disparity-gradient hypothesis. This is because the additional vertical lines (due to the bar and rectangle to the left of the basic rectangle) in the frontoparallel condition (figure 6b), though somewhat spatially removed from the test lines, could have contributed some weight to the stereoscopic system. Consequently, the salience of the test lines is increased, which results in the observer perceiving a greater depth separation in the frontoparallel condition. Conversely, the absence of the additional vertical lines in the slant-surface condition reduces the salience of the test lines, resulting in a reduced perception of depth separation.

To investigate this possibility, we made slight modifications to both displays of the slant-surface and frontoparallel conditions (figure 8). First, an additional rectangle has been added to the left of the original basic rectangle display (of figure 6a) in the slant-surface condition. This effectively balances out the additional pair of vertical lines in the

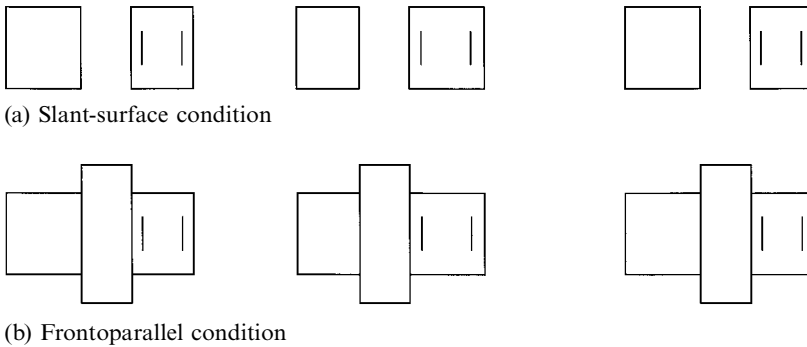


Figure 8. Stimuli used in the additional control experiment for experiment 3. When fused, the two vertical test lines in (a) are seen against a slanted rectangular background surface, while in (b) they are seen against a frontoparallel rectangular background surface. The surface hypothesis predicts seeing more depth separation in (b) than in (a), whereas the salience model predicts equal depth perception.

display belonging to the frontoparallel condition. Thus, the salience of the stimulus in both conditions should now be the same (note that the salience model considers only the vertical components of the display). Second, to reduce the weighted contribution of the additional lines to the test lines, we increased the horizontal separation between the basic rectangle and the additional lines to 63 min. Since the stimulus displays in both conditions now have similar attributes in terms of the salience model, the disparity-gradient hypothesis would predict equal performance when judging the depth separation between the test lines in the two conditions. However, the surface hypothesis would still predict that the observer underestimates the depth separation of the test lines in the slant-surface condition compared to the frontoparallel condition. Indeed, the reader can qualitatively confirm the prediction of the surface hypothesis by free-fusing the displays in figure 8.

During the experiment (using the two-temporal-alternative forced-choice method), the observer was presented consecutively, one at a time, with displays from the two conditions. The order of stimulus presentation was randomized such that sometimes the display from the slant-surface condition was presented first, sometimes the display from the frontoparallel condition. The observer's task was to remember the depth separation of the test lines (binocular disparity was fixed at 8.8 min) from the first presentation and compare it to the depth separation from the second presentation. In this way, the stimulus displays from the two conditions were compared directly, unlike those in the main experiment, in which they were compared to a third standard comparison stimulus display. The observer's task was to report the display that resulted in a larger depth separation.

Four naïve observers (S1, S2, S5, and S6) were tested with 100 trials each. They all reported perceiving more depth separation in the frontoparallel condition than in the slant-surface condition (S1: 76%; S2: 91%; S5: 82%; S6: 80%), in agreement with the prediction of the surface hypothesis.

5 Experiment 4. Relative depth on a surface as a function of perceived surface slant

So far, we have reasoned that the reduction in perceived depth separation between objects that are seen in the vicinity of a slanted surface is due to an underestimation of the slant of the surface itself. We now provide a more direct support for this idea by testing the prediction that the perceived relative depth between objects in the vicinity of a slanted surface varies with the extent of the underestimation of the slant of this surface.

To design a display that provides a more accurate perception of surface slant, we capitalized on the fact that a linear perspective cue can add to the perceived surface slant under stereoscopic viewing condition (Backus et al 1999; Banks and Backus 1998; Gillam 1968; Gillam and Sedgwick 1996; Ogle 1946; Stevens and Brookes 1988; Youngs 1976). For instance, Youngs (1976) reported that the perception of surface slant is improved when a linear perspective cue is added to the stereoscopic display to produce the slanted surface, ie the surface becomes less underestimated for its slant. For the purpose of our current experiment, this observation and its stimulus design were incorporated to produce a more compelling perception of a slanted surface.

Thus, we now have two stimulus conditions to provide different extents of surface slant underestimation, as shown in the stereograms in figures 9a and 9b. As before, the left and middle half-images are for divergent fusers and the middle and right ones for convergent fusers. In the stereo-only condition (a), the slant percept of the illusory rectangular surface is created solely by the binocular-disparity cue. Conceptually, this stimulus is similar to the slanted surface stimuli employed in the last three main experiments. In the stereo + perspective condition (b), the slant percept of the illusory trapezoidal surface is created by both the binocular disparity and linear perspective cues. The linear perspective cue is introduced by having the right side of the illusory trapezoid smaller, to create an impression of it being farther away. Together with the binocular-disparity cue, the illusory trapezoidal surface is seen as a slanted surface whose left side is closer to the reader. The reader can readily verify that this latter condition results in a better appreciation of the slant of the surface, ie less underestimation, than in the former condition. Furthermore, it can be seen that the depth separation between the two vertical lines on the slanted surface is larger in the latter condition. This observation provides a qualitative support for the prediction that the reduction in perceived depth separation between objects on a slanted surface is due to an underestimation of the surface slant (as in the stereo-only condition).

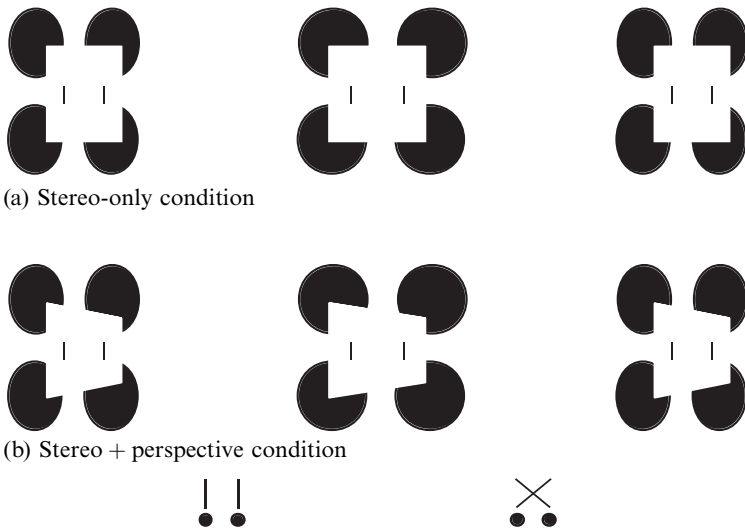


Figure 9. Stimulus for experiment 4. (a) Stereo-only condition: The stereo display is similar to the test display in experiment 1 (figure 2a). (b) Stereo + perspective condition: The stimulus is similar to (a) except that the illusory surface is made trapezoidal in shape, to create a perspective cue (right-side farther) that is consistent with the disparity gradient (slant) of the surface. This has the consequence of allowing the surface to be perceived in greater slant. In turn, the two vertical lines on the surface are also perceived with a larger depth separation than in (a).

5.1 Methods

5.1.1 Stereo-only condition. To produce a slanted illusory rectangle, the diameter of each pacman in the right eye's half-image was 105 min, while that in the left eye's half-image (elliptically shaped pacman) was 105 min vertically and 84 min horizontally. The overall size of the illusory surface was 157.5 min \times 157.5 min in the right eye, and 126.0 min \times 157.5 min in the left eye. The horizontal binocular disparity between the stereoscopic illusory surface and the four coplanar pacmen was 10.8 min. The two vertical lines (2.25 min \times 52.5 min in size) on the illusory surface had a horizontal separation of 48 min in the left eye, and 60 min in the right eye. This difference provided an effective horizontal binocular disparity of 12.0 min between the two lines.

5.1.2 Stereo + perspective condition. The parameters stipulating the stereoscopic design of the display in the stereo + perspective condition (b) was the same as that in figure 9a. To create the illusory trapezoidal surface (for the perspective cue), the left and right vertical edges of the figure were given differing lengths of 157.5 min and 120 min, respectively.

5.1.3 The comparison display (not shown). The display was similar to the one used in experiment 1 (figure 3b), except for its size which was 157.5 min \times 157.5 min. The pair of vertical lines on the surface were similar to the ones in the two conditions above (figures 9a and 9b) in all respects, except for the binocular-disparity value. As in the previous experiments, the two vertical lines could randomly assume one of the seven disparity values (4.5, 6.0, 7.6, 9.0, 10.5, 12.0, and 13.5 min) at different trials.

5.1.4 Observers. One author and two naïve observers (S4 and S5) with corrected-to-normal visual acuity and at least 40 s of arc of stereoacuity, participated in the current experiment. This being the first time they had participated in a stereopsis experiment, the new observers were given about 500 practice trials to familiarize them with the depth-judgment task before commencing the proper experiment. The stimuli used in the practice sessions were similar, but not identical, to the test display in the stereo-only condition (eg dots were used instead of lines for depth judgment, and the dimension of the overall display was different too).

5.1.5 Procedure. The observer pushed a computer mouse button to initiate a trial. Thereupon, the test display was presented for 1.3 s, which was followed by a mask of random dots for 0.5 s. Then the comparison display was presented also for 1.3 s and was followed by a 0.5 s mask. The observer's task was the same as that in experiment 1.

5.2 Results

The results from the three observers are shown in separate graphs in figure 10. These graphs are plotted in a manner similar to that of experiment 1. On comparing between the data for the stereo-only condition (inverted triangles) and stereo + perspective condition (circles), it is clear that the psychometric function for the stereo-only condition is relatively shifted to the left for each observer. This indicates that the observers saw less depth separation between the two vertical lines in the stereo-only condition. This finding agrees with our prediction that a reduction in perceived depth separation between two objects on a surface occurs when the slant of the surface is underestimated.

6 General discussion

We have tested the surface hypothesis—that the common surface is used as a reference frame for coding binocular depth perception. Our experiments relied on one critical prediction of the surface hypothesis that, if the common visual surface which acts as the reference frame is misperceived, the relative depth separation between two objects on

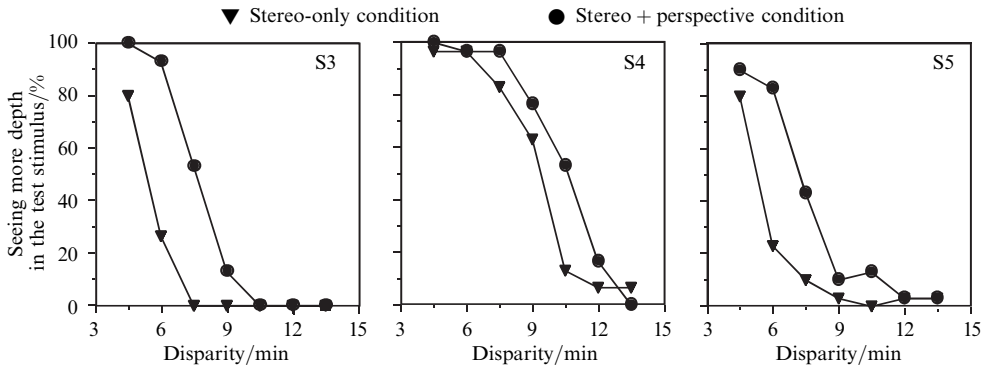


Figure 10. Results of experiment 4 from three observers. The percentage of seeing more depth between the two vertical lines in the test displays from the two conditions in experiment 4 is plotted as a function of the disparity of the comparison display (not shown). For each graph, the curve from the stereo-only condition (inverted triangles) is shifted to the left relative to the curve from the stereo + perspective condition (circles). This indicates that less depth is seen in the stereo-only condition, where the slant of the background surface is underestimated.

or near the surface is also misperceived. To test this prediction, we capitalized on the established observation where surface slant is underestimated owing to the compression of depth. This allowed us to demonstrate that the depth separation between objects on the common surface is likewise compressed or underestimated. We also showed that when the slant of the common surface is better estimated, as in the stereo + perspective condition of experiment 4, the perceived depth separation between the two objects on the common surface increases. Overall, our findings underscore the role of the common visual surface in binocular depth perception.

6.1 Edge/line versus surface factor in binocular depth perception

In our effort to show that the surface-representation level contributes to binocular depth perception, we had purposely used subjective surfaces as the background in some of our experiments. This is because subjective surfaces are thought to be formed at the surface-representation level, rather than at the earlier filtering level. Accordingly, when a pair of vertical test lines located on or near the subjective surface are seen as reduced in depth, we can attribute the reduction in depth judgment to the impact of the surface-representation level.

Yet, one might argue that the above explanation is unnecessary since the outlines and edges of the pacmen that induce the subjective surface could themselves have contributed local disparity information to affect binocular depth perception. To rule out this possibility, we wish to point out an important premise for forming subjective surfaces. The premise is that subjective surface formation depends on occlusion information inherent in the inducing elements (He and Ooi 1998; Kanizsa 1955). When the occlusion information is unavailable, for instance when the solid pacmen (figure 11a) are exchanged for outlines (wire-frame pacmen; figure 11b), the subjective surface cannot be formed. This is because the explicit delineation of the pacmen by the wire frames encourages the visual system to interpret the wire pacmen as completed figures or independent perceptual units, rather than as parts of occluded disks (Kanizsa 1979).

On the basis of this premise, we have constructed two types of stereo displays in figure 12, to show that the reduced depth perception between the two test lines is due to the presence of the subjective surface. By free-fusing figure 12a, the reader will perceive a slanted subjective rectangular surface with two vertical test lines. When the relative depths of these test lines are compared to those in figure 12b, where the subjective surface is absent owing to the inducers being invalid wire-frame figures, the reader can readily verify that the depth perception is reduced in figure 12a.

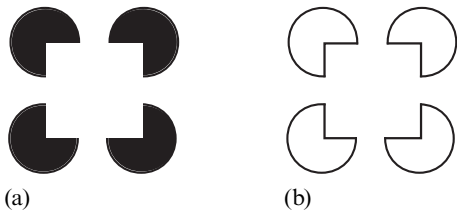


Figure 11. A demonstration of the typical Kanizsa-square display (a); and wire-frame display (b) which does not induce subjective surface formation.

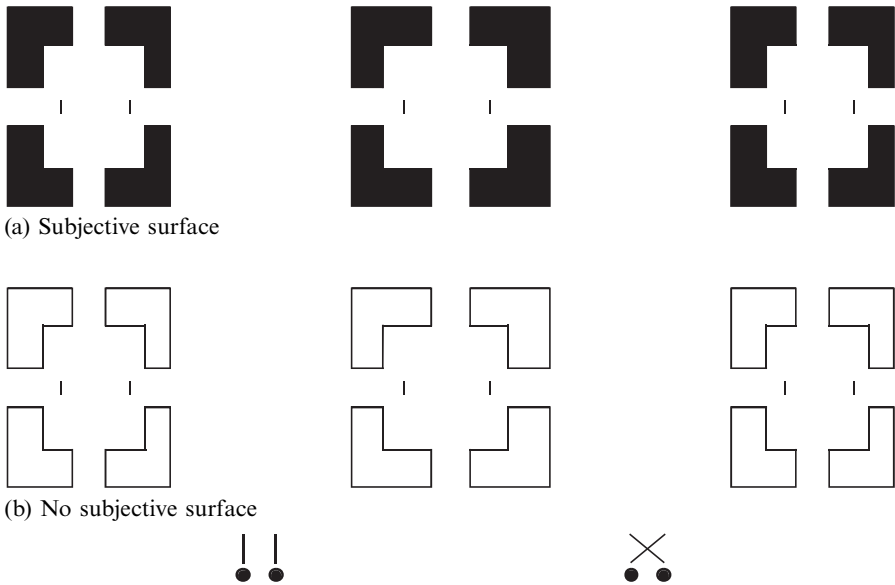


Figure 12. Stereo stimuli employed to investigate the impact of subjective surface on depth perception. (a) Subjective surface: When fused, a slanted subjective rectangular surface in front of four partially occluded and slanted black rectangles is formed. (b) No subjective surface: Unlike (a), this wire-frame display does not induce the formation of a subjective rectangular surface despite having the same spatial dimensions. Further, when the depth separations between the two test lines are compared, display (a) produces a smaller depth impression than (b). The stimulus dimensions used for the experiments were as follows. The two test lines were 36.4 min long and their horizontal separation was 118.7 min in the right eye, and 98.9 min in the left eye. The induced subjective rectangular surface was 185.4 min \times 193.2 min and 155.7 min \times 193.2 min, respectively, in the right and left eyes. The dimension of each of the four partially occluded black rectangles was 121.1 cm \times 106.4 min in the right eye, and 98.9 min \times 106.4 min in the left eye. The vertical spatial separation between the top and bottom rectangles was 53.2 min; while the horizontal spatial separations were 49.4 min and 44.5 min, respectively, in the right and left eyes. The horizontal disparity between the subjective surface in (a) and the four partially occluded slanted rectangles was 4.94 min.

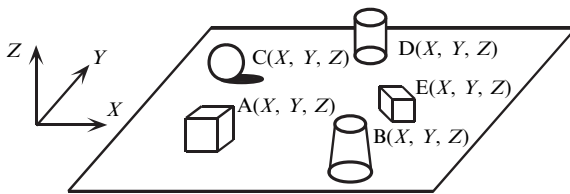
To provide further confirmation, we have also tested three naïve observers (S1, S2, and S5) with these two displays, using the same experimental procedures as that described in section 4.3. Their results show that a larger depth separation was perceived between the pair of test lines in figure 12b, where the subjective surface is absent (S1: 73%; S2: 76%; S5: 83%). Thus, we can conclude that the reduced depth perception on a slanted surface is attributable to the presence of the subjective surface, ie the impact of the surface-representation level. In other words, it cannot be due to processes at the early filtering level because similar local disparity information is present in both displays of figure 12.

Our finding underscores an important insight by McKee (1983) who revealed that, when two vertical lines are joined by two horizontal lines to form a square, the depth

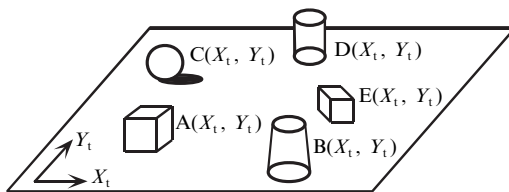
threshold between the two vertical lines is increased (figure 1). This and other similar observations have led to the view that it is not the two horizontal lines per se, but the subsequent figure/object formed (square) that alters the depth perception (McKee 1983; Stevens and Brookes 1988). Our current study not only supports this view, but indicates that the figure/object is probably defined, in part, by properties of the surface-representation level.

6.2 Binocular depth and quasi 2-D coding hypothesis

It is conceivable that our visual system chooses the common visual surface as a reference frame for distance judgment and navigation predominantly because it is most prevalent in our terrestrial environment (Gibson 1950, 1979). Figure 13 illustrates an important regularity of our spatial layout, in which objects that we frequently interact with in the real world are often located on a common surface. As shown, the objects are atop a common surface. Clearly, to code the relative distances of these objects, the visual system could adopt different strategies. For instance, these objects could be coded by the visual system using a 3-D Cartesian coordinate system (X, Y, Z) (figure 13a), or a quasi 2-D coordinate system (X_t, Y_t) with respect to the common background surface upon which they lie (figure 13b). (Note here that the common surface itself is a 3-D surface, which can either be a plane or a curved surface relative to the retinal coordinates. But projections of objects onto the reference common surface can be represented by two coordinate points. Therefore we refer to the coding strategy as quasi 2-D coding.) We propose that it is more advantageous for the visual system to use the quasi 2-D coding strategy, for it enables the visual system to enhance its coding efficiency as the 3-D coordinates of the objects are in essence reduced to quasi 2-D coordinates. In other words, by representing the objects on a common surface with a 2-D coordinate system with respect to the surface, other computations involving interactions among the objects on the common surface will become a 2-D process. We coin this scheme a quasi 2-D coding scheme, and it can be taken as a more explicit reformulation of Gibson's ground theory of space perception.



(a) 3-D Cartesian representation of objects



(b) Quasi 2-D representation of objects on a common surface

Figure 13. Two hypothetical space-coding schemes for representing 3-D objects that are located on a common surface. See text for details.

According to our quasi 2-D coding scheme, the stereoscopic mechanism for coding objects' locations could be described by two arbitrarily distinct stages. The first stage represents the common surface which will be used as the reference frame. Meanwhile, the second stage defines the coordinates of each individual object with respect to the

reference frame. Thus, when the relative disparities between the objects are transformed into metric depth representations, they will be scaled according to their relationships to the reference surface and the spatial relationship of the reference surface to the observer.

In our experiments reported above we used a smooth surface with a linear disparity gradient as the objects' background surface, which, when seen alone, was underestimated for its slant (eg McKee 1983). The underestimation of the slant of the surface, we believe, is the consequence of the first-stage process. It should be pointed out that the output of the first stage in this case, a misperceived slanted surface, does not necessarily reflect the inefficiency of the first-stage process itself, but rather the idiosyncrasy of the disparity distributions or depth cues associated with the stimulus. This is because it has been shown that, when a higher-order disparity-gradient information that defines a curved surface is used as the input, the output of the first stage, or the perception of the curved surface, is more accurate (eg Glennerster et al 1996; Rogers and Cagenello 1989). In the real world, accurate representation of surfaces is no doubt aided by various monocular cues such as linear perspective, texture gradient, height in the field of view, etc. Thus, when future experiments examine the depth judgments of objects seen near or on a curved background surface, or a surface rich in monocular cues, more accurate performances in depth judgment would be expected.

Another issue that needs to be considered in future experiments is how the objects' coordinates with respect to the common surface are determined at the second stage. Clearly, when the objects are located directly on the common surface (eg experiment 1) computing each object's coordinate is straightforward. However, when the objects are raised above the common surface (eg experiment 2), computing their coordinates with respect to the surface becomes more complex. Presumably, the visual system has then to compute how the images of the objects are projected onto the common surface, before obtaining their coordinates with respect to the surface. In fact, a somewhat similar problem has been raised by other researchers for intermediate-range distance perception where the ground surface is used as the reference frame (Gibson 1950, 1979; Sedgwick 1983, 1986; Wu et al 2000).

Is there a precedence for the human visual system to employ the common surface for coding stereoscopic distances? We believe so, given that surfaces are regular occurrences in our visual world (niche) and that our brains have a remarkable ability to exploit extant regularities as a way to reduce coding redundancy (Attneave 1954; Barlow 1961). A good example is the use of the ground surface for coding distances (Gibson 1950; Sinai et al 1998). Because the orientation and vertical distance (eye height) of the ground surface from the adult observer are, statistically speaking, invariant factors, it would be beneficial for the brain to utilize the ground surface as a reference frame for coding depth perception both on-line and off-line (eg under degraded conditions such as in the dark). Incidentally, the critical role of the ground surface was previously recognized by Helmholtz when he formulated the vertical horopter (Helmholtz 1867/1962; Tyler 1991).

Even though our study is the first to explicitly test the surface hypothesis in binocular depth perception, its results are by no means surprising. In fact, there are a number of empirical findings in the past, such as the depth-contrast phenomenon, that have clearly revealed the contribution of the background to binocular depth perception (eg Gillam et al 1988; Gillam et al 1993; Gillam and Sedgwick 1996; Glennerster and McKee 1997, 1999; Gogel 1954, 1977; Gulick and Lawson 1976; Koffka 1935; Kumar and Glaser 1991; Mitchison and Westheimer 1984; Stevens and Brookes 1988; van Ee et al 1999; Werner 1938). Often, however, the explanation given for these observations were based primarily on the processing of binocular disparity, or according to other general perceptual principles. In this respect, our study differs from the previous ones in that we suggest that binocular depth processing is influenced by the later level of surface representation. Incidentally, our view to some extent also resembles an important insight from a recent

study by Glennerster and McKee (1999). To explain how a background consisting of a grid of dots can alter the depth threshold of their test line, they pointed out the possibility that the slanted grid has the effect of recalibrating the visual system's estimate of the frontoparallel so that the relative disparity determining threshold is the disparity of the test line with respect to this recalibrated plane (also see Gillam et al 1988; Gillam and Sedgwick 1996; McKee 1983; Sedgwick and Nicholls 1993; Sedgwick et al 1996; Stevens and Brookes 1988).

The common surface also plays a role in other types of perceptual performances where binocular depth information is present (He and Ooi 1999; Watamaniuk and McKee 1995). For example, it has been shown that objects tend to group together on a common background surface which traverses multiple depth planes. In a recent study, using the 3-D Ternus apparent motion display (He and Ooi 1999), we tested two experimental conditions. In the first condition, the inner motion tokens of the Ternus display were given crossed disparity with respect to the outer motion tokens. This led to our observers perceiving more element motion than group motion. In the second condition, we inserted a curved 3-D background surface into the display, so that the curved surface formed a common surface which directly supported both the inner and outer motion tokens from the first condition. By doing so, the same observers now reported perceiving more group motion, in contrast to their perception in the first condition. This indicates that objects on a common surface tend to be perceptually grouped together, and their consequent interactions are referenced to the common surface.

Finally, we wish to point out that while we have indicated that the quasi 2-D coding scheme could be a very efficient strategy employed by the visual system in the natural environment, we are mindful that the visual system could resort to other types of space-coding schemes when necessary. This fact can be indirectly gauged from our finding in experiment 2, which shows that depth judgment is less affected by the surface as the objects are raised farther away from the common surface. As speculated earlier, this suggests that depth perception in this instance was accomplished by alternative means, perhaps related to the formation of an internal representation or reference frame that is associated with the horopter. Similarly, in our daily activity, we are sometimes confronted with an impoverished visual scene (eg due to poor illumination) where the common surface is not readily accessible. Clearly, to cope with this situation in the interest of survival, the visual system needs to either depend on a different space-coding strategy (which may or may not be less accurate and efficient), or slightly modify the quasi 2-D coding strategy. No doubt, the agility of the visual system in employing different space-coding strategies and depth cues, is an important merit that enables us to survive in our complex visual world. Indeed, this is part of the fascination of the visual system—its ability to resort to whatever means that allows it to reduce its coding redundancy and enhance its efficiency.

Acknowledgements. This research was supported in part by grants from the ONR (994984), the College of Arts and Sciences, and the CEG from the University of Louisville to ZJH; and grants from the Knights Templar Eye Foundation and the Southern College of Optometry to TLO. We thank the anonymous reviewers for their helpful comments and suggestions.

References

- Anderson B L, Julesz B, 1995 "A theoretical analysis of illusory contour formation in stereopsis" *Psychological Review* **102** 705–743
- Attneave F, 1954 "Some informational aspects of visual perception" *Psychological Review* **61** 183–193
- Backus B T, Banks M S, Ee R van, Crowell J A, 1999 "Horizontal and vertical disparity, eye position, and stereoscopic slant perception" *Vision Research* **39** 1143–1170
- Banks M S, Backus B T, 1998 "Extra-retinal and perspective cues cause the small range of the induced effect" *Vision Research* **38** 187–194

- Barlow H B, 1961 "Possible principles underlying the transformation of sensory messages", in *Sensory Communication* Ed. W A Rosenblith (Cambridge: MIT Press) pp 217–234
- Cutting J E, Vishton P M, 1995 "Perceiving layout and knowing distance: The integration, relative potency, and contextual use of different information about depth", in *Handbook of Perception and Cognition: Perception of Space and Motion* Eds W Epstein, S Rogers (San Diego, CA: Academic Press) pp 69–117
- Ee R van, Banks M S, Backus B T, 1999 "An analysis of binocular slant contrast" *Perception* **28** 1121–1145
- Gibson J J, 1950 *The Perception of the Visual World* (Boston, MA: Houghton Mifflin)
- Gibson J J, 1979 *The Ecological Approach to Visual Perception* (Hillsdale, NJ: Lawrence Erlbaum Associates)
- Gillam B, 1968 "Perception of slant when stereopsis and perspective 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
- Gillam B, Ryan C, 1992 "Perspective, orientation disparity, and anisotropy in stereoscopic slant perception" *Perception* **21** 427–439
- Gillam B, Sedgwick H, 1996 "The interaction of stereopsis and perspective in the perception of depth" *Perception* **25** Supplement, 70
- Gillam B, Sedgwick H, Cook M, 1993 "The interaction of surfaces with each other and with discrete objects in stereoscopic vision" *Perception* **22** Supplement, 35
- Glennester A, McKee S P, 1997 "Sensitivity to depth or lateral displacement on a slanted reference plane" *Investigative Ophthalmology & Visual Science* **38**(4) S907
- Glennester A, McKee S P, 1999 "Bias and sensitivity of stereo judgements in the presence of a slanted reference plane" *Vision Research* **39** 3057–3069
- Glennester A, Rogers B J, Bradshaw M F, 1996 "Stereoscopic depth constancy depends on the subject's task" *Vision Research* **36** 3441–3456
- Gogel W C, 1954 "Perception of the relative distance position of objects as a function of other objects in the field" *Journal of Experimental Psychology* **47** 335–342
- Gogel W C, 1970 "The adjacency principle and three-dimensional visual illusions" *Psychonomic Monograph Supplement* **3** 153–219 (whole number 45)
- Gogel W C, 1972 "Depth adjacency and cue effectiveness" *Journal of Experimental Psychology* **92** 176–181
- Gogel W C, 1977 "The metric of visual space", in *Stability and Constancy in Visual Perception, Mechanisms, and Processes* Ed. W Epstein (New York: John Wiley) pp 29–181
- Gulick W L, Lawson R B, 1976 *Human Stereopsis* (New York: Oxford University Press)
- He Z J, Ooi T L, 1997 "Common surface as reference for coding relative 3D distance and depth: A Quasi-2D coding hypothesis" *Investigative Ophthalmology & Visual Science* **38**(4) S908
- He Z J, Ooi T L, 1998 "Illusory contour formation affected by luminance contrast polarity" *Perception* **27** 313–335
- He Z J, Ooi T L, 1999 "Perceptual organization of apparent motion in Ternus display" *Perception* **28** 877–892
- Helmholtz H von, 1867/1962 *Treatise on Physiological Optics* volume 3 (New York: Dover, 1962); English translation by J P C Southall for the Optical Society of America (1925) from the 3rd German edition of *Handbuch der physiologischen Optik* (Hamburg: Voss, 1909; first edition, Leipzig: Voss, 1867)
- Howard I P, Rogers B J, 1995 *Binocular Vision and Stereopsis* (New York: Oxford University Press)
- Kanizsa G, 1955 "Margini quasi percettivi in campi con stimolazione omogenea" *Rivista di Psicologia* **49** 7–30 [Quasiperceptual margins in homogeneously stimulated fields] translated by W Gerbino, 1987, in *The Perception of Illusory Contours* Eds S Petry, G E Meyer (New York: Springer) pp 40–49
- Kanizsa G, 1979 *Organization in Vision: Essays on Gestalt Perception* (New York: Praeger)
- Koffka K, 1935 *Principles of Gestalt Psychology* (New York: Harcourt, Brace & Jovanovitch)
- Kumar T, Glaser D A, 1991 "Influence of remote object on local depth perception" *Vision Research* **31** 1687–1699
- McKee S P, 1983 "The spatial requirements for fine stereoacuity" *Vision Research* **23** 191–198
- Mitchison G J, 1993 "The neural representation of stereoscopic depth contrast" *Perception* **22** 1415–1426
- Mitchison G J, McKee S P, 1990 "Mechanisms underlying the anisotropy of stereoscopic tilt perception" *Vision Research* **30** 1781–1791

- Mitchison G J, Westheimer G, 1984 "The perception of depth in simple figures" *Vision Research* **24** 1063–1073
- Nakayama K, He Z J, Shimojo S, 1995 "Visual surface representation: A critical link between lower-level and higher-level vision", in *An Invitation to Cognitive Science* volume 2 *Visual Cognition* (second edition) Eds S Kosslyn, D O Osherson (Cambridge, MA: MIT Press) pp 1–70
- Nakayama K, Shimojo S, 1990 "Toward a neural understanding of visual surface representation" *Cold Spring Harbor Symposia on Quantitative Biology* **55** 911–924 (Cold Spring Harbor, MA: Cold Spring Harbor Laboratory Press)
- Ogle K N, 1946 "The binocular depth contrast phenomenon" *American Journal of Psychology* **59** 111–126
- Rogers B J, Cagenello R, 1989 "Disparity curvature and the perception of three-dimensional surface" *Nature (London)* **339** 135–137
- Sedgwick H A, 1983 "Environment centered representation of spatial layout: available information from texture and perspective", in *Human and Machine Vision* Eds A Rosenthal, J Beck (New York: Academic Press) pp 425–458
- Sedgwick H A, 1986 "Space perception", in *Handbook of Perception and Human Performance* Eds K R Boff, L Kaufman, J P Thomas (New York: John Wiley) pp 21.1–21.57
- Sedgwick H A, 1989 "Combining multiple forms of visual information to specify contact relations in spatial layout" *SPIE (Sensor Fusion II: Human and Machine Strategies)* **1198** 447–458
- Sedgwick H A, Nicholls A L, 1993 "Cross talk between the picture surface and the pictured scene: Effects on perceived shape" *Perception* **22** Supplement, 109
- Sedgwick H A, Raul C, Flagg T, 1996 "Components of visual information specifying the surface of a picture: their relative effectiveness in decreasing cross-talk from the depicted scene" *Perception* **25** Supplement, 60
- Sinai M J, Ooi T L, He Z J, 1998 "Terrain influences the accurate judgement of distance" *Nature (London)* **395** 497–500
- Stevens K A, Brookes A, 1988 "Integrating stereopsis with monocular interpretations of planar surfaces" *Vision Research* **28** 371–386
- Tyler W, 1991 "The horopter and binocular fusion", in *Vision and Visual Dysfunction* Ed. J R Cronly Dillon, volume 10 *Binocular Vision* Ed. D Regan (London: Macmillan) pp 19–37
- Watamaniuk S N J, McKee S P, 1995 "Seeing motion behind occluders" *Nature (London)* **377** 729–730
- Werner H, 1938 "Binocular depth contrast and the conditions of the binocular field" *Psychological Monographs* **49** 1–27
- Wu B, Ooi T L, He Z J, 2000 "Perceived object's location in the dark is not veridical, but not fortuitous" *Investigative Ophthalmology & Visual Science* **41**(4) S228
- Youngs W M, 1976 "The influence of perspective and disparity cues on the perception of slant" *Vision Research* **16** 79–82