Perception, 2000, volume 29, pages 211 – 220

DOI:10.1068/p3011

Depth capture by kinetic depth and by stereopsis

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Received 28 July 1999, in revised form 30 October 1999

Abstract. The perceived depth of regions within a stereogram lacking explicit disparity information can be captured by the surface structure of regions where disparity is explicit: stereo capture. In two experiments, observers estimated surface curvature/depth of an untextured object (a 'ribbon') superimposed on a cylinder textured with dots, the cylinder curvature being defined by disparity (stereo depth) or by motion parallax (kinetic depth: KD). With the stereo-defined cylinder, depth capture was obtained under conditions where the disparity of the ribbon was ambiguous; with the KD, cylinder depth capture was obtained under conditions where the motion flow of the cylinder was in a direction parallel to that of the ribbon. These results demonstrate yet another similarity between KD and stereopsis.

1 Introduction

Vision exploits multiple sources of optical information to specify the three-dimensional layout of objects and their surfaces. One of these sources is stereoscopic vision — the strong, immediate sense of 3-D provided by the slight parallax differences between left-eye and right-eye views (Wheatstone 1838). The very keen sense of depth (Ogle 1964) and 3-D shape (Julesz 1971) from stereopsis provides the most plausible raison d'être for frontal eye placement in diverse species spanning mammals, fish, and birds (Fox 1978). Another reliable, accurate source of 3-D structure comes from the differential optic flow generated by contours and surface markings of moving 3-D objects (Wallach and O'Connell 1953). Termed kinetic depth (KD), the perception of volume and shape from motion can be as compelling and as accurate as that created by stereopsis (Rogers and Graham 1982). Indeed, under some conditions observers find it impossible to distinguish KD from kinetic stereopsis (Nawrot and Blake 1993).

Besides yielding comparable impressions of 3-D shape, stereopsis and KD have other things in common. For example, both stereopsis and KD generate compelling impressions of surface structure within regions of the visual field where there is no explicit depth information specified by motion (Saidpour et al 1992) or by binocular disparity (Grimson 1981) — both, in other words, support vivid depth and shape interpolation.

Converging lines of psychophysical and neurophysiological evidence suggest that KD and at least some forms of stereopsis may involve similar neural mechanisms (see review by Freeman 1998). Psychophysically, it has been shown that adaptation to a stereoscopically defined surface can temporarily bias the otherwise ambiguous appearance of a 3-D surface specified by KD (Rogers and Graham 1984; Nawrot and Blake 1989, 1991a). In a similar vein, KD can bias perception of surface depth from ambiguous or weak stereoscopic signals (Nawrot and Blake 1993). Neurophysiologically, several laboratories have identified neurons in primate visual areas whose responses are selective for both stereoscopic disparity and direction of motion (Maunsell and Van Essen 1983; Bradley et al 1995; DeAngelis et al 1998). In fact, the responses of some neurons in visual area MT wax and wane in synchrony with the behaving monkey's report of depth in a bistable KD display (Bradley et al 1998).

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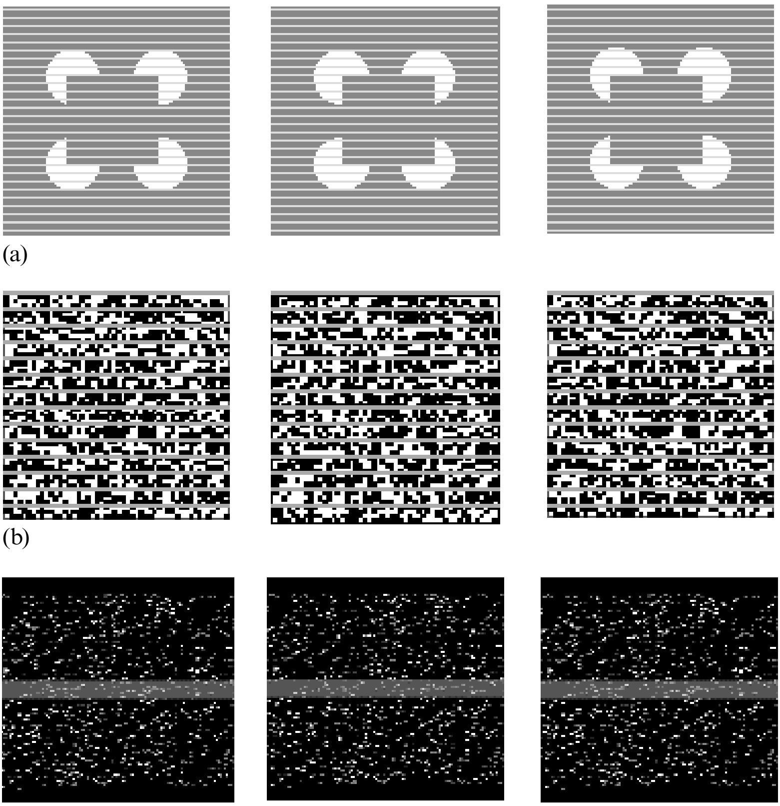
In this paper we describe new evidence that the perception of surface structure from stereopsis and from KD obeys common constraints. Our work utilizes the phenomenon of stereo capture, whereby the perceived depths of regions within a stereogram where disparity is zero or is ambiguous are appropriated, or captured, by the surface structure of regions where disparity is explicit (Ramachandran and Cavanagh 1985; Ramachandran 1986). Shown in figure 1a is an example of stereo capture in which a Kanizsa subjective square stands out in depth, carrying with it the portion of the pattern of repeating lines falling within the boundaries of the subjective square. In unpublished work we have found that stereo capture can also readily be observed in stereograms in which the Kanizsa square is replaced by random-dot stereograms. Thus, when a random-dot pattern with central square in crossed disparity is superimposed on a background pattern with zero disparity, one can see standing in depth an opaque square with a series of lines texturing its surface (figure 1b). Even a single horizontal stripe is easily captured by stereo depth in random-dot surfaces, and the 3-D shape of the stripe conforms exactly to that of the 3-D surface specified by disparity. Thus, for example, the horizontal stripe appears to wrap around a curved stereoscopic surface (figure 1c).



(a) (b) (c)

Figure 1. Three examples of stereo capture by surfaces appearing nearer in depth (crossed disparity) than their backgrounds Viewers who achieve binocular fusion by crossing their eyes will want to use the left-hand and middle stereo half-images; those who uncross the eyes may use the middle and right-hand half-images. (a) The horizontal lines falling within the boundaries of the subjective square are pulled forward into the same depth plane as that square, which is specified by crossed disparity of the cut sectors. (b) The horizontal lines falling within the central portion of the random-dot stereogram are pulled into the same depth plane as the central square which is specified by crossed disparity of the texture elements. (c) The horizontal strip—'ribbon'—appears painted semi-transparently on the curved cylinder defined by the gradient of crossed disparities among the dots texturing the cylinder.

Can a 3-D surface specified by motion also capture an ambiguous stimulus? It should be stressed that we are not referring to motion capture, wherein physically stationary elements appear to move in synchrony with a large moving object (eg Ramachandran and Inada 1985). Nor are we studying perception of illusory figures with rotating inducers (eg Kojo and Rovamo 1999). Instead, we have asked whether KD can capture an ambiguous stimulus, causing that captor to conform to the 3-D shape specified by KD. By way of preview, we find that an untextured, stationary object is altered in 3-D shape by virtue of its proximity to depth surfaces specified by stereopsis and by motion parallax, but only under certain conditions.

2 Experiment 1: Stereo capture and KD capture

2.1 *Method*

2.1.1 *Observers.* Two adult males participated in this experiment, one the author (KK) and the other an individual naive about the purpose of the experiment. Both have corrected-to-normal acuity and excellent stereopsis. In addition, the phenomena described in this report have been experienced by others in our laboratory, and interested readers may inspect depth capture from stereopsis and from motion by navigating to our webpage: http://www.psy.vanderbilt.edu/faculty/blake/DepthCapture/DepthCapture.html or to http://www.perceptionweb.com/perc0200/kham.html (archived in the annual CD-ROM supplied with issue number 12 of *Perception*).

2.1.2 *Apparatus and displays.* Displays were generated by a Power Macintosh computer and presented on a 21-inch NEC color monitor (1152 H $\times$ 870 V; 75 Hz frame rate). The observer viewed the displays through a mirror stereoscope in a darkened room at a viewing distance of 113 cm.

A cylindrically curved surface textured with small (2 min of arc width) randomly spaced dots was created either by retinal disparity or by motion parallax; the dots were white (15.7 cd m^{-2}) against a black background. For the stereo cylinder, disparity varied smoothly (within the limits of pixel size) from zero disparity at the edge to 5 min of arc disparity at the center; dots defining the stereo cylinder were static. In the motion condition, an equivalent cylindrical surface was simulated by parallel projections of random dots (7% density) onto the surface of a cylinder rotating at constant angular velocity of 3°/frame about its vertical axis. All dots moved in the same direction of motion, thus simulating an opaque cylinder. Each motion frame was repeated for 3 monitor refresh cycles (approximately 40 ms), and the cylinder appeared to rotate smoothly and continuously, either clockwise or counterclockwise (with direction varied randomly over trials). Although viewed through the stereoscope, the simulated KD cylinder was presented monocularly to one eye (the stimulated eye being varied randomly over trials), with the corresponding area of the other eye viewing a blank field of the same mean luminance. (We elected to use monocular viewing because the impression of KD was more vivid than with binocular viewing.)

For both conditions, the cylinder subtended 1 deg 35 min $\times$ 1 deg 35 min visual angle, and was flanked by a zero-disparity random-dot pattern always presented binocularly to provide a reference plane for depth judgments. The total angular subtense of the cylinder plus reference plane was 2 deg 30 min wide $\times$ 1 deg 35 min high. In the initial experiment, the axis of rotation of the cylinder was vertical (meaning that the KD version of the cylinder appeared to rotate left to right, or vice versa). In a follow-up experiment, the axis of rotation of the cylinder was horizontal (meaning the KD cylinder rotated from top to bottom or vice versa).

For both stereo and motion conditions, a stationary vertical 'ribbon' or a stationary horizontal 'ribbon' appeared superimposed on the surface of the cylinder (the ribbon dimensions were 2 deg $\times$ 9 min of arc). The luminance of the ribbon was 6.9 cd m^{-2}, and it appeared semi-transparent because the dots were not occluded by its presence. The horizontal ribbon was always centered midway along the vertical extent of the cylinder; the vertical ribbon appeared either at the edge of the cylinder, at the middle of the cylinder, or intermediate between the edge and the center. Figure 2 illustrates schematically the KD version of some of these displays.

We were interested in deducing the perceived curvature of the ribbon in depth. To estimate depth values along the curvature of the ribbon, we measured perceived depth at three different positions along the cylinder using a small (15 min of arc $\times$ 15 min of arc), briefly presented (240 ms) square as a depth probe; the luminance of the probe was the same as that of the ribbon, 6.9 cd m^{-2}. For both stereo and motion conditions, perceived depth was measured at three positions along the horizontal ribbon (edge, middle, and intermediate position) and at the three different locations of the vertical ribbon. The depth of the probe dot was unambiguously specified by binocular disparity.

2.1.3 *Procedure.* The observer first adjusted the mirrors of the stereoscope to achieve accurate, stable binocular alignment of the half-images. On each trial, a random-dot pattern with zero disparity was presented. When ready, the observer pressed a key triggering presentation of the 'half-cylinder' together with either a horizontal or a vertical ribbon.

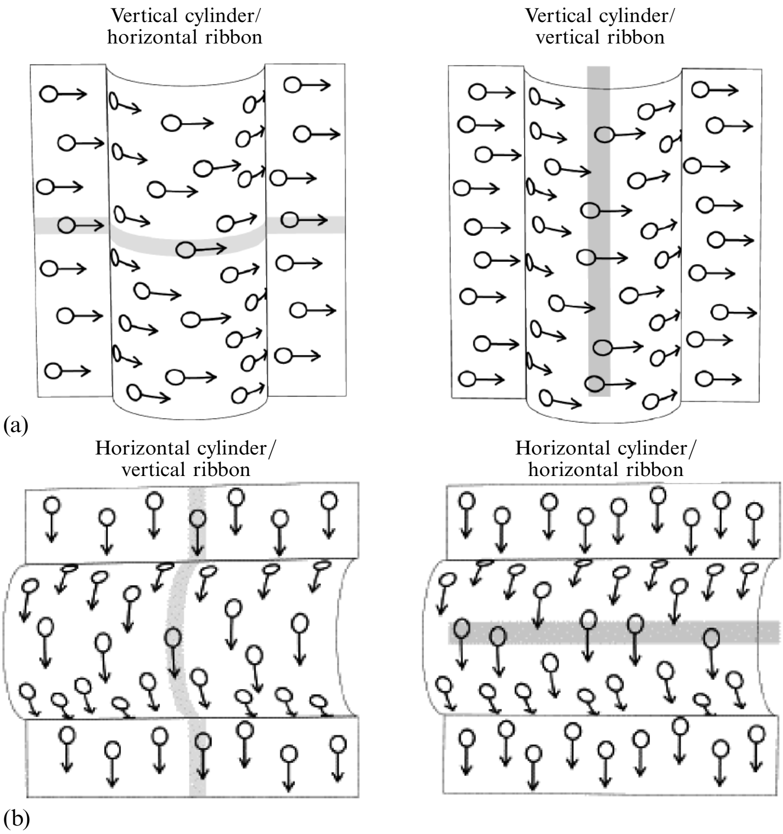


Figure 2. Schematic depicting the stimulus used to create a kinetic depth version of the stereo cylinder shown in figure 1c. In the actual animation, of course, the dots moved in one direction over the flat face of the video monitor, their speeds mimicking travel over a curved surface. The axis of curvature could appear vertical (a) or horizontal (b); the dots defining the cylinder could flow leftward or rightward (vertical cylinder) or downward or upward (horizontal cylinder). A stationary, semi-transparent 'ribbon' appeared in the center of the cylinder, oriented either horizontally or vertically.

The observer next initiated presentation of the probe dot if the half-cylinder appeared convex. (On rare occasion in the KD condition, the cylinder appeared concave for a few moments.) The observer judged the depth of the probe (which was governed by its binocular disparity) relative to the depth of the portion of the ribbon being assessed. The probe dot was presented 14 min of arc above or below the horizontal ribbon and 14 min of arc to the left or right of the vertical ribbon. The observer always fixated that portion of the ribbon at which perceived depth was being measured, and judged the depth of the probe ("closer" versus "farther") relative to that portion of the ribbon.

For a given block of trials, the perceived depths of the horizontal ribbon and the vertical ribbon were measured for a given cylinder condition (stereo versus KD) and for a given position of the ribbon on the cylinder. Within each block of trials, the disparity of the probe dot assumed one of seven different values, with the specific value determined randomly from trial to trial. Each of the seven probe disparities was compared with the vertical and the horizontal ribbon 10 times within a block of trials. Each block of trials was repeated twice, yielding 20 trials for each of the seven disparity values for all conditions. The specific disparity values used for a given condition were established in pilot measurements, such that the set of values approximately straddled the 'equi-depth' point (ie 50% "in-front" responses) for that condition. In all conditions, the seven values differed from one another in 1 min of arc steps.

2.2 *Results and discussion*

Simply looking at these displays foretells the depth-probe results. When superimposed on either the stereo cylinder or the KD cylinder, the horizontal ribbon appeared to be painted on the convex surface of the cylinder—the ribbon was captured by the binocular disparity or by the motion parallax of the elements defining the 3-D surfaces. This was not true, however, for the vertical ribbon superimposed on either the stereo or the KD cylinders: regardless of its position on the cylinder, this ribbon was always perceived at the zero-disparity reference plane. These observations (which can be verified by navigating to the webpages given earlier) are borne out in the data.[(1)]

Depth-probe data for each condition (stereo versus KD; horizontal versus vertical ribbon; edge/middle/center position) were fitted with a cumulative Gaussian function by probit analysis (Finney 1971). Results appear in figure 3a; we averaged results for the two observers, since the pattern of results was identical for both. Each data point corresponds to the disparity (average of the two observers) associated with 50% point on the psychometric function (the disparity at which the probe was subjectively equal in depth to the ribbon). Consider first the stereo cylinder. At the middle of this cylinder, the perceived depth of the horizontal ribbon, gauged by the stereo probe, was slightly less than the 5 min of arc disparity associated with the center of the cylinder. This small discrepancy may arise from limitations in the spatial resolution of the graphics board and monitor. The perceived depth of the vertical ribbon was unaffected by the stereo cylinder at any of the three positions—this ribbon always appeared at the zero-disparity reference plane and, when situated at the center of the cylinder, appeared within the interior the cylinder at its axis of rotation.

Similar results for both observers were obtained in the KD condition. It is noteworthy that the KD cylinder and the ribbon were presented monocularly and therefore had

[(1)] It is natural to wonder whether depth capture is observed when the surface of the cylinder appears concave, not convex. The answer is impossible to obtain in the case of a KD cylinder for, even though the implied depth is ambiguous, observers nearly always see the cylinder surface as convex. It is, of course, simple to create a stereo cylinder with graded uncrossed disparities simulating a concave surface. While we did not collect complete psychometric functions on this condition, our observations lead us to conclude that a concave surface, like a convex one, can impart curvature in depth to the horizontally oriented ribbon; readers may confirm this observation using figure 1c.

no explicit binocular disparity. Aside from dot motion, are there other cues that might impart depth to the ribbon? It is known that luminance differences among elements can imply depth ordering (Dosher et al 1986), but the luminance of the ribbon cannot account for our results. In preliminary measurements, the perceived depth planes of both ribbons (vertical and horizontal) positioned in the center of cylinder were measured in a static condition where none of the dots moved and consequently no cylindrical surface was perceived ('no motion' condition, right-hand panel in figure 3a). For this control condition both ribbons were perceived at zero-depth reference plane, even though ribbon luminance was equivalent to that used in the KD condition. This result is not surprising and merely replicates earlier work by others (Collett 1985; Buckley et al 1989). When the 'cylinder' was created by animating the random dots, the 3-D shape of the horizontal ribbon almost immediately assumed a curved appearance. For both observers, however, the 3-D appearance of the vertical ribbon was unaffected by the 3-D structure of the KD cylinder. The magnitude of perceived curvature of the horizontal ribbon superimposed on the KD cylinder was slightly less than the perceived curvature measured with the stereo cylinder. This is not particularly surprising, since we did not try to match the perceived cylindrical curvature of the two conditions. Consequently, the 3-D shape of the horizontal ribbon will not necessarily be the same in the two conditions.

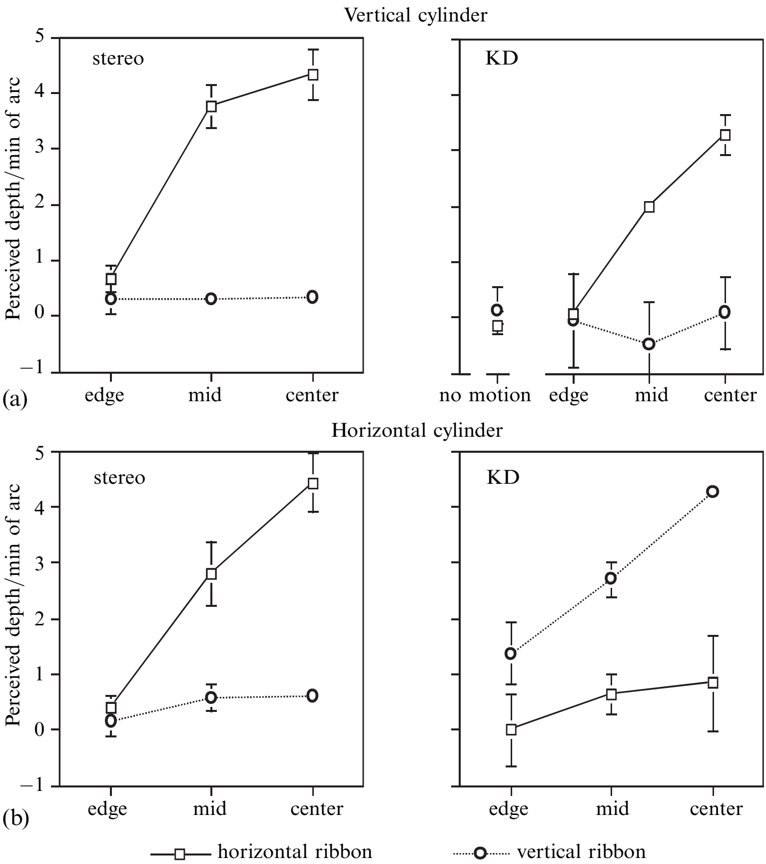


Figure 3. Results (mean of two observers, with ± 1 SE) from depth-probe procedure used to assess perceived surface curvature/depth. The inducing object—a cylinder—was defined either by stereopsis or by motion parallax (KD), and depth of the ribbon was measured at three positions relative to the cylinder: its edge, the center of curvature, and a point midway between the edge and center. In (a) the axis of rotation of curved cylinder was vertical; in (b) the axis of rotation of curved cylinder was horizontal.

The important point is that in both conditions the horizontal ribbon appeared bowed in depth toward the observer, its shape conforming to the curvature of the cylinder.

Others have hypothesized that stereo capture results from the spread of disparity signals (Mather 1989; Ishigushi and Wolfe 1993). Of course, the KD cylinder does not explicitly portray disparity, which would seem inconsistent with this hypothesis. However, it has been proposed that neural mechanisms registering KD are also disparity-selective (eg Nawrot and Blake 1991b), and there is neurophysiological evidence for exactly this kind of neural integration of stereo and motion signals in visual area MT (Maunsell and Van Essen 1983; Bradley et al 1995). Perhaps the spread of signals within disparity-selective mechanisms accounts for depth capture by the KD cylinder. Stereo capture is, of course, vividly observed with static stereograms, whereas depth capture from KD involves moving dots. We tend to think of MT as a visual area specialized for motion analysis (Britten et al 1996). However, at least some neurons in area MT respond to stationary dots imaged at a given disparity (DeAngelis et al 1998), so our conjecture about the possible role of MT in depth capture is not inconsistent with known physiological properties in this visual area.

But why is the vertical ribbon immune to capture? In the case of the stereo cylinder, the two half-images of the ribbon were always imaged with zero disparity, which would unambiguously specify depth for the vertical ribbon but not for the interior regions of the horizontal ribbon. Evidently the mechanism underlying depth capture operates primarily on image features whose depth is ambiguous. This account, however, leaves unexplained the failure of the KD cylinder to capture the monocularly viewed vertical ribbon when it appeared centered on the cylinder. The depth of that ribbon is potentially ambiguous, yet the ribbon always appeared within the interior of the cylinder, not on its surface. Of course, motion vectors in the KD display were orthogonal to the orientation of the vertical ribbon, meaning that a given dot's motion passed very quickly over the ribbon. What would happen if we repeated these measurements using stereo and KD cylinders whose axis of rotation was horizontal? Would the vertically oriented, monocular ribbon now be captured since the motion paths of the KD dots would pass over the entire length of the ribbon?

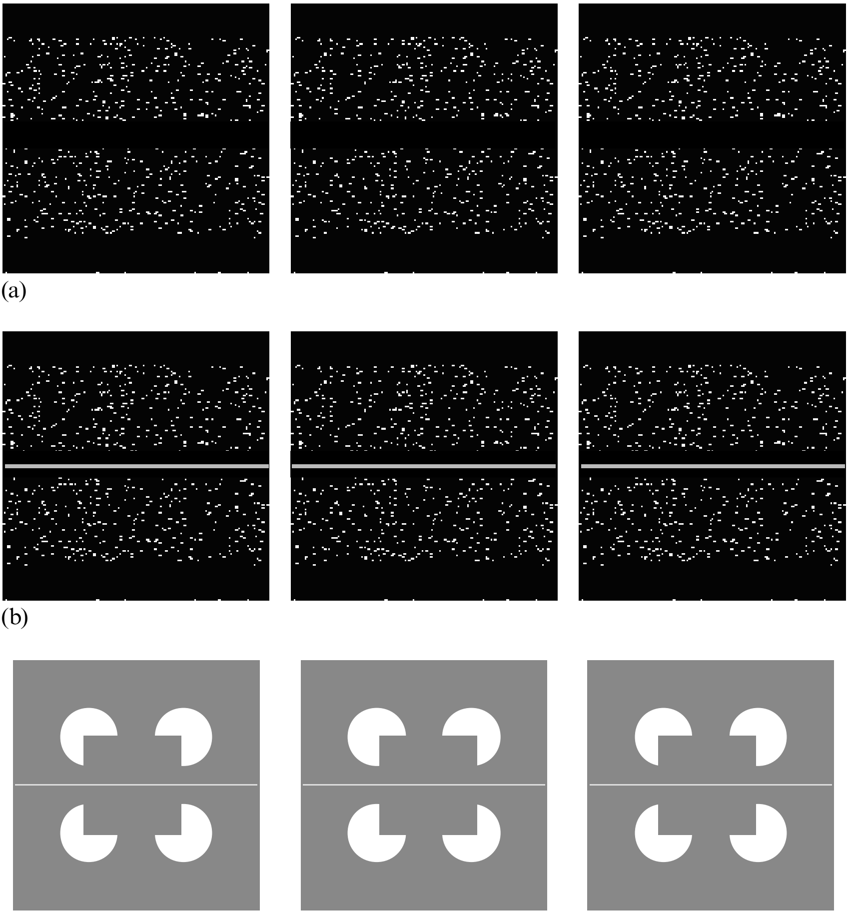
To answer this question, we repeated experiment 1 using exactly the same procedures, only now employing stereo and KD cylinders that were horizontally elongated (figure 2b).

Results from these conditions are summarized in figure 3b. Once again the stereo cylinder readily captured the horizontal ribbon (whose depth is ambiguous within its interior regions) but not the vertical ribbon (whose depth from disparity is explicitly specified by disparity). With the KD cylinder, however, the pattern of results was reversed. Now it is the vertical ribbon, but not the horizontal one, that is captured by the cylinder.[2] Evidently, then, it is the motion vectors themselves (together, perhaps, with the oriented motion paths they trace out) that impart depth information to the static, captured object, not the global surface created by those vectors. This implies that depth capture is a more local, 'low-level' process operating on explicit features in the image, not more abstract, global representations based on those features.

3 Experiment 2: Failure of depth capture within interpolated surface regions

Surfaces specified by disparity (eg Grimson 1981) or by motion parallax (Saidpour et al 1992) can appear to extend across empty regions, implying that depth signals can indeed propagate spatially. The half-images in figure 4a show a stereoscopic example of 3-D surface interpolation—upon fusion of these two half-images, one sees a single, vertically elongated cylinder with an untextured portion in the very middle. The same kind of depth interpolation is readily seen in a comparably configured KD cylinder.

[2] As an aside, both observers sometimes noted that the KD cylinder itself sometimes appeared concave, not convex, when presented together with the uncaptured, horizontal ribbon.



(a) (b) (c)

Figure 4. Depth capture within the region of an object where surface curvature must be interpolated. (a) Extrapolated surface is seen within the untextured portion of a stereo-defined cylinder (which is not surprising since the untextured portion could be construed as a black, horizontal ribbon). (b) Depth capture is not observed within the extrapolated region of the stereo cylinder; instead, the presence of the object within this region destroys surface extrapolation of the cylinder. (c) Failure of stereo capture within a Kanizsa-type stereogram where the resistant object (a single horizontal line) falls within a region of the stereogram where neighboring disparities are not explicitly defined. The note in the caption to figure 1 on binocular fusion of the half-images applies also to this figure.

Can this interpolated 3-D surface capture ambiguous portions of the horizontal ribbon? An answer to this question would have bearing on the nature of the depth signals supporting capture.

3.1 *Method*

The apparatus and procedure for measuring depth of the horizontal ribbon were identical to those used in the experiment 1. The stimuli were the same as those used in experiment 1 except that an untextured, blank area subtending 32 min $\times$ 1 deg 35 min was introduced across the horizontal extent of the center of a simulated cylinder—this was accomplished simply by removing random dots within this region of the display. With both KD and stereo presentation, observers still perceived one entire cylinder, not two short ones separated by a gap.

We tested only with the horizontal ribbon, since the previous experiment showed that explicit depth signals cannot capture the vertical ribbon. Once again, we used the briefly flashed disparity probe to assess depth of the horizontal ribbon at three positions within the cylinder.

Observers in this experiment were KK (who also participated in experiment 1) and JL (who did not serve in experiment 1, but experienced strong depth capture under the same conditions as KK when viewing the displays used in experiment 1).

3.2 *Results and discussion*

For neither observer did the horizontal ribbon appear curved in depth—depth-probe estimates did not differ significantly from zero disparity at any position along the cylinder (see stereogram in figure 4b). Evidently, depth signals producing an interpolated 3-D surface are impotent as captors. In fact, the horizontal ribbon annulled the appearance of an extrapolated surface—observers often perceived two smaller cylinders separated by a gap with a flat 'ribbon' running through it.

Failure of depth capture by an interpolated 3-D surface at first glance seems inconsistent with the stereo capture in Kanizsa-type stereograms like the one illustrated in figure 1a. After all, in these displays repetitive elements within the interior of the illusory figure are also pulled into depth even though there are no explicit disparity cues specifying that depth plane. Suppose, however, we modify the Kanizsa-type stereogram to isolate the elements in the central region from elements within the regions associated with the sectored disks that explicitly specify disparity—this maneuver more nearly approximates the interpolation condition tested in our experiment. As can be seen in the stereogram in figure 4c, a horizontal line within this blank region now appears to lie on the same depth plane as the background, just as in our KD and stereo displays. This implies that it is the proximity of the ambiguous elements to unambiguous ones that governs the effectiveness of depth capture. Thus, depth capture within the interior of a Kanizsa-type stereogram can be explained by the influence of depth signals associated with the upper and lower rows of elements whose depth is inherited from that specified by the disparity of the sectored disks. This conclusion is entirely in line with conclusions drawn by Mitchison (1988) on the importance of spatial proximity in stereoscopic depth perception.

4 Conclusion

As summarized in section 1, earlier work has documented ways in which stereopsis and KD are comparable and interrelated. The present results reveal another point of similarity but, also, disclose a way in which they are different. Three-dimensional surfaces specified either by disparity or by motion parallax can readily capture image features that are potentially ambiguous with respect to 3-D surface assignment. While not incontrovertible proof, this equivalence adds further weight to the idea that KD and stereopsis involve comparable neural operations that specify surface layout in 3-D. At the same time, there exist conditions where depth capture does occur with stereopsis but does not occur with KD, and vice versa. So stereopsis—at least static stereopsis—and KD are not strictly equivalent.

Acknowledgements. We thank Sang-Hun Lee and Jung-Yoon Lee for participating in these experiments. The work was supported by grants from NIH (EY07760 and EY01826) and from the Discovery Program (Vanderbilt University). KK was supported by a postdoctoral training fellowship from the Korea Research Foundation.

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