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Judging distance across texture discontinuities

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Abstract. Sinai et al (1998 *Nature* **395** 497 – 500) showed that less distance is perceived along a ground surface that spans two differently textured regions than along a surface that is uniformly textured. We examined the effect of texture continuity on judged distance using computer-generated displays of simulated surfaces in five experiments. Discontinuities were produced by using different textures, the same texture reversed in contrast, or the same texture shifted horizontally. The simulated surface was either a ground plane or a frontoparallel plane. For all textures and both orientations, less distance was judged in the discontinuous conditions than in continuous conditions. We propose that when a surface contains a texture discontinuity, a small area adjacent to the perceived boundary is excluded from judged distances.

1 Introduction

Gibson (1946, page 420) proposed that "the problem of three-dimensional vision is basically a problem of the perception of a *continuous surface* (his italics) which is seen to extend away from the observer". This hypothesis became the basis for Gibson's 'ground theory' (1950b, page 6). Gibson (1946) asserted that retinal gradients provide the stimulus information for the perception of continuous surfaces. One of these gradients is the retinal gradient of texture, based on the relative size of texture elements and of the spaces between the elements in the projected image of a receding or slanting surface. The magnitude of the gradient is related to the slant of the surface (Gibson 1950a). Thus, the density of the texture elements provides information for the perception of distance, and the rate of increase of the density of the elements provides information for the perception of slant (Gibson 1950a). Since Gibson's formulation of ground theory, a large body of research has affirmed the relationship between surface texture and the perception of slant and distance (see Howard and Rogers 2002; Sedgwick 1986, 2001 for reviews).

In the last few years there has been an increased interest in the influence of the ground surface on the perception of spatial layout. Basing their ideas on Gibson's ground theory, Sinai et al (1998) proposed that, since the ground surface is a regularity in the visual world, the human visual system might use this regularity as a reference frame for the coding of distance. They suggest that this would be an efficient manner of coding location, since it can be based upon a "quasi-two-dimensional coordinate system" with respect to the ground surface, rather than upon a three-dimensional coordinate system (Sinai et al, page 497). One prediction of this hypothesis is that visual grouping and segregation ought to be more efficient when the stimuli are arranged on the ground surface, rather than on other environmental surfaces. This prediction was supported in a study by McCarley and He (2000) who found that reaction times in a detection task were faster when the targets were located in the ground plane rather than in the ceiling plane. He and Ooi (2000) found that underestimation of surface

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slant in binocular disparity displays produces underestimation of the depth separation of objects on or near that surface. This provides evidence that the ground surface serves as a reference frame for processing binocular disparity information (He and Ooi 2000).

Meng and Sedgwick (2001) suggested that objects at different locations can normally be related to one another through a series of contact relations among objects, intermediate surfaces, and the ground surface. They found that observers were efficient at determining distance relationships based on these contact relations. As the series of contact relations became more complex, distance perception suffered, suggesting that the local spatial relations between objects and the surfaces on which they rest are not fully integrated with the global spatial relations of the scene as a whole (Meng and Sedgwick 2002).

Gibson's (1950b) ground theory stresses the importance of a continuous ground surface in the perception of distance. The presence of a continuous texture on a ground surface may be useful in extracting information about distance and slant, but environmental surfaces may not be covered by uniform textures. The environment may contain ground surfaces containing regions of grass, sand, cobblestones, and many other substances. Where a region composed of one substance borders on a region composed of another substance, there is a discontinuity in the texture of the ground surface. This raises the question how the presence of a discontinuity in the texture of the ground surface affects the perception of distance over that surface. Sinai et al (1998) examined this question in outdoor experiments in which the ground surface either was continuous, was interrupted by a gap, or was separated into two differently textured regions. In the continuous condition, the ground was homogeneously textured. In the gap condition, the ground texture was interrupted by a 0.5-m deep and 1.3-m wide gap. In the distinct regions condition, the ground between the observer and the target had two textured regions, one containing grass and one containing concrete. Two tasks were used. In the blindfolded walking task, the observer viewed the target, was then blindfolded and turned 90°, and walked the remembered distance. In the perceptual matching task, the observer viewed the target, then turned 90°, and instructed the experimenter to adjust the location of another object to match the remembered distance of the target. The two tasks produced similar results. The perceived egocentric distance to objects across the continuous ground surface was accurate, whereas egocentric distance perception was impaired when the ground surface contained either a gap or a texture discontinuity. Specifically, when the ground surface contained a gap, distance was overestimated, and when it contained two distinct textures, distance was underestimated. This underestimation occurred regardless of which of the two textures was closer to the observer.

Wu et al (2002) replicated the results of Sinai et al (1998) in a virtual-reality environment using a perceptual matching task. Yarbrough et al (2002) also found an underestimation of perceived distance when distinct textures were present using a perceptual matching task, but not with a blindfolded walking task. Wu et al (2002) and Yarbrough et al (2002) proposed that the underestimation occurs because of an intrinsic bias in the visual system to perceive a ground surface as slanted with its far end upward. Ooi et al (2002) asserted that a ground surface will be perceived with a 0° slant (that is, 90° slant relative to the line of sight) only when sufficient depth cues are present. Whenever depth cues are insufficient, the slant bias will take effect. Wu et al and Yarbrough et al developed a 'surface integration hypothesis' to explain why distance is underestimated across a surface containing distinct textures. According to this hypothesis, the visual system uses near depth cues to determine the local geographical slant of a patch of the surface near the observer. Where the surface is continuous, the slant determined from the local patch is extrapolated over the more distant part of the surface, in a process called surface integration. This provides accurate perception of the distance to an object when the interval between the observer and the object contains a continuous texture. However, when there is a discontinuity in the texture, the visual system does not extend the slant determined from the local patch across the discontinuity. Instead, the visual system relies on the intrinsic slant bias to provide the slant of the surface on the other side of the discontinuity. Thus, when an object is located across a discontinuity from the observer, the greater slant in the distant region produces underestimation of the distance (Wu et al 2002; Yarbrough et al 2002).

We will refer to the perception of less distance in an interval along a surface when the interval contains a texture discontinuity as the 'discontinuity effect'. Although there are now several studies demonstrating the discontinuity effect, the underlying conditions for this effect have not been systematically examined. The previous research suggests two issues that require further investigation. The first issue is what type of texture differences must be present in regions of the ground surface in order for the discontinuity effect to occur. If the defining property in this effect is the discontinuity in the texture, then the particular properties that distinguish the two textures should not be of primary importance. However, if the discontinuity effect is based on distinctions in the sizes or shapes of texture elements in the regions, then the type of textures would be important. We examined conditions in which the two textures (a) consisted of texture elements which were quite different in size and shape, (b) consisted of texture elements which were the same in size and shape but differed in contrast polarity, and (c) were exactly the same but offset horizontally to produce a discontinuity.

The second issue is whether the discontinuity effect is specifically a depth effect, or whether it occurs more generally (such as in a frontoparallel plane). If the effect is explained by difficulties in depth perception that occur when a texture discontinuity is present, then no discontinuity effect should occur in the perception of frontoparallel intervals. The surface integration hypothesis, accordingly, would predict a discontinuity effect in depth only. Another possibility, however, is that any texture discontinuity, whether in depth or frontoparallel, leads to an underestimation of distance intervals along the surface. Since a major motivation for the study of surface texture discontinuities has been Gibson's ground theory, it is important to determine whether the surface containing the discontinuity must be a ground surface receding in depth. For these reasons, the present experiments will consider both three-dimensional (3-D) scenes and frontoparallel (2-D) displays. We will also examine the generality of the previous findings by using judgments of exocentric distance, rather than egocentric distance, as in the previous research.

In experiments 1 through 3, each display consisted of a simulation of a ground plane translating horizontally with objects positioned on it. Observers estimated the perceived distance between two objects on the plane that were separated in depth. In experiments 4 and 5, the displays were stationary and frontoparallel. Each display consisted of a textured plane with dots positioned on it. Observers estimated the perceived distance between two dots that were separated vertically. In all experiments, both continuous and discontinuous surfaces were used. In experiment 1, the discontinuous ground surface consisted of two differently textured regions. In experiment 2, the discontinuous ground surface contained two textured regions, but the two textures contained texture elements that were the same in size and shape, varying only in contrast polarity. In experiment 3, the discontinuous ground surface consisted of two regions of exactly the same texture, with one region shifted horizontally. Experiment 4 used the same textures as experiment 3, but in the frontoparallel plane. Experiment 5 used the same textures as experiment 2, but in the frontoparallel plane.

2 Experiment 1

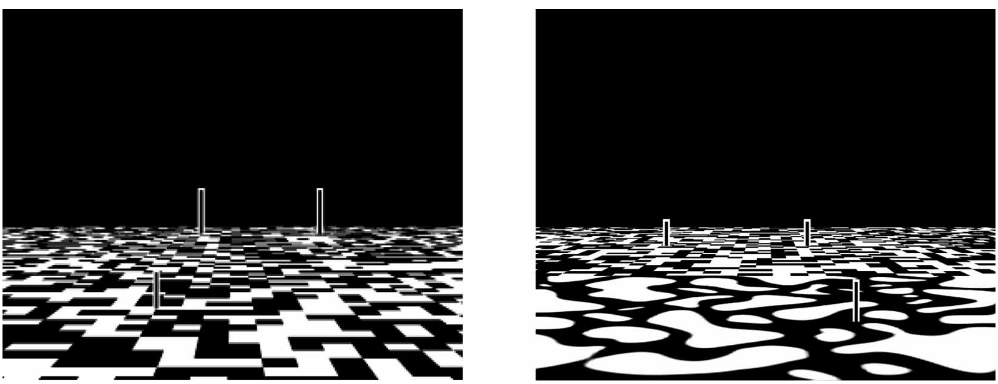
In the first experiment we attempted to replicate the discontinuity effect found in previous studies, using a simulated scene and exocentric depth judgments. The ground plane in this experiment consisted either of a uniform texture or of two differently textured regions (front and back). This configuration was similar to those used by Sinai et al (1998) and Wu et al (2002) in their experiments consisting of displays with two distinct textured regions. Depth in the scene was specified both by texture gradient information and by motion parallax. Motion parallax was used to enhance the perceived depth in the scene.

2.1 *Method*

2.1.1 *Observers.* The observers were four students from the University of California, Irvine. All observers had normal or corrected-to-normal visual acuity. None of the observers was familiar with the hypotheses of the experiment.

2.1.2 *Design.* The independent variables were (a) the type of texture in the front region (rectangle or blob pattern), (b) continuity of the back region with the front region (same or different textures in the two regions), (c) simulated distance of the front pole from the observer (780 or 858 cm), and (d) simulated distance between the back pole and the front pole (923 or 1229 cm). All variables were run within observers. Observers were presented with 10 replications of the 16 conditions (2 front textures $\times$ 2 continuity conditions $\times$ 2 front pole distances $\times$ 2 depth intervals). The dependent variable was the judged distance from the front pole to the back pole (cm). The order of presentation of the trials was random, and different for each observer. Observers were given 80 practice trials at the beginning of the experiment.

2.1.3 *Stimuli.* The displays consisted of simulated scenes containing a black and white textured ground plane with a slant of 90° extending 2392 cm in depth. (The dimensions of the simulated scene were calculated by using an eye height for the seated observer of 116 cm.) Three red poles were located on the plane (see figure 1). One pole was located in the front of the scene, the second pole was located directly behind it, and the third pole was located either to the left or the right of the second pole. (We will refer to these poles as the front, back, and side poles, respectively.) The heights of the poles in the image were varied randomly between 1.1 deg and 2.7 deg visual angle, to avoid size information for the distances to the poles. In the simulation, the front pole was either 780 or 858 cm from the observer, and the back pole was located at either 923 or 1229 cm from the front pole. The reason for the variations in front-pole distance and



(a) (b)

Figure 1. Examples of stimuli used in experiment 1. (a) A continuous ground surface with a rectangle texture. (b) A discontinuous ground surface with a blob texture in the front region and a rectangular texture in the back region. The red poles in the actual displays are shown as black poles, outlined in white.

the depth interval was primarily to prevent the observers from comparing distances among the trials. The distance between the eye and the display was 85 cm. The display was 30 deg wide by 24 deg high. The ground plane was 30 deg wide and 9 deg high.

In the simulation, the front region extended from 553 cm to 1664 cm from the observer. The back region extended from 1664 cm to 2392 cm from the observer. The entire scene translated back and forth horizontally, 111 cm in each direction (in the 3-D simulation), at a rate of 14 s per cycle. At the beginning of each trial, the front and back poles were located at the horizontal center of the display.

Two different texture patterns were used. One texture consisted of rectangular tiles randomly colored black or white. The rectangles had a width of 25.4 cm and a depth of 28.6 cm in the simulation. The other texture consisted of irregularly shaped white blobs on a black background. The blobs varied in width between 13 and 163 cm and in depth between 20 and 182 cm.

2.1.4 *Apparatus.* The displays were presented on a 21-inch (53 cm) flat screen CRT monitor with a pixel resolution of 1280 by 1024, controlled by a Windows workstation. The displays on the monitor were 38.2 cm wide and 30 cm high. A viewing hood covered the edges of the monitor. Observers viewed the displays binocularly through a 19-cm diameter collimating lens, which magnified the image by approximately 19%. The distance between the eye and the lens was 10.0 cm.

2.1.5 *Procedure.* Observers were run individually in a darkened room. They were instructed to use a joystick to adjust the location of the side pole, so that the distance between the side pole and the back pole matched the perceived distance between the front pole and the back pole. They were allowed to take as much time as they needed to make their responses. The observers were instructed to press a button on the joystick when they were satisfied with their response. This initiated the next trial.

2.2 *Results and discussion*

The mean judged depth interval was calculated for each observer for the 16 conditions and analyzed in an analysis of variance (ANOVA). The judged depth intervals were considerably smaller than the simulated depth intervals. This is consistent with the established finding that depth intervals are perceived as shorter than equal frontal intervals (eg Loomis et al 1992; Loomis and Philbeck 1999).

The main effect of continuity on judged distance was significant ($F_{1,3} = 12.8$, $p < 0.05$). Judged distance was greater when the ground surface consisted of one homogeneous texture ($M = 340.6$ cm) than when it consisted of different textures in the front and back regions ($M = 333.5$ cm). The judged distances for the continuous and discontinuous conditions are shown averaged across observers in figure 2 and for individual observers in figure 3. The mean judged distance was greater in the continuous condition than in the discontinuous condition for all four observers. A separate, single-subject analysis for each observer yielded $F_{1,9} = 16.1$, $p < 0.01$; $F_{1,9} = 7.7$, $p < 0.05$; $F_{1,9} = 0.39$, $p > 0.05$; and $F_{1,9} = 2.51$, $p > 0.05$, respectively, for the four observers for the main effect of continuity.

The main effect of the location of the front pole on the judged distance between the two poles was also significant ($F_{1,3} = 12.2$, $p < 0.05$). More distance was judged when the front pole was closer to the observer. The mean judged distances for the 780 and 858 cm front-pole locations were 345.2 and 329.6 cm, respectively. This result is consistent with several previous studies that have shown that the farther a depth interval is from the observer, the less depth will be perceived in that interval (Andersen et al 1998; Loomis et al 1992; Loomis and Philbeck 1999; Sauer et al 2001).

Finally, the main effect of the simulated distance between the front and back poles was significant ($F_{1,3} = 75.1$, $p < 0.01$). Judged distance was greater when simulated

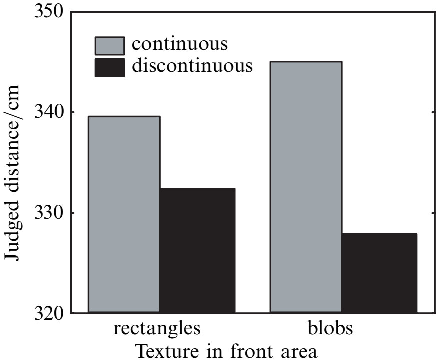


Figure 2. Judged distance as a function of continuity and front texture averaged across observers in experiment 1.

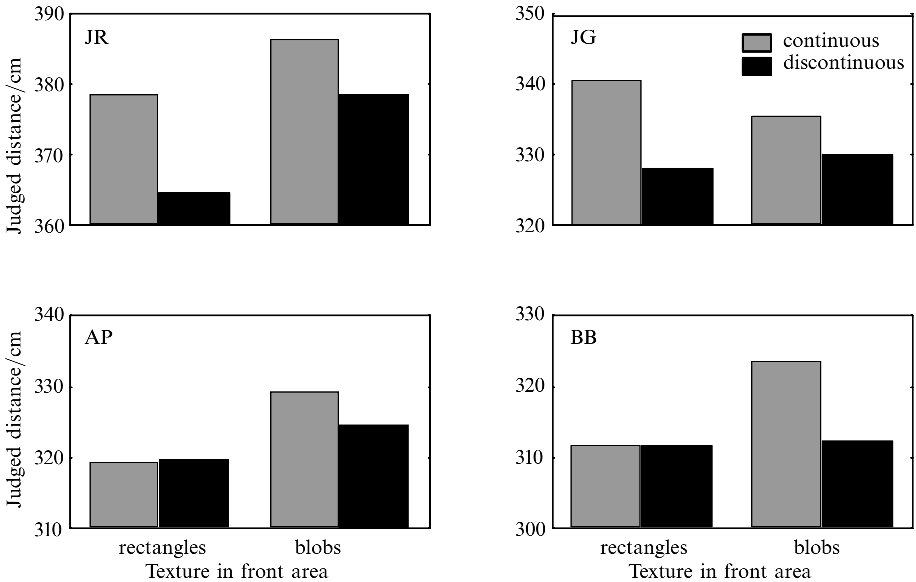


Figure 3. Judged distance as a function of continuity and front texture for individual observers in experiment 1.

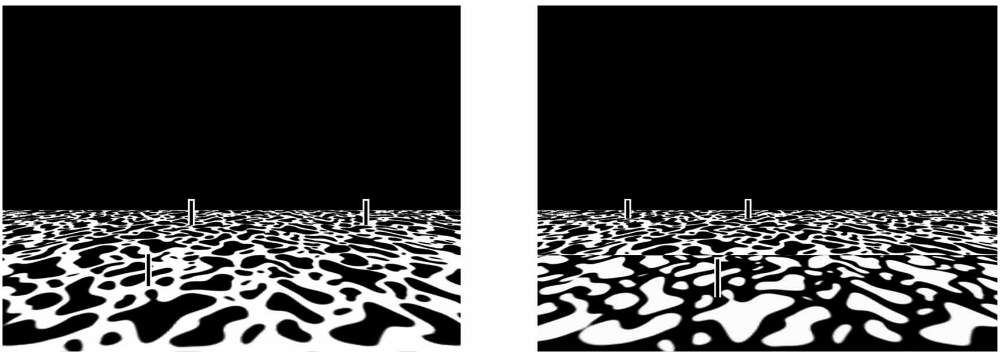
distance was greater. The mean judged distances for the 923 and 1229 cm pole separations were 296.4 and 378.3 cm, respectively. The type of texture present in the front region did not produce a significant main effect on the judged separation between the poles ($F_{1,3} = 4.5$, $p > 0.05$). There were no significant interactions between any of the variables. This experiment successfully replicated the finding of previous investigators that perceived distance is decreased when two distinct texture regions are present, relative to conditions in which the ground texture is homogeneous (Sinai et al 1998; Wu et al 2002).

The two objects that were separated in depth in this experiment were located in regions that differed in texture, and this could have been a factor in the difference in judgments in the discontinuous and continuous conditions. We conducted a control study in which the ground surface in the discontinuous condition was divided into three regions, with the same texture in the near and far regions and a different texture in the intermediate region. The poles that were separated in depth were thus in regions with the same texture, but there was a discontinuity in the surface between the two poles. As in the main experiment, judged distance was greater in the continuous condition than in the discontinuous condition ($F_{1,4} = 16.1$, $p < 0.05$). Wu et al (2002) and Yarbrough et al (2002) reported results for a related condition in their experiments on texture occlusion discontinuities. In Wu et al's experiment, a simulated brick wall stood between the observer and the target, occluding part of the ground texture. In Yarbrough et al's experiments a black box or a black cloth covering the ground occluded part of the texture. In perceptual matching tasks, in both of these studies there was an understimation of the discontinuous condition with respect to the continuous condition.

Our use of an adjustment in horizontal extent to measure the perceived depth extent raises the possibility that a texture discontinuity alters the perceived horizontal extent that the observer is asked to adjust, rather than the perceived depth extent, or alters both perceived extents. Suppose, for example, that the depth interval appeared larger in the discontinuous case. The horizontal interval should then appear more distant and a given projected horizontal interval would represent a larger horizontal extent in 3-D. The horizontal interval would then have to be made smaller to match the perceived depth extent. We have several reasons for discounting this possibility. First, the direction of our results matches those of Sinai et al (1998), who used both walking and judged distances to measure perceived egocentric distance. Second, in experiments 4 and 5 both the vertical extent being judged and the adjusted horizontal extent were frontal and there is no reason to expect that a discontinuity in the vertical extent would affect the perception of a horizontal extent which is exactly the same in the continuous and discontinuous conditions.

3 Experiment 2

In experiment 1, as in Sinai et al's (1998) study, the texture discontinuity was produced by including two regions with textures that differed in the shapes and sizes of the texture elements. The present experiment was designed to check whether the discontinuity effect also occurs when the textures in both regions consist of elements that are the same in shape and size. In experiment 2, we address this issue by using the blob texture from experiment 1 in one region and its reversed-contrast counterpart (see figure 4) in the other region.



(a) (b)

Figure 4. Examples of stimuli used in experiment 2. (a) A continuous ground surface with a black blob texture. (b) A discontinuous ground surface with a white blob texture in the front region and a black blob texture in the back region. The red poles in the actual displays are shown as black poles, outlined in white.

3.1 *Method*

3.1.1 *Observers.* The observers were three students from the University of California, Irvine. All observers had normal or corrected-to-normal visual acuity. None of the observers was familiar with the hypotheses of the experiment.

3.1.2 *Design.* The independent variables were (a) the type of texture in the front region (black blobs on white background or white blobs on black background), (b) continuity of the back region with the front region (same or different textures in the two regions),

(c) simulated distance of the front pole from the observer (780 or 858 cm), and (d) simulated distance between the back pole and the front pole (923 or 1229 cm). All variables were run within observers

3.1.3 *Stimuli.* The stimuli were similar to those used in experiment 1, with the following exception. In both of the textures, the blobs varied in width between 7 and 72 cm and in depth between 7 and 78 cm in the 3-D simulation.

3.1.4 *Apparatus and procedure.* The apparatus and procedure were the same as in experiment 1.

3.2 *Results and discussion*

An ANOVA showed a significant main effect of continuity on judged distance ($F_{1,2} = 68.7$, $p < 0.05$). Judged distance was greater when the ground surface consisted of one homogeneous texture ($M = 402.4$ cm) than when it consisted of different textures in the front and back regions ($M = 390.0$ cm). The judged distances for the continuous and discontinuous conditions are shown in figure 5 averaged across observers and are shown in figure 6 for individual observers. The mean judged distance was greater in the continuous condition than in the discontinuous condition for all three observers. A separate, single-subject analysis for each observer yielded $F_{1,9} = 19.2$, $p < 0.01$; $F_{1,9} = 20.2$, $p < 0.01$; and $F_{1,9} = 9.4$, $p < 0.05$, respectively, for the three observers for the main effect of continuity.

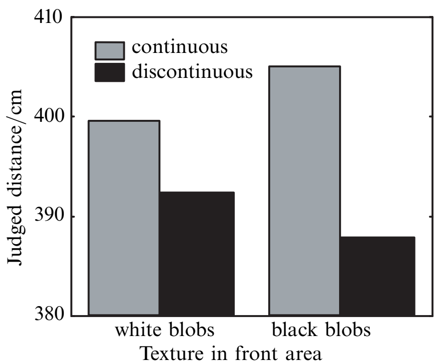


Figure 5. Judged distance as a function of continuity and front texture averaged across observers in experiment 2.

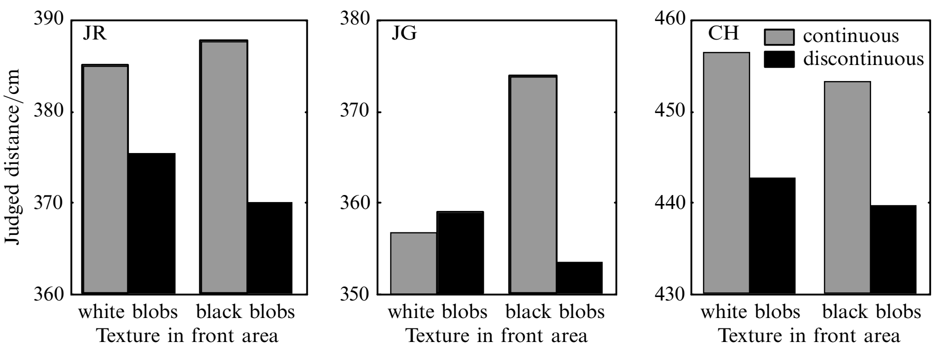


Figure 6. Judged distance as a function of continuity and front texture for individual observers in experiment 2.

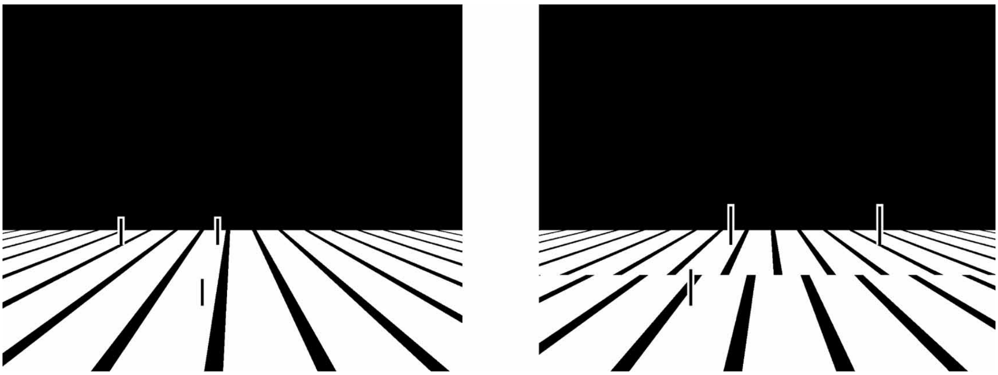
The main effect of the location of the front pole was significant ($F_{1,2} = 27.6$, $p < 0.05$). The mean judged distances for the 780 and 858 cm front pole locations were 405.6 and 387.4 cm, respectively. There was also a significant main effect of the simulated distance between the front and back poles ($F_{1,2} = 284.7$, $p < 0.01$). The mean judged distances for the 923 and 1229 cm pole separations were 342.6 and 449.8 cm, respectively.

The type of texture present in the front region did not produce a significant main effect ($F_{1,2} = 0.038$, $p > 0.05$). There were no significant interactions.

These results indicate that the discontinuity effect occurs even when the texture elements are the same size and shape in both regions. This suggests that the discontinuity effect is likely to be a result of the discontinuity in the textured surface, rather than a result of differences between the two textures. However, it is possible that differences in contrast polarity are related to the discontinuity effect. In order to eliminate all potential differences in the textures in the two regions, we used exactly the same texture in both regions in experiment 3.

4 Experiment 3

This experiment addressed the issue whether the discontinuity effect will occur if the two textured regions contain exactly the same texture. The texture that was used consisted of black parallel lines on a white background (see figure 7). In the continuous condition, the lines were continuous over the ground surface. In the discontinuous condition, the lines were offset horizontally near the center of the surface.



(a) (b)

Figure 7. Examples of stimuli used in experiment 3. (a) A continuous ground surface. (b) A discontinuous ground surface with offset parallel lines. The red poles in the actual displays are shown as black poles, outlined in white.

4.1 *Method*

4.1.1 *Observers.* The observers were five students from the University of California, Irvine. All observers had normal or corrected-to-normal visual acuity. None of the observers was familiar with the hypotheses of the experiment.

4.1.2 *Design.* The independent variables were (a) the horizontal position of the front texture, (b) continuity of the back region with the front region (lines continuous or offset), (c) simulated distance of the front pole from the observer (780 or 858 cm), and (d) simulated distance between the back pole and the front pole (923 or 1229 cm). All variables were run within observers.

4.1.3 *Stimuli.* The stimuli were similar to those used in experiment 1, with the following exceptions. Only one texture was used—the parallel lines texture. In the 3-D simulation, the width of each black line was 12.4 cm and the distance between the black lines was 61.8 cm. In the discontinuous condition, one region was shifted horizontally with respect to the other region by one half the distance between the black stripes.

4.1.4 *Apparatus and procedure.* The apparatus and procedure were the same as in experiment 1.

4.2 *Results and discussion*

An ANOVA showed a significant main effect of continuity on judged distance ($F_{1,4} = 41.5$, $p < 0.01$). Judged distance was greater when the ground surface consisted of a continuous texture ($M = 336.1$ cm) than when it contained a texture discontinuity ($M = 314.6$ cm). The judged distances for the continuous and discontinuous conditions are shown in figure 8, averaged across observers, and in figure 9 for individual observers. The mean judged distance was greater in the continuous condition than in the discontinuous condition for all five observers. A separate, single-subject analysis for each observer yielded $F_{1,9} = 45.1$, $p < 0.01$; $F_{1,9} = 8.4$, $p < 0.05$; $F_{1,9} = 66.4$, $p < 0.01$; $F_{1,9} = 106.6$, $p < 0.01$; and $F_{1,9} = 79.3$, $p < 0.01$, respectively, for the five observers for the main effect of continuity.

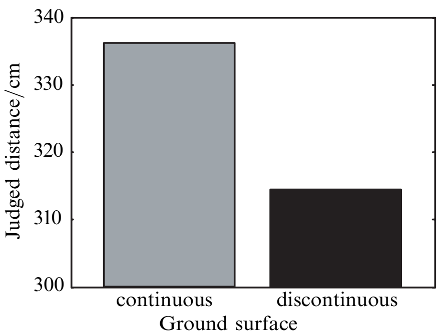


Figure 8. Judged distance as a function of continuity averaged across observers in experiment 3.

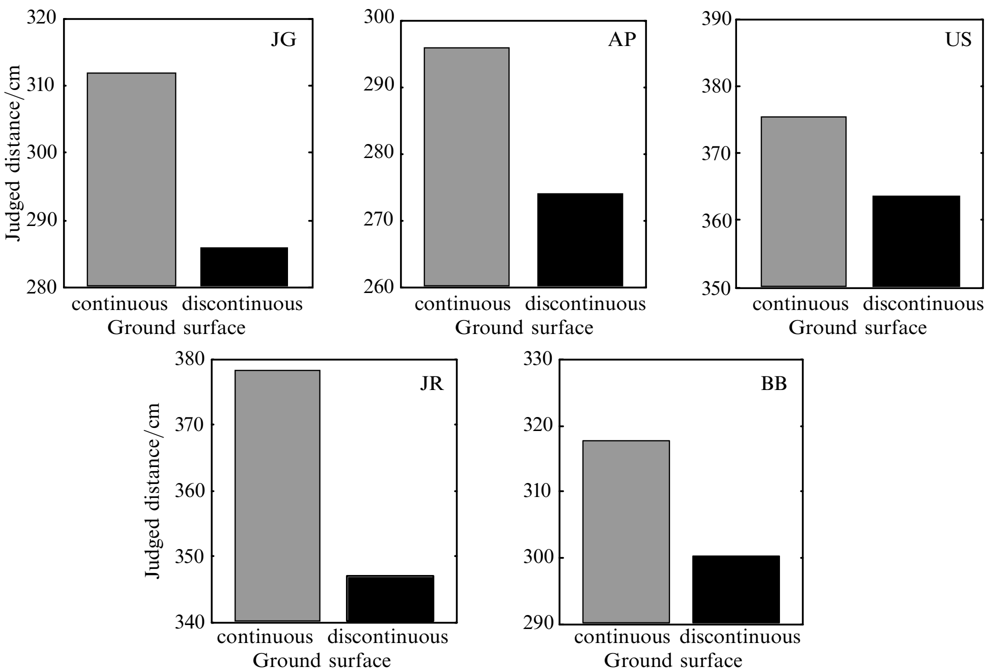


Figure 9. Judged distance as a function of continuity for individual observers in experiment 3.

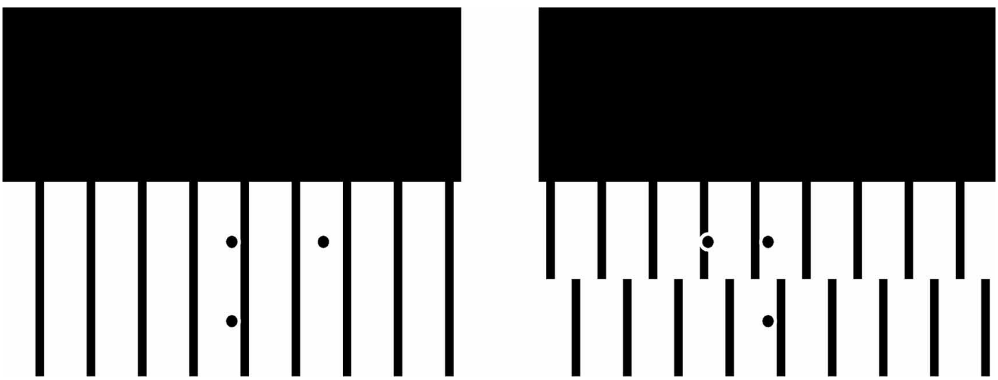
The main effect of the location of the front pole was significant ($F_{1,4} = 25.2$, $p < 0.01$). The mean judged distances for the 780 and 858 cm front pole locations were 331.5 and 319.2 cm, respectively. There was also a significant main effect of the simulated distance between the front pole and the back pole ($F_{1,4} = 120.4$, $p < 0.001$). The mean judged distances for the 923 and 1229 cm pole separations were 290.6

and 360.1 cm, respectively. The horizontal position of the texture in the front region did not produce a significant main effect ($F_{1,4} = 0.034$, $p > 0.05$). A significant interaction was found between continuity and the location of the front pole ($F_{1,4} = 18.3$, $p < 0.05$), with the effect of continuity greater for the near position. The mean judged distances for the 780 cm pole location were 344.5 and 318.5 cm for the continuous and discontinuous conditions, respectively. The mean judged distances for the 858 cm pole location were 328.3 and 310.1 cm for the continuous and discontinuous conditions, respectively. There were no other significant interactions between variables.

The results show that the discontinuity effect occurs even if the discontinuity does not involve a change in the type of texture. The results of experiments 2 and 3 together provide strong evidence that the discontinuity effect is not due to differences between the two regions in the shapes or sizes of the texture elements. Rather, the effect appears to be due to the presence of the discontinuity in the textured surface.

5 Experiment 4

Experiments 1 through 3 demonstrate that the discontinuity effect occurs for the perception of intervals along a plane extending in the depth dimension. The effect could be due to factors that are specific to depth extents, or to more general factors affecting extents at all orientations. In order to address this issue, in experiment 4 we used a frontoparallel surface rather than a surface extended in depth (see figure 10). The intervals judged by observers were now height intervals instead of depth intervals. If the discontinuity effect does not occur for intervals along a frontoparallel surface, then the effect is likely to be due to factors that are specific to depth extents. However, if the discontinuity effect does occur under these circumstances, then the effect is likely to be due to other, more general properties of texture discontinuities.



(a) (b)

Figure 10. Examples of stimuli used in experiment 4. (a) A continuous surface. (b) A discontinuous surface with offset parallel lines. The red dots in the actual displays are shown as black dots, outlined in white.

In experiment 4 we used a texture consisting of vertically oriented parallel lines, similar to the texture used in experiment 3. The lines were either continuous over the frontoparallel surface or interrupted by a horizontal offset. The discontinuous condition produced a stimulus that is similar to the abutting grating illusion, in which abutting gratings of lines produce an illusory contour at the texture discontinuity. This illusion was first presented by Kanizsa (1974) and has since been studied by many researchers (eg von der Heydt and Peterhans 1989; Soriano et al 1996). Observers in experiment 4 matched the separation of two vertically aligned dots (the 'top' dot and the 'bottom' dot) by adjusting the separation between the top dot and a third dot (the 'side' dot), aligned horizontally with the top dot.

5.1 *Method*

5.1.1 *Observers.* The observers were four students from the University of California, Irvine. All observers had normal or corrected-to-normal visual acuity. Three (ZB, RN, and HZ) had knowledge of the purpose of the research; one (JR) was naïve.

5.1.2 *Design.* The independent variables were (a) the horizontal position of the bottom texture, (b) continuity of the top region with the bottom region (lines continuous or offset), (c) height of the bottom dot (4.3 or 5.2 cm), and (d) distance between the bottom dot and the top dot (small or large). All variables were run within observers. Observers were presented with 10 replications of the 16 conditions (2 bottom texture positions × 2 continuity conditions × 2 bottom dot heights × 2 distance intervals). The dependent variable was the judged distance from the bottom dot to the top dot (cm). The order of presentation of the trials was random and different for each observer. Observers were given 10 practice trials at the beginning of the experiment.

5.1.3 *Stimuli.* The displays consisted of a stationary frontoparallel surface. Three red dots of diameter 0.9 cm were present on the surface. The bottom dot was either 4.3 or 5.2 cm from the bottom of the display. These positions were the same as the projected positions of the front poles in experiments 1 through 3. The top dot could be located at a small or a large distance from the bottom dot. The distances were the same as the projected distances between the front and back poles in experiments 1 through 3. Because the simulated depth intervals were matched in experiments 1 through 3, the separation of the dots was different for the two positions of the bottom dot. To match the projected pole positions in experiments 1 through 3, the small and large distances were set at 5.5 cm and 6.2 cm when the height of the bottom dot was 4.3 cm, and 4.8 cm and 5.4 cm when the height of the bottom dot was 5.2 cm. The side dot was located at the same height as the top dot. The visual angle of the display was 30 deg by 24 deg. The distance between the eye and the display was 85 cm.

The bottom region extended from the bottom of the display to a height of 7.6 cm. The top region extended from 7.6 cm to 15.2 cm. The visual angle of the surface was 30 deg by 12 deg. The height of the discontinuity in experiment 4 was the same as the projected height of the discontinuity in experiments 1 through 3.

The black lines had a width of 0.7 cm and the distance between the black lines was 3.5 cm. Nine lines were visible in the top and bottom regions. In the discontinuous condition, either the bottom or the top texture was shifted horizontally by one half the distance between the black stripes.

5.1.4 *Apparatus and procedure.* The apparatus and procedure were the same as in experiment 1 with the following exception. Observers were instructed to use the joystick to adjust the location of the side dot, so that the distance between the side dot and the top dot matched the perceived distance between the bottom dot and the top dot.

5.2 *Results*

An ANOVA showed a significant main effect of continuity on judged distance ($F_{1,3} = 140.5$, $p < 0.01$). Judged distance was greater when the surface consisted of continuous texture ($M = 7.19$ cm) than when it contained a texture discontinuity ($M = 6.66$ cm). The judged distances for the continuous and discontinuous conditions are shown averaged across observers in figure 11 and for individual observers in figure 12. The mean judged distance was greater in the continuous condition than in the discontinuous condition for all four observers. A separate, single-subject analysis for each observer yielded $F_{1,9} = 118.9$, $p < 0.01$; $F_{1,9} = 176.0$, $p < 0.01$; $F_{1,9} = 55.0$, $p < 0.01$; and $F_{1,9} = 46.2$, $p < 0.01$, respectively, for the four observers for the main effect of continuity.

There was also a significant main effect of the location of the bottom dot ($F_{1,3} = 1152.9$, $p < 0.001$). Judged distance was greater when the bottom dot was

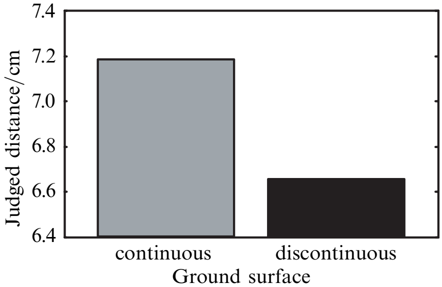


Figure 11. Judged distance as a function of continuity averaged across observers in experiment 4.

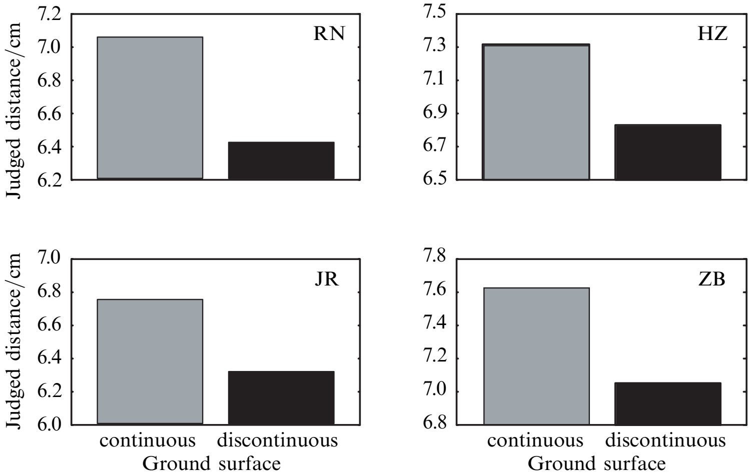


Figure 12. Judged distance as a function of continuity for individual observers in experiment 4.

at the lower height in the display. This is not surprising, because the 2-D separation of the top and bottom dots varied with the position of the bottom dot (in order to match the pole positions in the 3-D simulation used in experiments 1 – 3). The mean judged distances for the 4.3 and 5.2 cm bottom-dot locations were 7.38 and 6.47 cm, respectively. A significant interaction was found between continuity and the location of the bottom dot ($F_{1,3} = 12.3$, $p < 0.05$). The mean judged distances for the 4.3 cm dot location were 7.68 and 7.09 cm for the continuous and discontinuous conditions, respectively. The mean judged distances for the 5.2 cm dot location were 6.70 and 6.23 cm for the continuous and discontinuous conditions, respectively. This indicates that there was a larger effect of continuity when the bottom dot was located at the lower height.

The main effect of the distance between the bottom and top dots was significant ($F_{1,3} = 823.6$, $p < 0.001$). Judged distance was greater for the large distance intervals ($M = 7.29$ cm) than for the small distance intervals ($M = 6.56$ cm). The horizontal position of the texture present in the bottom region did not produce a significant main effect ($F_{1,3} = 0.095$, $p > 0.05$). There were no other significant interactions.

5.3 *Discussion*

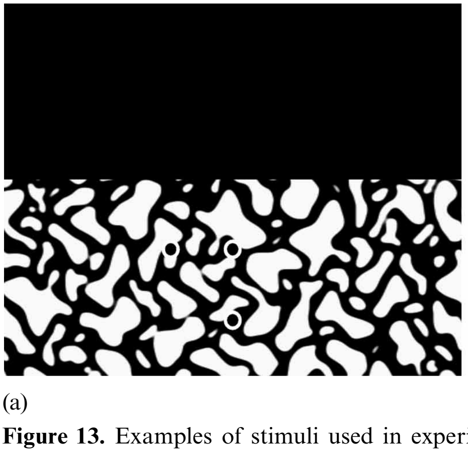
These results indicate that the discontinuity effect is not limited to surfaces extending in depth and to judgments in the depth dimension. The discontinuity effect also occurs for judgments along a frontoparallel plane. Apparently, the discontinuity effect is due to some general property of texture discontinuities that is not specific to depth extents.

The judged intervals were considerably larger than the simulated intervals. This overestimation is consistent with the horizontal – vertical illusion (eg Coren and Girgus 1978; Kunnapas 1955a; Prinzmetal and Gettleman 1993; Robinson 1972). Another explanation for the observed overestimation is the framing effect, in which the perceived length of a line decreases as the size of a surrounding frame increases (Kunnapas 1955b). Since in the present experiment the display was wider than it was high, the variable horizontal interval would be expected to be underestimated with respect to the vertical interval.

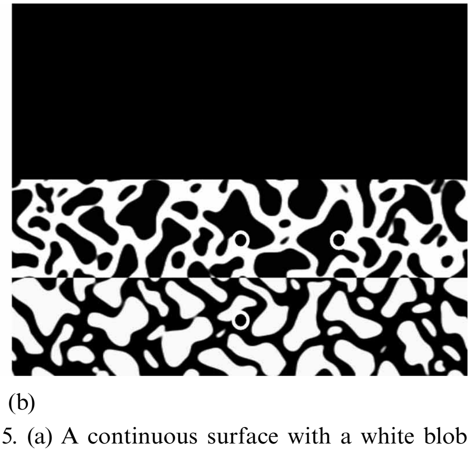
In the discontinuous condition, the texture discontinuity at the border between the two regions produces an illusory horizontal contour, which crosses the vertical interval between the bottom and top dots (eg Kanizsa 1974). When the contour was present (in the discontinuous condition) the judged distance was found to be smaller than when the contour was not present (in the continuous condition). This finding is in opposition to the well-known Oppel–Kundt illusion, also called the filled-space illusion, in which a divided interval is perceived as longer than an equivalent undivided interval (Coren and Girgus 1978; Robinson 1972). The Oppel–Kundt illusion has been established by a number of studies (Bulatov et al 1997; Long and Murtagh 1984; Suzuki and Arashida 1992). However, there are also a few studies which have shown a reverse Oppel–Kundt illusion (Obonai 1954; Tedford and Gray 1976; Tedford and Murphy 1978) when the intervals are relatively large and there is only one dividing element. In this case, the divided interval is perceived as shorter than the equivalent undivided interval. Several studies have demonstrated a related effect called the bisection illusion (Harris et al 1974; Kunnapas 1955a; Masin and Vidotto 1983), in which a line that is bisected by a perpendicular line is judged as shorter than a line that is not bisected. The reversed Oppel–Kundt illusion and the bisection illusion are consistent with the discontinuity effect, but there are no established explanations of these illusions.

6 Experiment 5

Experiment 4 showed that the discontinuity effect occurs in a frontoparallel plane as well as in depth. In order to verify that this result was not specific to the parallel line texture, we replicated experiment 4 with the blob texture studied in experiment 2. As in experiment 2, the two textured regions in the discontinuous condition consisted of the same blob texture, reversed in contrast in one region (see figure 13).



(a)



(b)

Figure 13. Examples of stimuli used in experiment 5. (a) A continuous surface with a white blob texture. (b) A discontinuous surface with a white blob texture in the bottom region and a black blob texture in the top region. The red dots in the actual displays are shown as black dots, outlined in white.

6.1 *Method*

6.1.1 *Observers.* The observers were five students from the University of California, Irvine. All observers had normal or corrected-to-normal visual acuity. Three (ZB, RN, and HZ) had knowledge of the purposes of the research; two (JR and CH) were naïve.

6.1.2 *Design.* The independent variables were (a) the type of texture in the bottom region (black blobs on white background or white blobs on black background), (b) continuity of the bottom region with the top region (same or different textures in the two regions), (c) height of the bottom dot (4.3 or 5.2 cm), and (d) distance between the bottom dot and the top dot (small or large). Otherwise, the design was the same as in experiment 4.

6.1.3 *Stimuli.* The stimuli were the same as in experiment 4, with the following exception. The two texture patterns were irregularly shaped white blobs on a black background, and irregularly shaped black blobs on a white background. In both of the textures, the blobs varied in width and height between 0.5 and 6 cm.

6.1.4 *Apparatus and procedure.* The apparatus was the same as in experiment 1. The procedure was the same as in experiment 4.

6.2 *Results and discussion*

An ANOVA showed a significant main effect of continuity on judged distance ($F_{1,4} = 22.2$, $p < 0.01$). Judged distance was greater when the surface consisted of one homogeneous texture ($M = 7.18$ cm) than when it consisted of different textures in the bottom and top regions ($M = 6.90$ cm). The judged distances for the continuous and discontinuous conditions are shown averaged across observers in figure 14 and for individual observers in figure 15. The mean judged distance was greater in the continuous condition than in the discontinuous condition for all five observers. A separate, single-subject analysis for each observer yielded $F_{1,9} = 25.1$, $p < 0.01$; $F_{1,9} = 227.1$, $p < 0.01$; $F_{1,9} = 72.9$, $p < 0.01$; $F_{1,9} = 3.03$, $p > 0.05$; and $F_{1,9} = 22.6$, $p < 0.01$, respectively, for the five observers for the main effect of continuity.

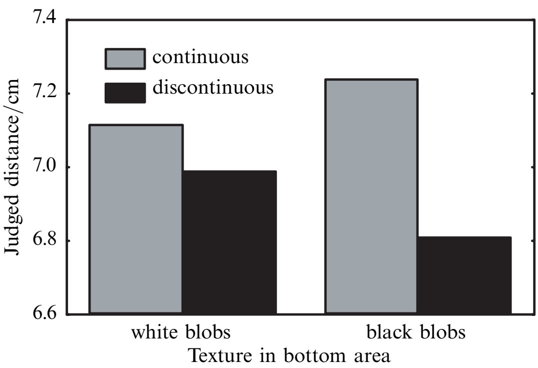


Figure 14. Judged distance as a function of continuity and bottom texture averaged across observers in experiment 5.

The main effect of the location of the bottom dot was significant ($F_{1,4} = 351.5$, $p < 0.001$). The mean judged distances for the 4.3 and 5.2 cm bottom-dot locations were 7.43 and 6.65 cm, respectively. There was also a significant main effect of the distance between the bottom and top dots ($F_{1,4} = 385.5$, $p < 0.001$). The mean judged distances for the small and large dot separations were 6.68 and 7.40 cm, respectively. The type of texture present in the bottom region did not produce a significant main effect ($F_{1,4} = 0.309$, $p > 0.05$). A significant interaction was found between continuity and the type of texture in the bottom region ($F_{1,4} = 34.2$, $p < 0.01$). The mean judged distances when the white blob texture was in the bottom region were 7.12 and 6.99 cm for the continuous and discontinuous conditions, respectively. The mean judged distances when the black blob texture was in the bottom region were 7.24 and 6.81 cm for the continuous and discontinuous conditions, respectively. This indicates that there

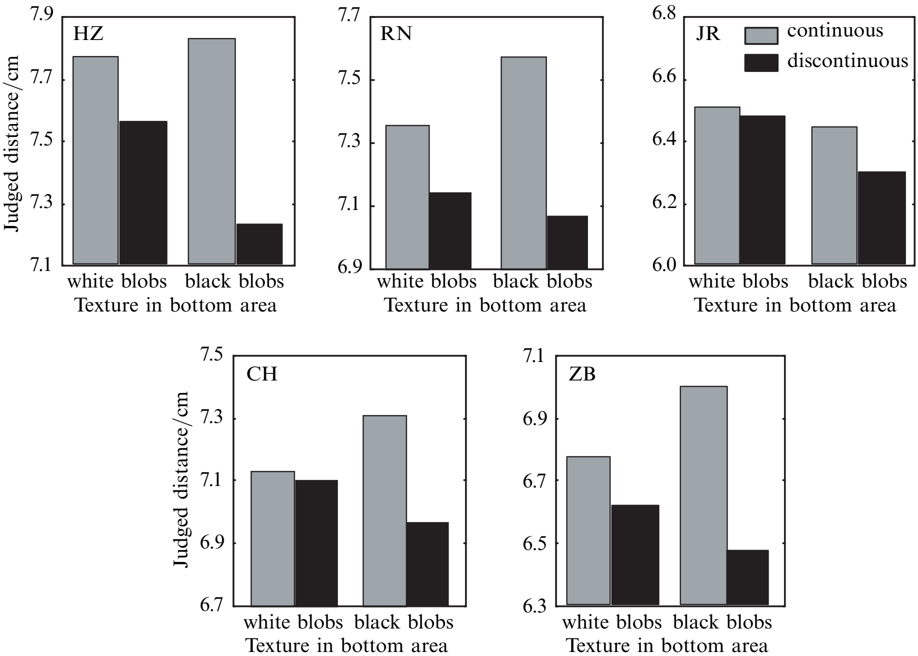


Figure 15. Judged distance as a function of continuity and bottom texture for individual observers in experiment 5.

was a larger effect of continuity when the bottom texture was black blobs on a white background. There were no other significant interactions between variables.

These results demonstrate that the 2-D discontinuity effect found in experiment 4 is not limited to discontinuities produced by horizontally displaced regions in parallel line textures. The discontinuity effect occurs with very different types of textures in 2-D displays, as well as in displays simulating 3-D scenes.

7 General discussion

In the present experiments we investigated the 'discontinuity effect', in which less distance is perceived in an interval along a surface when the interval contains a texture discontinuity. The first issue addressed by the experiments was whether there are limitations in the types of textures that must be present in the different regions of the surface in order for the discontinuity effect to occur. Discontinuous conditions were investigated in which the two textures (a) consisted of texture elements which were quite different in size and shape, (b) consisted of texture elements which were the same in size and shape but different in contrast polarity, and (c) were exactly the same, but one region was shifted horizontally. Regardless of the types of texture present in the two regions, discontinuous surfaces produced less perceived distance than did continuous surfaces. This result indicates that differences in the texturing of the two regions cannot be the primary cause of the discontinuity effect. Rather, it suggests that the discontinuity in the texture is the defining property that produces the decrease in judged distance.

The second issue addressed was whether the discontinuity effect is specifically a depth effect, or whether it occurs more generally. We found a discontinuity effect in three experiments with 3-D scenes and two experiments with frontoparallel displays, indicating that this effect cannot be explained solely by difficulties in depth perception that occur when a texture discontinuity is present in a surface extending in depth. Rather, it suggests that there is likely to be a general property of all texture discontinuities that produces underestimation of distance intervals regardless of the orientation of the surface relative to the observer. The surface integration hypothesis (Wu et al 2002; Yarbrough et al 2002) provides a possible explanation of the discontinuity effect in the depth dimension, but it cannot account for the occurrence of the discontinuity effect in a frontoparallel plane.

In the surface integration hypothesis, distance is judged in a single step when the texture is continuous and in two steps when the texture is discontinuous. We propose a similar account, except for the explanation why the results of the two measurements, one up to the boundary and the other from the boundary to the target, do not add up to the result of the single measurement. Although the boundary mathematically is a line with no extent in the direction across which the judgment is made, perceptually it may occupy a small amount of space. If a small amount of space immediately adjacent to the boundary was not included in the distance computation, the sum of the distance to the boundary and the distance from the boundary to the target would be less than the distance measured in a single step. This proposed explanation, while speculative, can account for the results of the present experiments and for previous results showing a discontinuity effect. It predicts that the discontinuity effect will occur whenever a boundary is present in the interval to be judged, regardless of whether there is a change in texture type. The explanation also predicts that the discontinuity effect will occur whether a surface is extended in depth, frontoparallel, or at any other orientation relative to the observer.

There was some variation in the magnitude of the discontinuity effect across the five experiments. The simulated distances were different in the 3-D and 2-D displays, so to compare the results of all five experiments we calculated the discontinuity effect as a percentage of the simulated distance, that is, $100 \times$ (judged distance in the continuous condition − judged distance in the discontinuous condition)/simulated distance. The discontinuity effect expressed as a percentage of the simulated distance (with 95% confidence limits) was 0.65 ($\pm$0.35), 1.13 ($\pm$0.27), 2.03 ($\pm$0.62), 9.65 ($\pm$1.59), and 5.07 ($\pm$2.11) in experiments 1 – 5, respectively. This comparison indicates that the effect was smaller for the 3-D displays than for the 2-D displays. Among the 3-D displays, the effect was smallest for the textures with the different shape elements, largest with the same texture in both regions offset horizontally, and intermediate for the reverse contrast textures. Similarly, the discontinuity effect was larger for the 2-D displays with the horizontally offset striped texture than with the reverse contrast texture. It may seem surprising that the discontinuity effect was greatest when the textures were most similar in the two regions, but it is likely that the salience of the boundary in the discontinuous displays, and not the difference between the textures, determined the size of the effect. The horizontally offset regions of striped texture appear to have produced the most salient boundary—a strong subjective contour between the two regions.

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