

8-1-2000

The Perception of Ordinal Depth Relationship from Static and Deforming Boundary Contours

Shane Raines

Western Kentucky University

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THE PERCEPTION OF ORDINAL DEPTH RELATIONSHIPS FROM
STATIC AND DEFORMING BOUNDARY CONTOURS

A Thesis

Presented to

the Faculty of the Department of Psychology

Western Kentucky University

Bowling Green, Kentucky

In Partial Fulfillment

of the Requirements for the Degree

Master of Arts

by

Shane Ryan Raines

August 2000

THE PERCEPTION OF ORDINAL DEPTH RELATIONSHIPS FROM
STATIC AND DEFORMING BOUNDARY CONTOURS

Date Recommended 7/17/2000

J. Farley Norman
Director of Thesis

Joy Phillips

Scott Phillips

Elmer Gray 8/8/00
Dean, Graduate Studies and Research Date

Acknowledgments

First and foremost, I must thank the director of this thesis, Dr. J. Farley Norman, for his direction, support, and dedication throughout my study at Western. I could not have asked for a better advisor and mentor than Dr. Norman. I would also like to thank the other members of my committee, Dr. Joseph Bilotta and Dr. Scott Richter, for their suggestions and for introducing me to the fields of neuroscience and statistics. Lastly, I wish to thank my family for their love and encouragement.

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THE PERCEPTION OF ORDINAL DEPTH RELATIONSHIPS FROM
STATIC AND DEFORMING BOUNDARY CONTOURS

Shane Ryan Raines

August 2000

37 Pages

Directed by: J. Farley Norman, Ph.D., Joseph Bilotta, Ph.D., and Scott Richter, Ph.D.

Department of Psychology

Western Kentucky University

Previous investigations of the perception of 3-D shape from deforming boundary contours have focused on judgments of global shape (Cortese & Anderson, 1991), judgments of rigid vs. nonrigid motion (Norman & Todd, 1994), and object recognition (Norman, Dawson, & Raines, 2000). Raines and Norman (1999) provided the first study demonstrating that deforming boundary contours could support the accurate perception of local 3-D surface structure. The present set of experiments extend the Raines and Norman study by further investigating whether the distance from the boundary contour or the amount of overall boundary deformation affect the human ability to make local judgments about 3-D shape. In these experiments, the observers viewed either static or moving silhouettes of randomly shaped, smoothly curved objects (see Raines & Norman, 1999; Norman & Todd, 1996, 1998) before making ordinal depth judgments about two highlighted regions on the object's surface. Two local regions on the objects' surface were highlighted, and the observers were required to judge which of the two regions was closer to them in depth. In Experiment 1, the proximity of the highlighted regions to the objects' occlusion boundary was manipulated as well as the presence or absence of binocularly disparate views. Viewing regions closer to the boundary contour led to more precise judgments of ordinal depth than those regions further away. The results also

showed that the presence of disparate views had a different effect on the two motion types. While stereoscopic views improved performance dramatically in the stationary conditions, the same disparities had little effect on performance in the motion conditions. In Experiment 2, the observers viewed apparent motion sequences that presented varying degrees of boundary deformation. Although performance decreased as the amount of deformation decreased, the observers' judgments remained relatively precise even at the smallest angles of oscillation. In summary, these results confirm previous findings showing that boundary contours, especially deforming contours, are an important source of information about 3-D shape. These results also show that information from the boundary contour propagates inward to regions far from the boundary and that even small amounts of deformation can support the accurate perception of ordinal depth.

Chapter 1

Introduction

Many sources of optical information contribute to the perception of an object's 3-D shape. These sources of information include binocular disparity (Wheatstone, 1838; Julesz, 1971; Norman, Lappin, & Zucker, 1991), motion (Braunstein, 1976; Todd & Norman, 1991), texture, shading, specular highlights (Todd, 1985; Norman, Todd, & Phillips, 1995), and the projected 2-D shape of an object's boundary contour (Richards, Koenderink, & Hoffman, 1987; Norman, Dawson, & Raines, 2000). Most of these sources have been extensively studied in psychophysical experiments. However, the importance of the boundary contour, especially deforming contours, for the perception of 3-D shape remains virtually unstudied.

To understand the possible importance of the contour for the perception of 3-D shape, imagine a person looking towards a 3-D object. Rays of light that are tangent to this object's surface (i.e., that just graze its surface) and which pass through the nodal point of the observer's eyes touch the object along a smooth space curve called the rim (Koenderink, 1984). This 'rim' is a 3-D space curve that separates visible surface regions from invisible ones (Norman & Todd, 1994). The projection of the 3-D rim onto the 2-D retina (or onto a background plane) creates an outline or a silhouette of the object (Koenderink & van Doorn, 1982). It is this outline of the object's shape that is referred to as the boundary contour (see Figure 1).

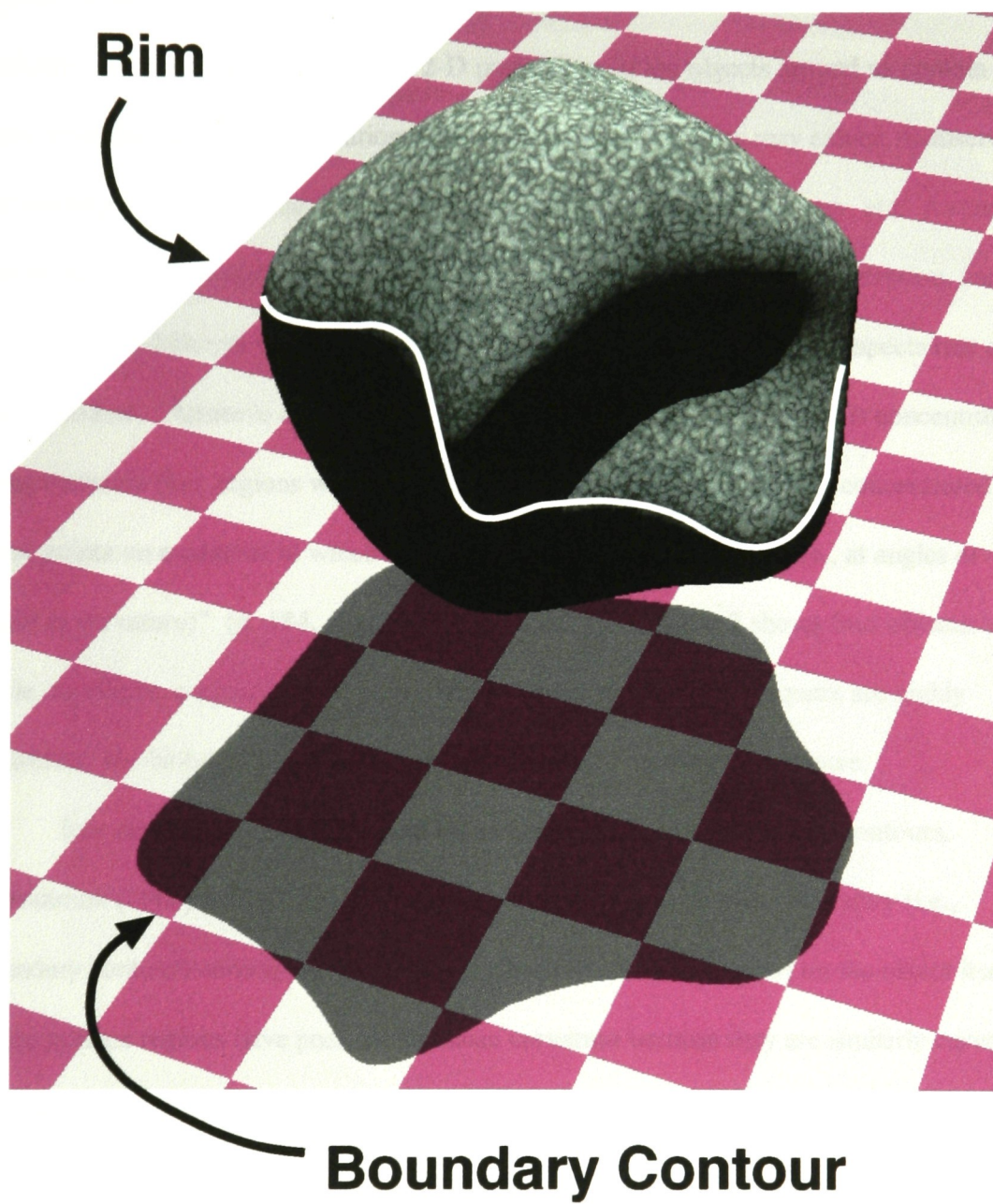


Figure 1. An illustration of how boundary contours are formed. The rim is shown in white. The projection of this rim to the checkerboard background creates a boundary contour.

In a study examining redundant visual information, Attneave (1954) made a number of very important findings relating to the information contained in boundary contours. Attneave observed that the 2-D projections of the objects around us contain many redundancies in an informational sense. These redundancies may exhibit themselves in consistencies of color, the direction or curvature of a contour, symmetry, etc. Attneave concluded that while these consistencies were relatively unimportant for perception, the majority of the information about an object's 2-D shape is contained in its aspects that are not redundant. Attneave discovered that this non-redundant "information is concentrated along contours (i.e., regions where color changes abruptly), and is further concentrated at those points on a contour at which its direction changes most rapidly (i.e., at angles or peaks in curvature)" (p. 184, also see Figure 2, p. 185). Figure 2 shows four objects: a circle, an ellipse, a square, and a blob. While the circle, ellipse, and square are highly redundant, the blob contains much more information, according to Attneave.

In a more recent analysis of the information provided by boundary contours, Koenderink (1984) proved that convex parts of an object's occlusion boundary (i.e., boundary contour) correspond to convex surface regions (i.e., bumps) on the object itself. These convex regions have positive Gaussian curvature because they are similarly curved (i.e., same sign of curvature) in orthogonal directions (Hilbert & Cohn-Vossen, 1952; Koenderink, 1990). Likewise, concave parts of an object's occlusion boundary correspond to saddle-shaped surface regions. These regions have negative Gaussian curvature due to their opposite signs of curvature in orthogonal directions. It is important to note that, in general, all smoothly curved objects can be described in terms of these two qualitatively different types of surface regions (see Figure 3). The contour, then, can

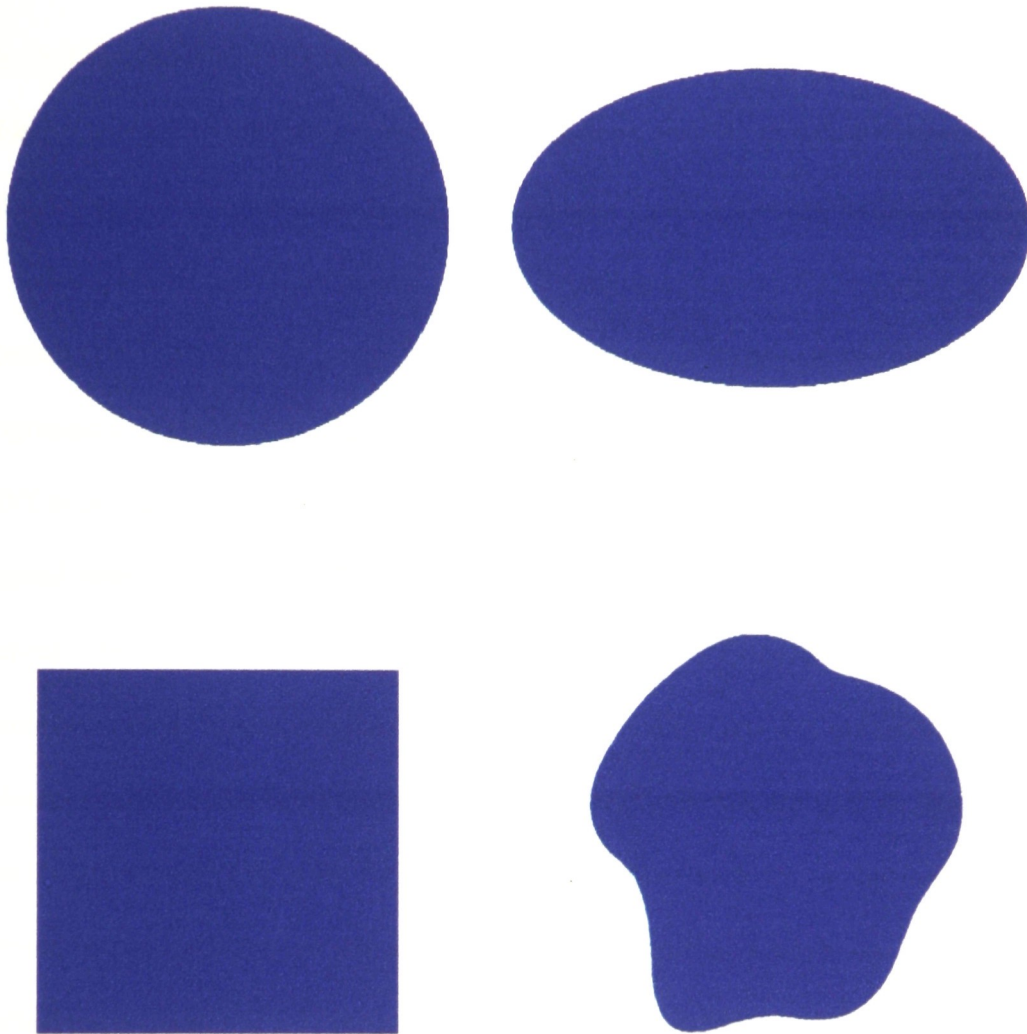


Figure 2. Four objects demonstrating the non-redundancies of each. While the circle is totally redundant after determining its contour's curvature, the other object's contours become progressively more complex and less redundant in an informational sense.

provide information about the 3-D shape of surface regions that are projecting to the contour at any given time. If an object rotates in depth, new surface regions will project to the contour, thus providing information about the shape of those regions. Therefore, if an object undergoes a full rotation in depth, it should be possible to recover information about the shape of *all* of an object's surface regions from its deforming boundary contour.

In one of the first experimental studies of moving contours, Wallach and O'Connell (1953) found that the recovery of an object's 3-D shape was possible from the orthographic 2-D projections (i.e., boundary contours) of rotating solid objects. Wallach and O'Connell used the projected contours of bent wire-frame figures and flat surfaced polygonal objects as stimuli. When the observers viewed these deforming contours, they perceived solid 3-D objects rotating in depth. Wallach and O'Connell referred to this phenomenon as the "kinetic depth effect." However, Wallach and O'Connell observed that discontinuities in the deforming contour (i.e., identifiable regions such as sharp corners) were necessary in order for the kinetic depth effect to occur. If the objects contained no discontinuities or sharp corners (e.g., ellipsoids), the observers typically perceived the sequence of 2-D projections as nonrigid deformations of an elastic figure. Thus, Wallach and O'Connell concluded that perceived 3-D structure from the deformation of smooth contours wasn't possible in the general case.

While Wallach and O'Connell (1953) observed that contour deformations produced by the rotation of smoothly curved objects in depth led to perceived nonrigid distortions, studies by Todd (1985), Cortese and Anderson (1991), and Norman and Todd (1994) all found that the deformation of smoothly curved contours can produce the perception of a rigidly rotating 3-D object. The stimuli in all of these studies were

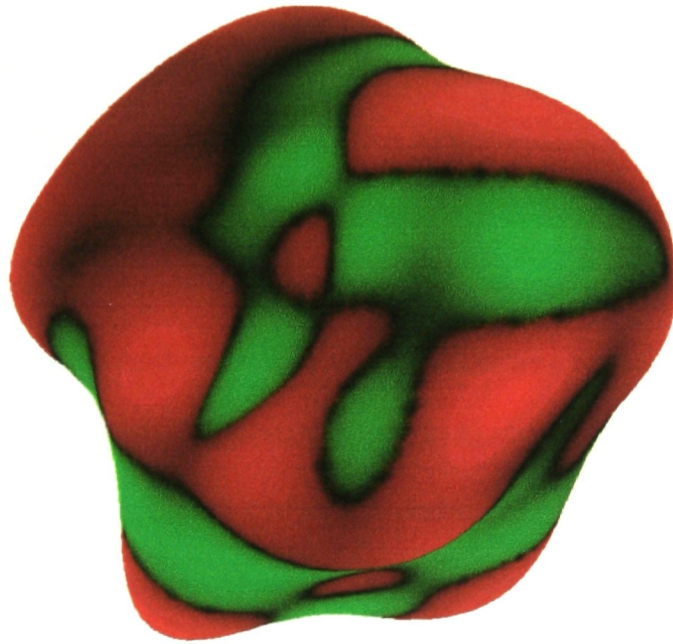


Figure 3. A smoothly curved 3-dimensional object illustrating regions of positive (red) and negative (green) Gaussian curvature. Note that regions of positive Gaussian curvature (bumps) correspond to convex regions along the boundary, while regions of negative Gaussian curvature (saddles) correspond to concave regions along the boundary.

ellipsoids, whose projections have no discontinuities or identifiable regions that could be tracked over time. Although these studies demonstrated that sharp corners or edges were not necessary for the perception of 3-D shape from motion, they did rely on overlapping ellipsoids or those with noncentral axes of rotation, object features that Attneave would consider non-redundancies. It seems that instead of the discontinuities that Wallach and O'Connell had assumed being essential, it was the non-redundancies that Attneave had referred to that were more important. Given that most objects in the 3-D world have more non-redundant features than ellipsoids, the use of ellipsoids to understand the importance of deforming boundary contours seems unusual since they are much too simplistic to generalize to most natural objects we encounter daily.

In an attempt to further understand how human observers perceive the 3-D shape of real world objects from boundary contours, Norman, Dawson, and Raines (2000) used cast shadows of naturally shaped objects (bell peppers) that underwent rigid rotations in depth. They found that the deformations of the resulting projected 2-D contours not only led to the perception of rigidly moving 3-D objects but they also were sufficiently informative for accurate object recognition to occur. The results of Norman, Dawson, and Raines also showed that accurate object recognition was invariant over the distortions in the 2-D contours caused by changes in the angle of illumination. This finding was important in that it showed that observers could recognize objects even when dramatic changes in the contour occurred due to changes in illumination angle. Obviously the information needed for recognition was not disrupted by the changes induced by varying the angle of illumination.

Since Norman, Dawson, and Raines (2000) had shown that the recovery of global aspects of 3-D shape is possible from deforming boundary contours, Raines and Norman (1999) used silhouettes of smoothly curved solid objects to determine whether observers could make *local* judgments about 3-D shape from an object's boundary contour. The stimuli were similar to those used by Norman, Todd, and Phillips (1995) and Norman and Todd (1996, 1998) (see Figure 4). The purpose of the Raines and Norman experiment differed from these previous studies in that it investigated the informativeness of boundary contours by removing all other possible sources of information about depth and shape from the stimulus displays. Their objects, defined only by their boundary contour (see Figure 5), were presented as either stationary or moving. The moving objects underwent a full 360 degrees of rotation, allowing all surface regions to come (i.e., to project) to the boundary contour at one time or another. After the movement had stopped, two points highlighting local regions on the object's surface appeared. The observers' task was to indicate which of the two regions was closer to them in depth. The distance or separation between the two highlighted regions on the object's surface was manipulated (see Figure 6). Raines and Norman found that the presence of motion (i.e., boundary deformations) dramatically increased the accuracy of the observers' judgments (i.e., lowered thresholds), while changes in separation between the local regions had smaller effects (see Figure 7). The observers were also presented with either monocular or binocular views of the deforming and static contours. Although the observers reported the binocular presentations as being more perceptually compelling, Raines and Norman found no significant differences in the accuracy of ordinal depth judgments between the monocular and binocular conditions.

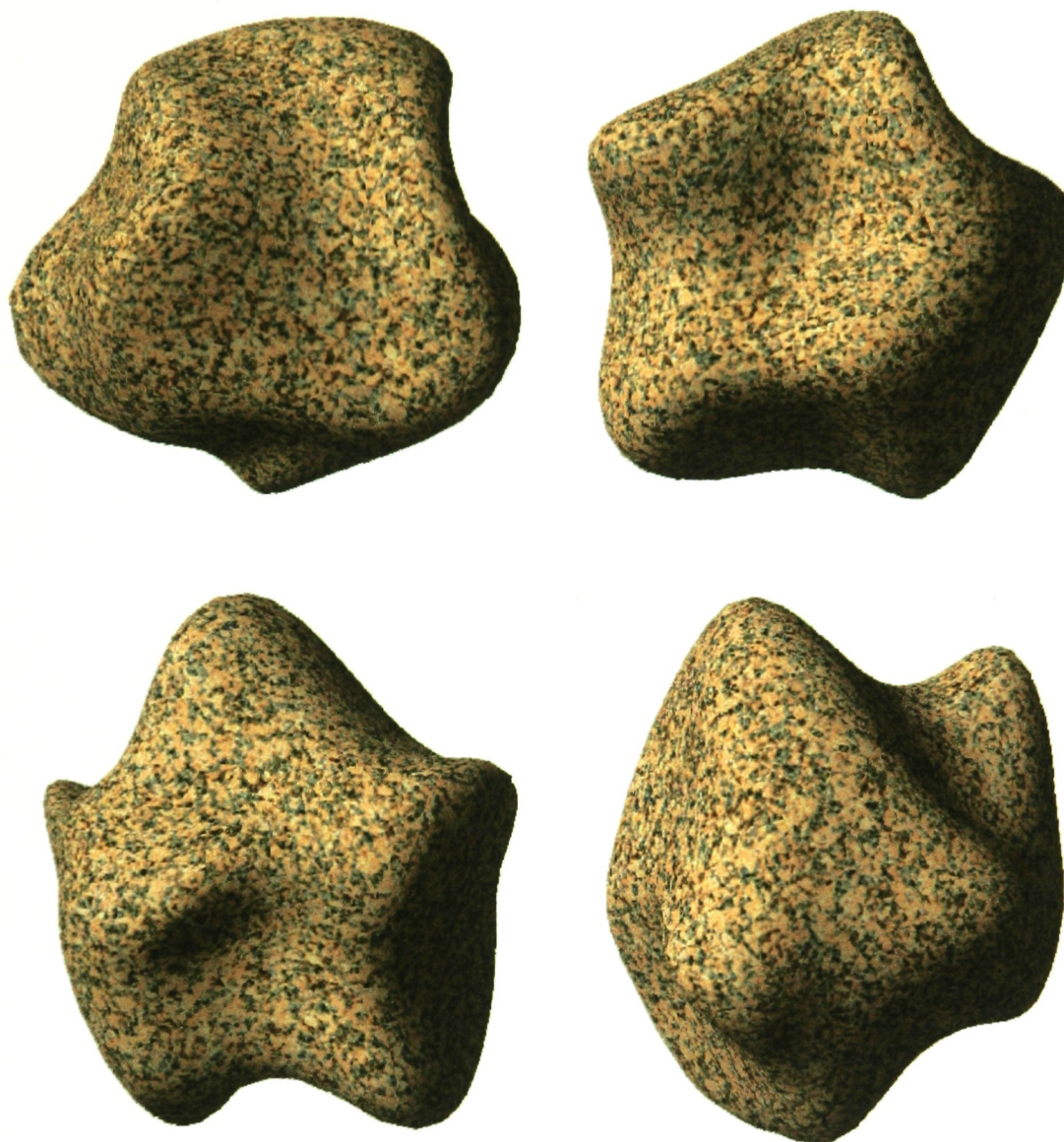


Figure 4. Four examples of the smoothly curved objects used in Raines and Norman (1999). These objects are similar to those used by Norman, Todd, and Phillips (1995) and Norman and Todd (1996, 1998).

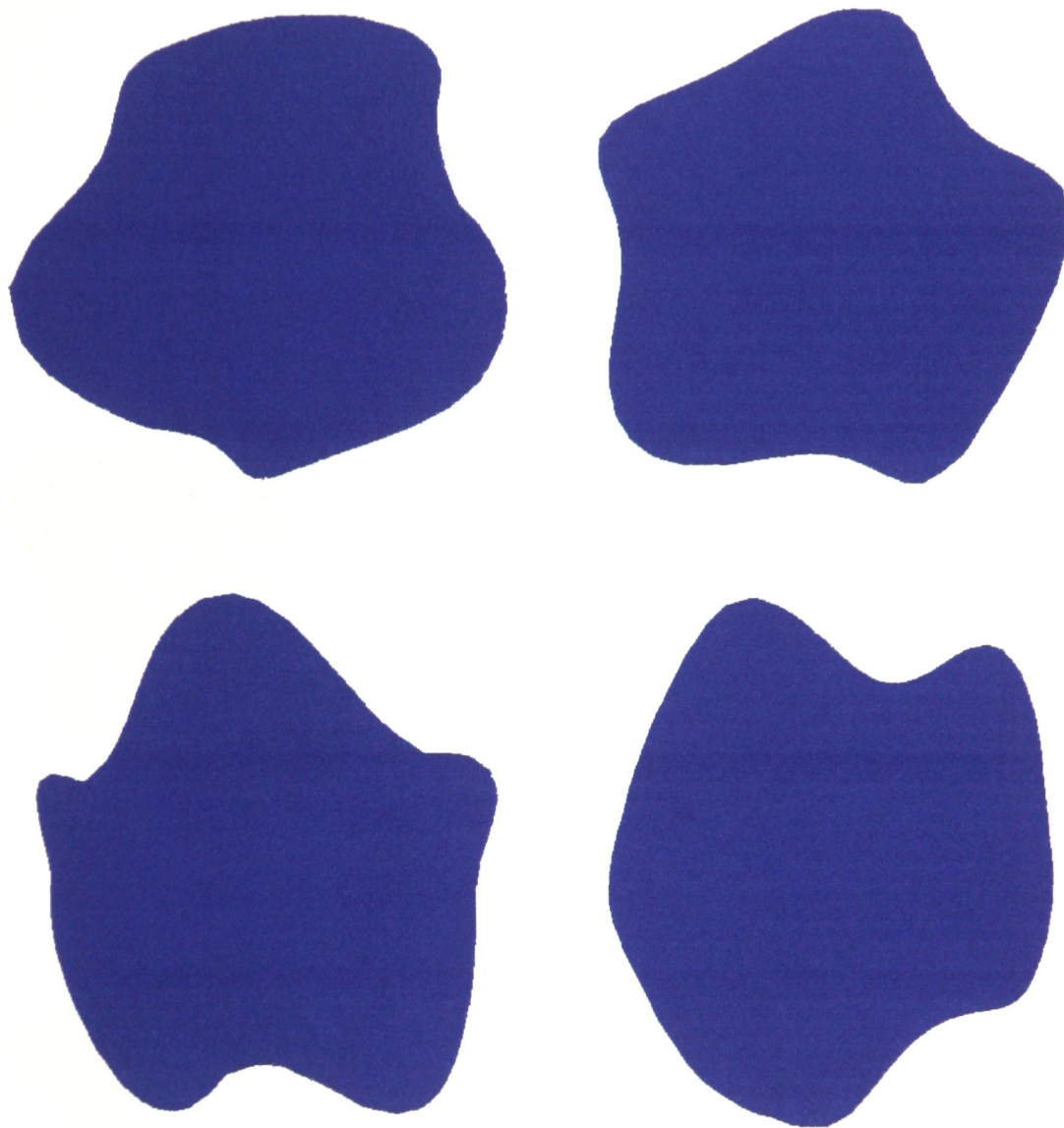


Figure 5. The respective silhouettes
of the objects shown in Figure 4.

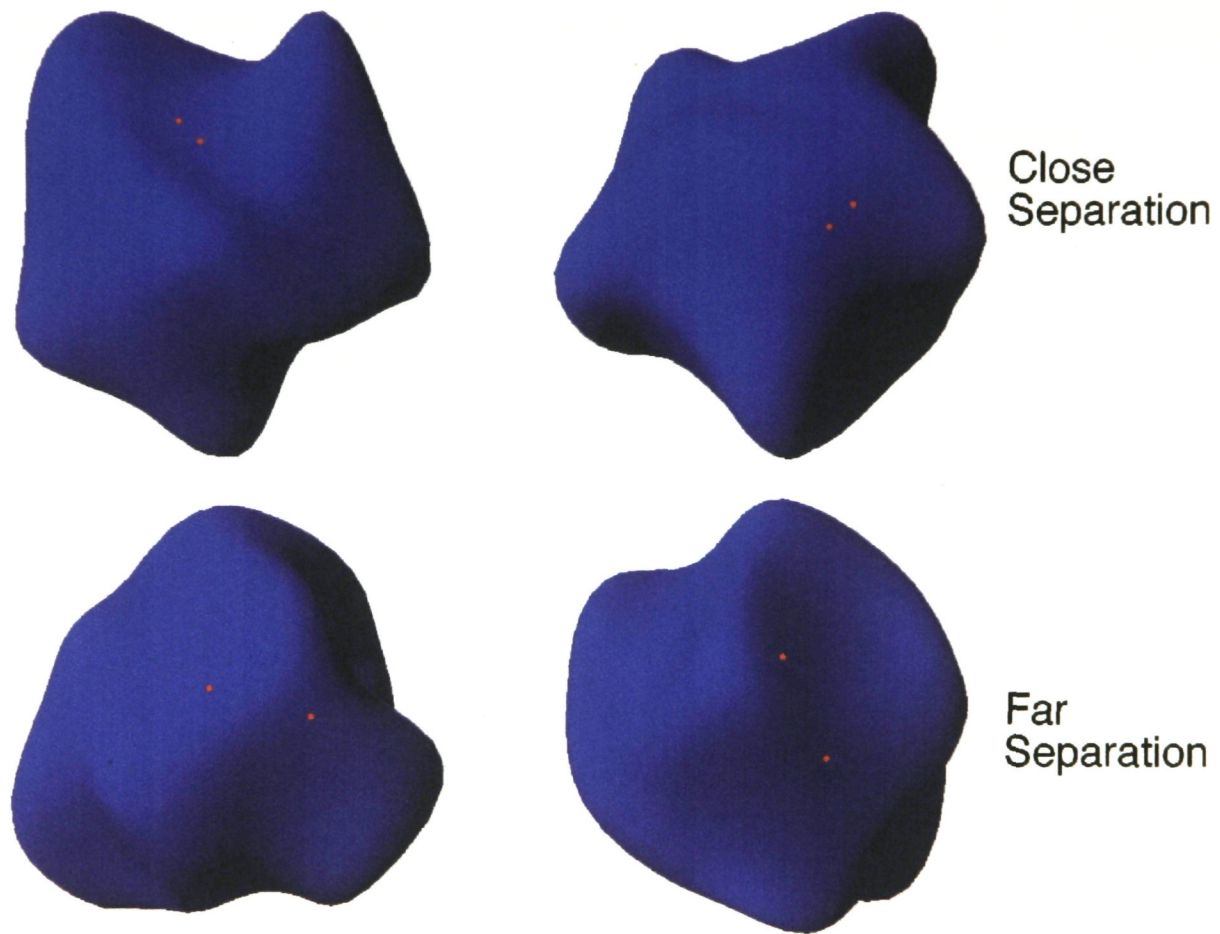


Figure 6. Examples of the different image separations used in the experiment by Raines and Norman (1999).

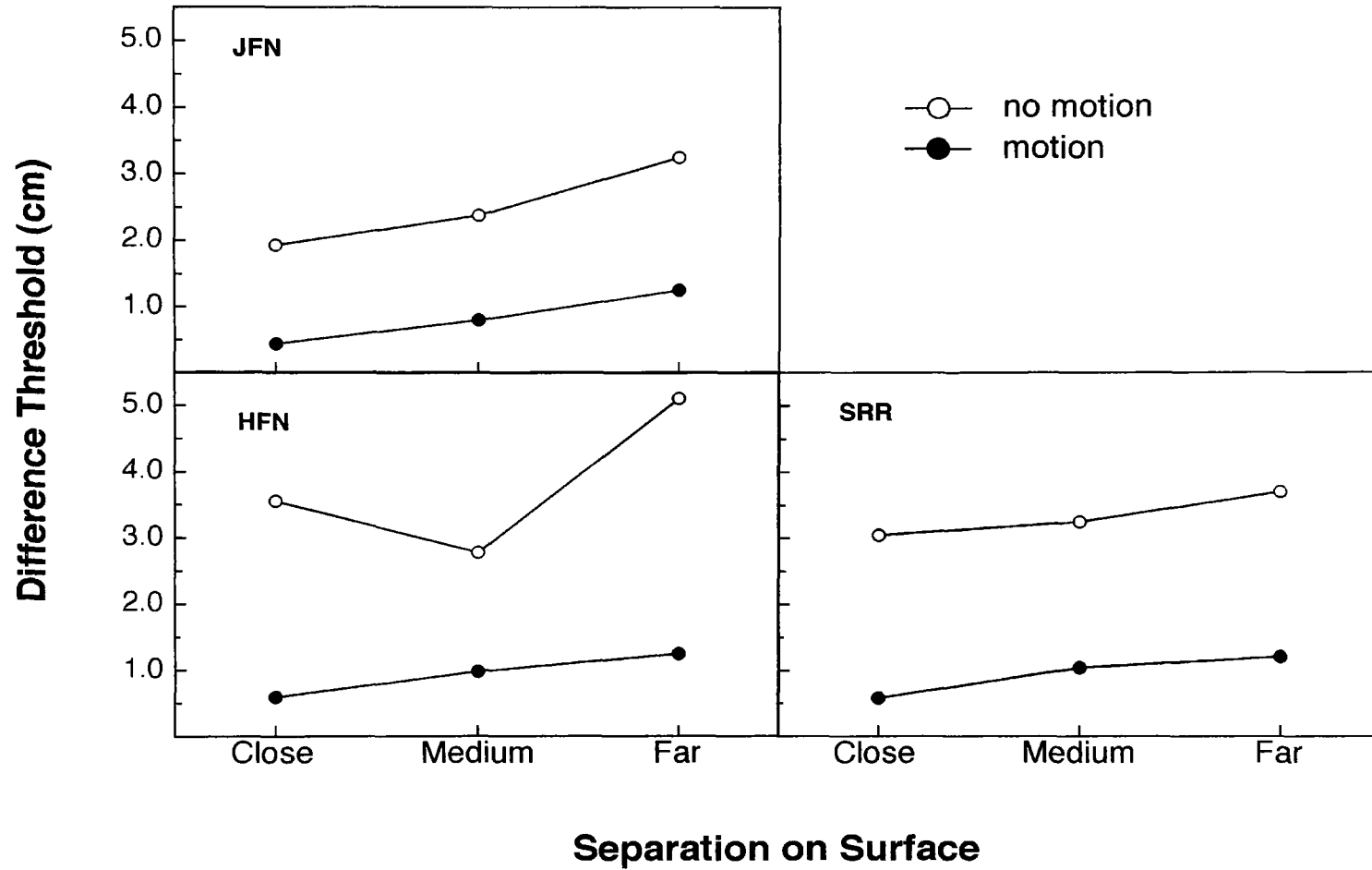


Figure 7. Results of the study by Raines and Norman (1999) showing that observers perceive ordinal depth relationships better when motion is present and when the separations between the regions judged are small.

Chapter 2

Experiment 1

The studies by Norman, Dawson, and Raines (2000) and Raines and Norman (1999) clearly show that human observers perceive the deformations of smoothly curved boundary contours as 3-D objects rotating rigidly in space. In addition, the experiments of Raines and Norman showed that local judgments about surface depth are possible, particularly if the regions to be judged are allowed to travel across (i.e., project to) the contour at some previous moment in time. However their study did not address instances in which the local regions do not project to the contour. Would performance remain at similar levels if the regions were not allowed to project to the boundary contour at some moment in time? If the 3-D information conveyed by the boundary contour tells us about local regions far from the boundary (i.e. the information propagates inward), we would expect similar levels of performance on a task in which the regions of interest do not project to the boundary contour. However, exactly how far the information propagates remains unknown. Therefore, the goal of Experiment 1 was to further understand the propagation of the information provided by the contour by manipulating the proximity of the regions to be judged to the contour (see Figures 8, 9, & 10).

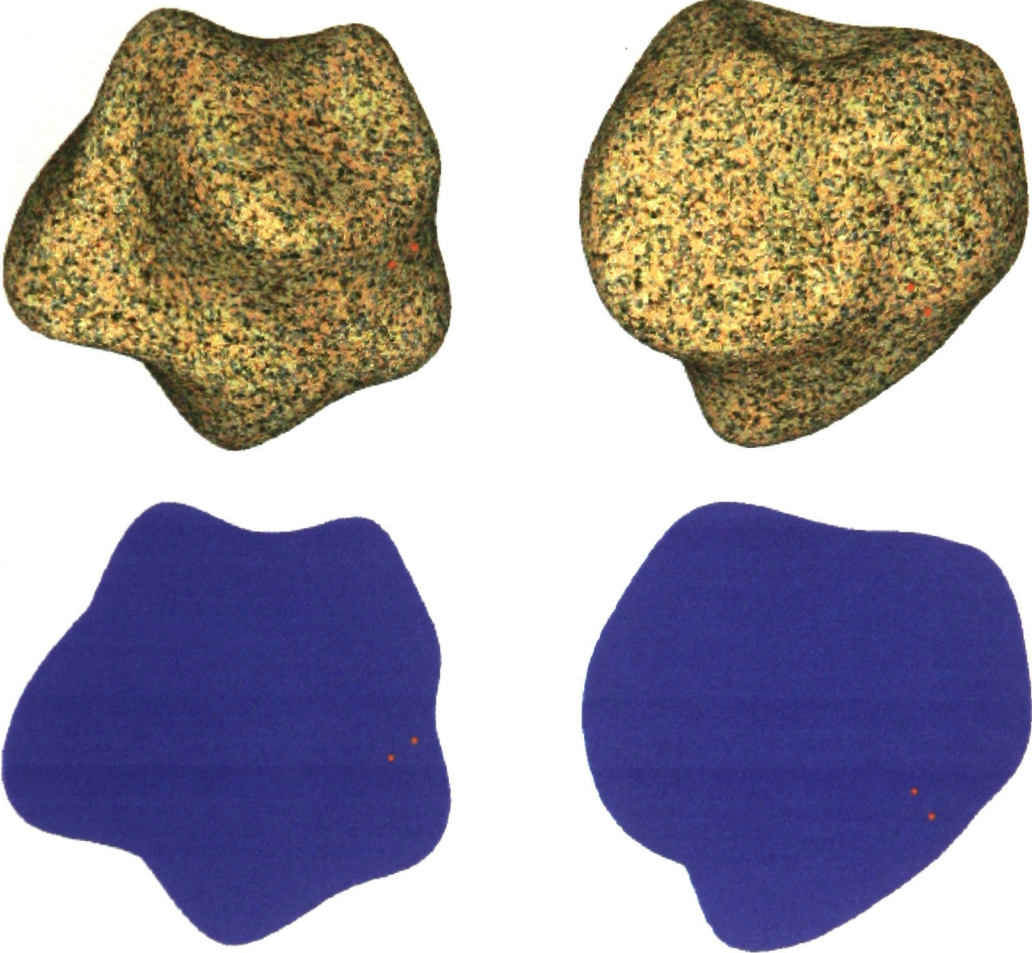


Figure 8. Schematic diagram illustrating the near to boundary condition of Experiment 1.

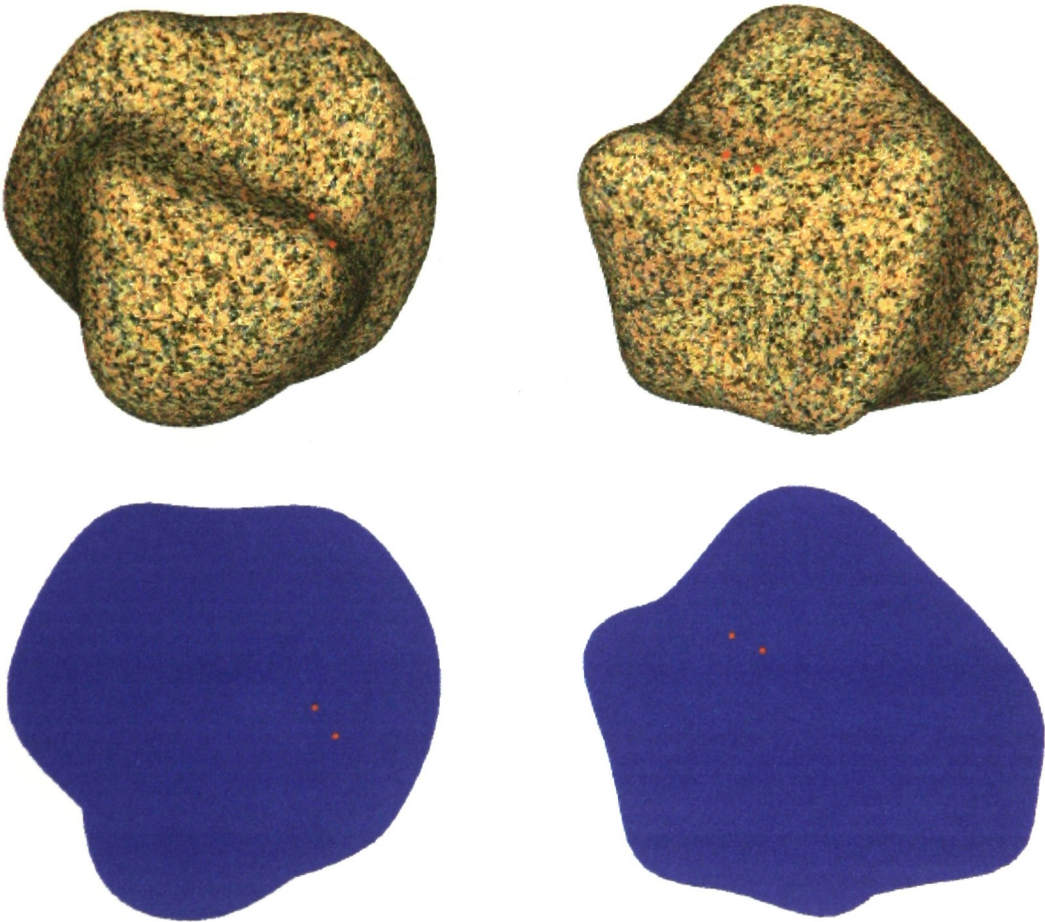


Figure 9. Schematic diagram illustrating the medium distance from boundary condition.

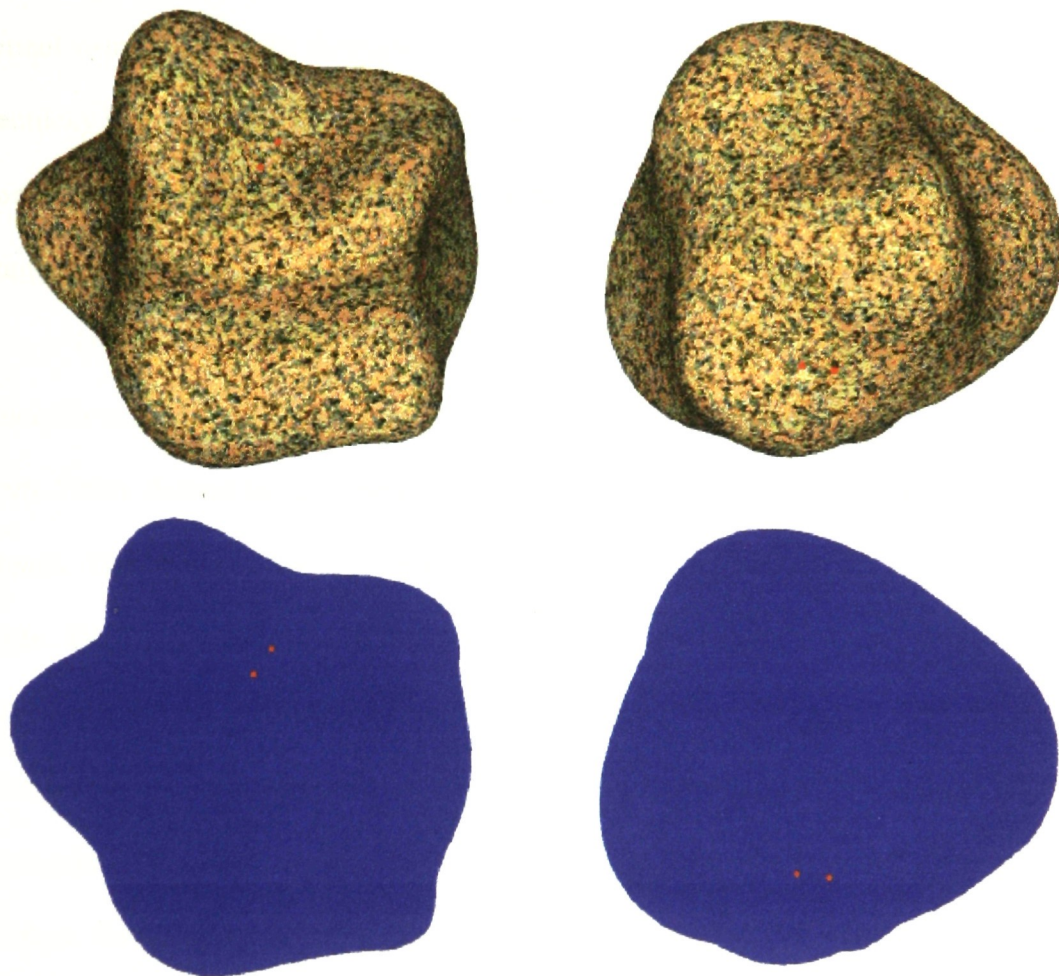


Figure 10. Schematic diagram illustrating the far from boundary condition.

Method

Observers

Three observers participated in the experiment, including the author (SRR) and two other experienced psychophysical observers (JFN & SMP). One observer (SMP) was naive to the purposes of the study. All observers had normal (i.e., 20/20) or corrected-to-normal visual acuity. The methods for this experiment were approved by the Western Kentucky University Human Subjects Review Board, and informed consent was obtained from all observers prior to the beginning of the experiment.

Stimulus Display

The stimulus displays were similar to those used by Raines and Norman (1999). Smoothly curved solid objects (see Norman, Todd, & Phillips, 1995; Norman & Todd, 1996, 1998), defined by the positions of 3840 connected triangular polygons, were used as stimuli. The 2-D projections of the objects subtended approximately 7.4 degrees visual angle. Unlike the stimulus patterns used in the above cited studies, those used in the present experiment contained no texture or shading; only the silhouettes of the objects were presented to the observers. The silhouettes were presented both binocularly and monocularly (i.e., with and without disparate views, respectively). For the monocular displays, the monitor's vertical refresh rate was 75 Hz, while for the binocular displays it was 150 Hz (i.e., 75 Hz for each eye's view). For disparate (i.e., binocular) presentations, two different silhouettes of the same object (corresponding to the left and right eyes' perspective views) were presented to the observer's left and right eyes. Each eye's view was computed based on each observer's interpupillary distance (ipd). The left and right lenses of the LCD glasses shuttered synchronously (i.e., alternately opening and closing)

with the vertical refresh of the monitor, ensuring that only the appropriate eye viewed each stereoscopic half-image. For the stimulus displays with boundary deformation, SRR and SMP viewed objects oscillating in depth about a Cartesian vertical axis between -22.5 and +22.5 degrees (i.e., 45 total degrees of oscillation) from their starting “home” position. These objects oscillated 3 times, with 2.5 degrees of rotation between adjacent views in the apparent motion sequences. Due to individual differences in sensitivity to the boundary deformation, observer JFN was required to view objects oscillating for a total of 24 degrees of oscillation (i.e., +/- 12.0 degrees). The moving objects shown to JFN still oscillated 3 times but the individual frames of the apparent motion sequences were separated by 3.0 degrees of rotation.

Apparatus

The stimulus displays were generated and displayed using an Apple Power Macintosh 8600/300. The observers viewed these displays at a 1280x1024 pixel resolution on a Mitsubishi 91TXM 21-inch monitor placed at a viewing distance of 100 cm from the observer. The stimulus displays were accelerated using a Nexus 128 graphics accelerator card (ATI Technologies, Inc.). The stereoscopic (i.e. binocular) stimuli were viewed using CrystalEyes 2 liquid-crystal-display (LCD) shuttered glasses (StereoGraphics, Inc.). All displays were viewed in a dimly lit room under photopic conditions.

Procedure

The experimental design consisted of a 2 (binocular vs. monocular presentation) x 2 (moving vs. stationary) x 3 (near vs. medium vs. far distances of regions to be judged from the boundary) factorial arrangement of treatments in a randomized complete block

design. Since the objects rotated about a vertical axis, most of the boundary deformation occurred on the left and right sides. Therefore, the distance from the boundary manipulated was the distance from either the left or right side of the boundary. Each observer completed 24 (12 conditions x 2 repetitions) experimental sessions.

Each experimental session consisted of 20 practice trials containing feedback and 300 experimental trials without feedback (50 trials x 6 magnitudes of depth differences). Depth differences of 0.2, 0.6, and 1.0 cm, with either the left or right region being closer, were used. The order of experimental conditions within each session was randomly determined for each observer. The observers wore the CrystalEyes 2 glasses for the stereoscopic conditions; for the monocular conditions the glasses were worn along with an eye patch over the observers' right eye. On any given trial, the observers viewed one of 100 possible randomly shaped objects with a particular depth difference chosen from a set of 3000 possible pairs of surface regions. Within any particular trial, a fixation point was displayed on the object's surface, allowing the observer to direct his/her attention towards the overall surface region within which the test depth difference would occur. After the termination of the boundary deformation (or after an equivalent period of time for static boundary presentations), two red probe points (small spheres) appeared on the object's surface. These points highlighted the two regions with the test depth difference. The observers' task was to respond which of the surface regions was closer to them in depth by pressing one of two keys on the computer's keyboard. Upon an appropriate response by the observer, the stimulus display for the next trial was initiated.

After completion of all sessions, the observers' responses for the two sessions per condition were combined. Using these totals for each of the six depth differences,

maximum likelihood estimates of ordinal depth thresholds were computed for each condition using a probit analysis procedure developed by Foster and Bischof (1991). These computed ordinal depth thresholds indicate the depth difference that each observer needed to reliably detect (i.e. 25th and 75th percentage points of the observer's psychometric functions) ordinal depth relationships. Figure 11 provides a pictorial view of how these thresholds were calculated. The percentages of times that the left point was judged closer are plotted as a function of whether the left region was actually closer for each depth difference. The data are then fit with the best fitting cumulative normal function allowing for 25 and 75% values to be found. To test for the appropriateness of these functions to describe the data, χ^2 goodness of fit tests were performed.

Results

The ordinal depth thresholds for the three observers are shown in Figures 12, 13, and 14 (all observers' psychometric functions from which these thresholds are based were not significantly different from a cumulative normal, as shown by the χ^2 goodness of fit tests). These results show that the presence of disparate views (i.e., stereoscopic presentation) had a different effect on performance for each of the motion levels. In the absence of motion, disparate views proved to be very important and led to more precise ordinal depth judgments. However when deformation of the boundary contours was present, the observers performed at similar levels regardless of whether or not the displays were viewed stereoscopically. In support of these observations, a 2 x 2 x 3 within-subjects analysis of variance (ANOVA) revealed a significant two way interaction between the motion and stereo conditions ($F(1, 11) = 25.296, p < 0.01$). This interaction was further investigated using Fisher's LSD method of pairwise comparisons. In the motion

Stereo & Motion
condition

- Near to boundary
- Far from boundary

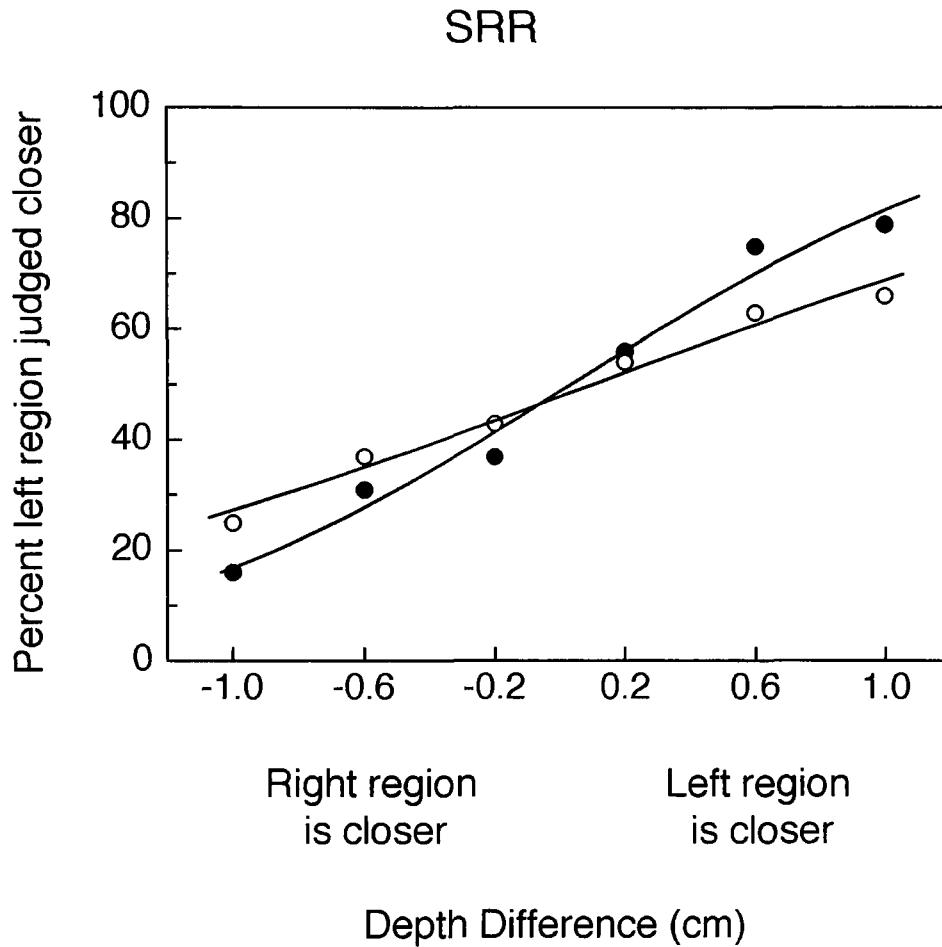


Figure 11. Percentage of 'left' judgments made by observer

SRR for the stereo and motion condition. The fitting of the data with a cumulative normal function allows for the computation of thresholds by locating the depth differences corresponding to 25% and 75% levels of performance for each condition.

SRR

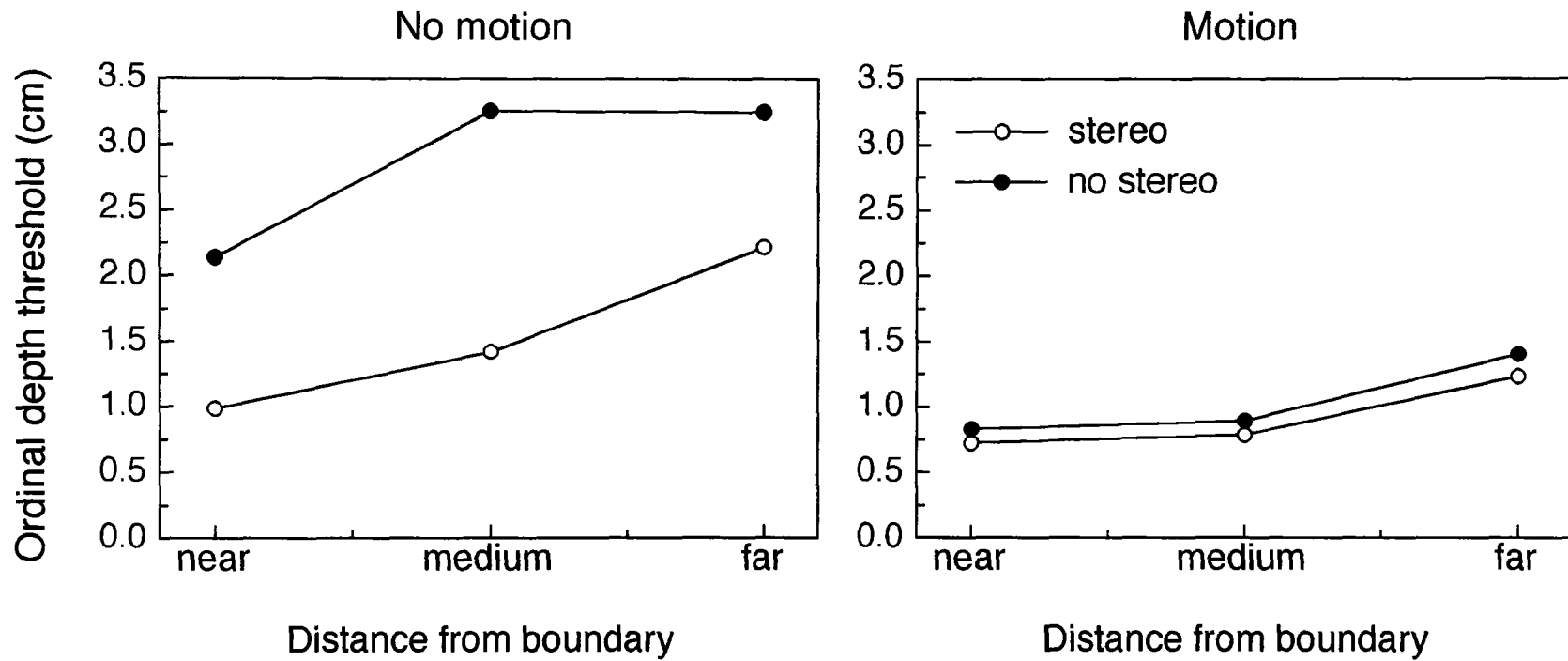


Figure 12. Ordinal depth thresholds of observer SRR. Performance declines as the distances of local regions become further from the boundary. Although disparate views (stereo) lead to higher performance for stationary displays, they do not appreciably alter the thresholds for moving displays.

SMP

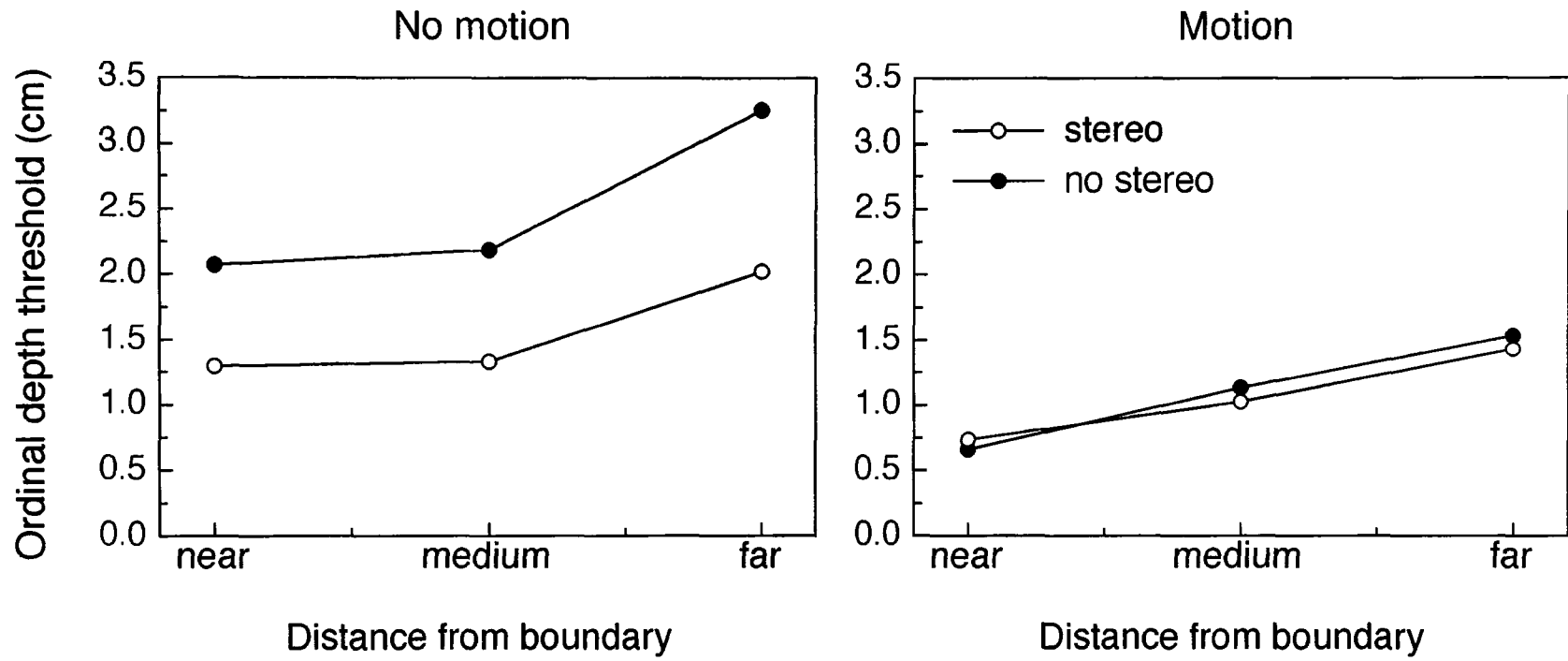


Figure 13. Results of observer SMP.

JFN

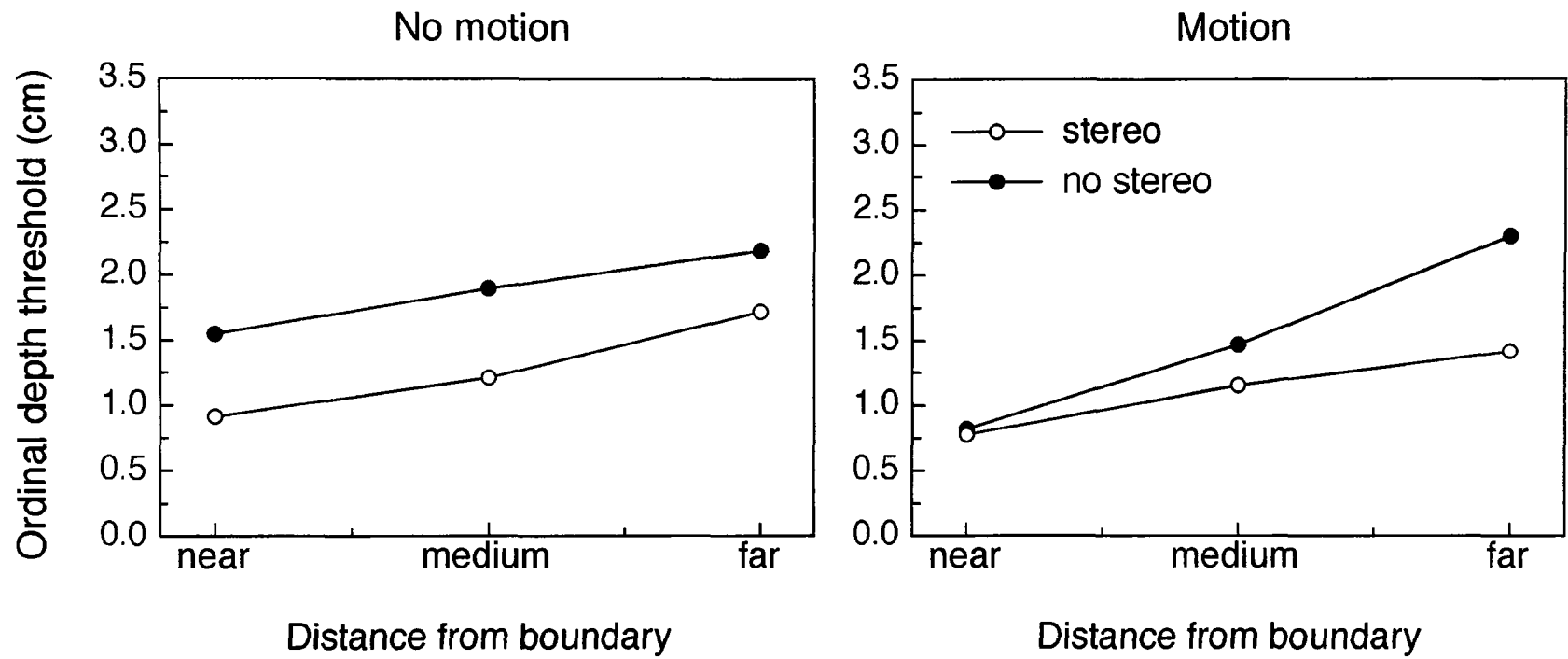


Figure 14. Results of observer JFN. Note that disparate views (stereo) improved performance at larger distances from the boundary in the motion conditions.

conditions, there were no significant differences between the stereo and no stereo conditions at all distances from the boundary. However, LSD comparisons of stationary conditions revealed a significant effect of disparate views for all three distances. Since observer JFN completed trials with different oscillation ranges and rotation speeds, the data from this observer were not included in the ANOVA. However, it is important to note that the data from this observer show similar trends. The ANOVA also revealed a main effect of distance from the boundary contour, $F(1, 11) = 45.732, p < .001$. All three observers showed a decline in performance (i.e., higher thresholds) as the regions to be judged were located at further distances from the boundary contour.

Discussion

The results of this experiment suggest that the information provided by the boundary contour does propagate inward. Although the relative strength of this propagation is limited by the proximity of the local regions to the boundary, the observers' performance, even at the far from boundary conditions, was far above chance levels. This study also helped to clarify the significance of disparate views for the perception of 3-D shape from boundary contours. First of all, the presence of stereoscopic views enabled better detection of ordinal depth relationships in stationary displays. Although the quantitative results do not reveal an increase in performance with stereoscopic viewing in the moving conditions (except perhaps for observer JFN), the subjective reports from the observers suggest that there is a benefit provided by disparate views. Since boundary contours serve to separate visible regions of an object from invisible ones, the information from any given contour is consistent with viewing either 'face' of an object, either the 'front' or the 'back.' In the monocular conditions with motion, the observers occasionally

reported problems in performing the task. The probe point would sometimes either appear to be attached to the back 'face' of an object or it would seem to move across the front 'face' in an opposite direction of motion. However, this alternative perception never occurred when viewing moving displays with disparate views of the boundary contour, suggesting that the perception of rigid rotation in depth is facilitated by the presence of disparate boundary contours.

Chapter 3

Experiment 2

The prior results from the studies of Norman, Dawson, and Raines (2000) and Raines and Norman (1999) indicate that the deformation of boundary contours leads to better performance than static contours for both recognition and ordinal depth discrimination tasks. The experiments in both studies showed observers a complete set of views corresponding to a full 360° rotation of the objects. However in a natural environment, human observers are not always allowed to see complete rotations of objects. At present it is not known how much boundary deformation is needed for observers to recover useful information about 3-D shape. The purpose of Experiment 2, therefore, was to evaluate how much deformation is needed for the accurate determination of ordinal depth.

Method

Observers

Three observers participated in the experiment, including two observers from the previous experiment (SRR & JFN). The third observer (HFN) was psychophysically experienced and had corrected-to-normal visual acuity. The methods for this experiment were also approved by the Western Kentucky University Human Subjects Review Board, and informed consent was obtained from all observers prior to experimentation.

Apparatus

The observers viewed the displays using the same apparatus as in the previous experiment.

Stimulus Display

The stimulus displays were identical to those of the near to boundary condition in Experiment 1. They were always viewed monocularly. For observers SRR and HFN, the objects oscillated in depth for 25, 35, and 45 total degrees of oscillation with 2.5 degrees of rotation between adjacent views. Observer JFN viewed objects that oscillated 12, 18, and 24 degrees with 3.0 degrees of rotation between views. As in Experiment 1, the depicted objects oscillated 3 times before stopping.

Procedure

The presentation of treatments was arranged in a randomized complete block design with each observer completing six (3 magnitude of deformation conditions x 2 repetitions) experimental sessions. Each experimental session consisted of 20 practice trials and 300 experimental trials (6 depth differences magnitudes x 50 repetitions), in which the observers were required to make the same ordinal depth discriminations as in the first experiment. All other details of the procedures were identical to those used in Experiment 1.

Results

The ordinal depth discrimination thresholds for the three observers are shown in Figures 15 and 16. The thresholds of observers SRR and HFN increased by a factor of 0.49 from the 45 degree to the 25 degree condition (Figure 15), indicating that a 50% larger depth difference was needed to do the task with the smaller amounts of boundary

deformation. These differences in performance across magnitudes of deformation were found to be statistically significant ($F(2, 2) = 48.080, p < 0.05$). The thresholds of observer JFN increased more sharply – there was a 78% increase in thresholds as the amount of oscillation was reduced from 24 to 12 degrees (Figure 16). With 12 degrees of oscillation, JFN's performance approached that obtained for the stationary displays in Experiment 1.

Discussion

The results from this experiment suggest that relatively little motion is necessary for the accurate perception of local 3-D shape from boundary deformation. Although the observers' performance declined with less deformation, they were still able to perceive ordinal depth relationships with reasonable precision. It appears as though the human ability to perceive 3-D shape from deforming contours declines gradually at least until 18 degrees of oscillation. Future studies should examine boundary deformations smaller than this to understand the precise effect of deforming boundary contours on ordinal depth judgments.

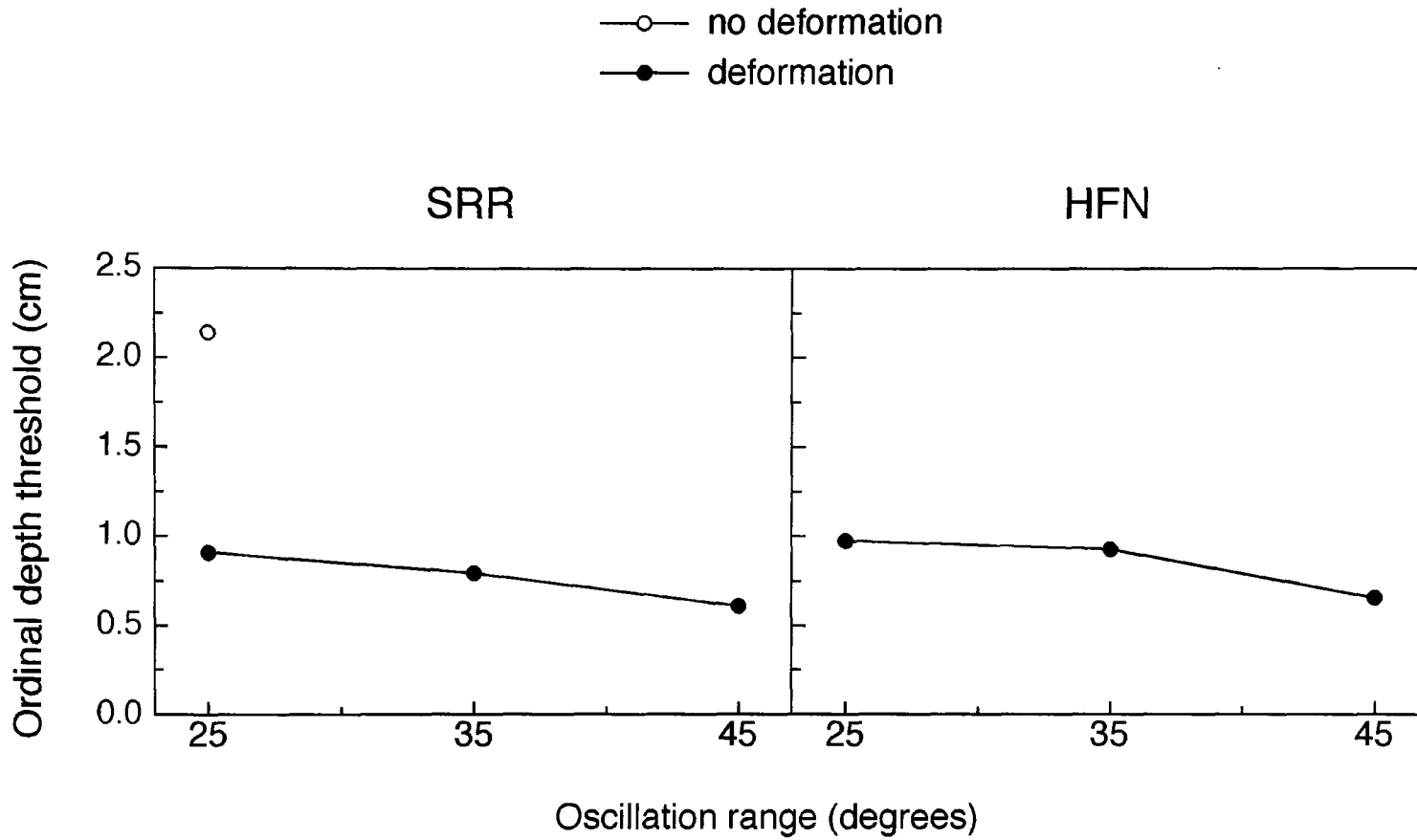


Figure 15. Ordinal depth thresholds of SRR and HFN for the 3 oscillation ranges. Performance decreases with decreased deformation of the boundary.

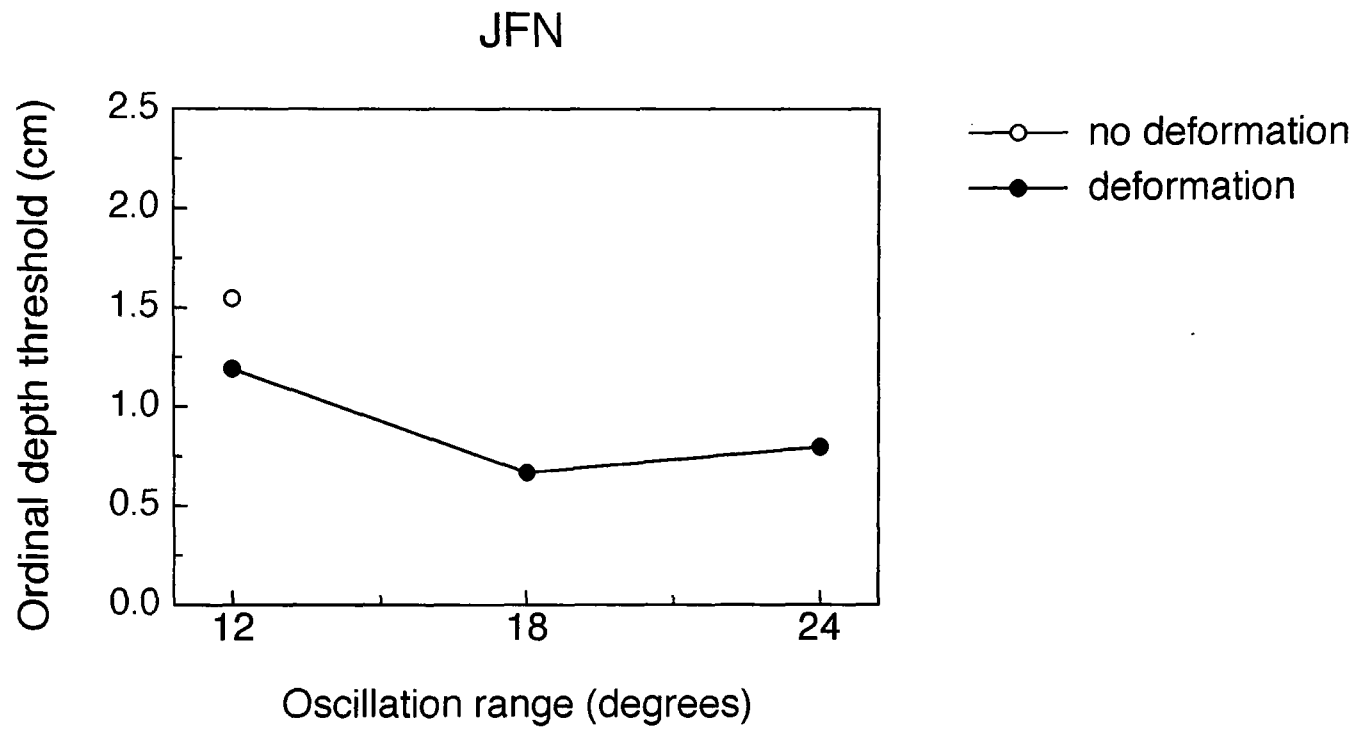


Figure 16. Thresholds of observer JFN.

Chapter 4

General Discussion

Early research investigating the informativeness of boundary deformations for the perception of 3-D shape focused on aspects of global shape. One of the first of these investigators was the physicist Ernst Mach. Mach (1886/1959) reported that the boundary deformations of the silhouettes of ellipsoids appeared nonrigid. However if an identifiable point was placed on the ellipsoid's surface, his observers reported rigid rotations in depth. These reports were later replicated by Wallach and O'Connell (1953), leading them to make an incorrect assumption that the deformations of smoothly curved boundary contours could not support the perception of an object rigidly rotating in depth. Later, studies by Todd (1985), Cortese and Anderson (1991), and Norman and Todd (1994) demonstrated that the perception of rigid rotation in depth was indeed possible under certain conditions.

The problem with the earlier research of Mach (1886/1959) and Wallach and O'Connell (1953) was related to the types of stimuli that were used. These experiments often used simple curved objects, like ellipsoids. However, later research by Attneave (1954) and Koenderink (1984) demonstrated that ellipsoids were a degenerate special case -- i.e., their boundary contours lacked concavities (i.e., ellipsoids have no "saddle-shaped" regions unlike most ordinary solid objects). Norman et al (2000) and Raines and Norman (1999) used more complex stimuli that possessed these concavities in their deforming

boundaries. Their studies demonstrated that not only could observers perceive rigid rotation in depth from deforming contours, but they could also recognize objects and perform ordinal depth discriminations between separated local regions on their surfaces.

The Raines and Norman (1999) study was the first to investigate the perception of local aspects of 3-D shape from deforming and static boundary contours. The results of this study found that the ability to make ordinal depth judgments varies with whether the boundary contours deform and how close the regions judged are to each other. The two present experiments replicate and extend the Raines and Norman study and serve to clarify how boundary contours influence the perception of local surface structure far removed from the boundary. Experiment 1 demonstrated that even for regions far from the boundary contour, observers are capable of making reasonably precise ordinal depth judgments. The results of this experiment also showed that disparate views of contours can be very informative, especially when the contours are stationary. The results of one observer (JFN) also suggest that there may also be a benefit of stereoscopic views even when the contours deform, particularly when making judgments far from the boundary. In Experiment 2, the results showed that ordinal depth thresholds increase with smaller deformations of the boundary.

The combined results from Raines and Norman (1999) and the present set of experiments provide substantial evidence that boundary contours are very important for the human visual system's analysis of shape. Given Koenderink's (1984) proof that there are only a small number of qualitatively different types of curved surface regions, the information gathered from boundary contours (i.e., convexities and concavities) places powerful constraints on the 3-D shape of an object. The results of Experiment 1 show

that these constraints are not limited to surface regions that project near to the boundary.

The information contained within boundary contours propagates inwards and provides observers with a substantial amount of information about the internal 3-D structure of an object. Furthermore, if either the object or the observer moves, even more constraints can be made on the object's possible 3-D shape. Experiment 2 showed that these constraints are robust even for small magnitudes of boundary contour deformation.

The findings of the current experiments conclusively show that boundary contours all by themselves contain a wealth of information to support the perception of 3-D shape. Given this, it is important that previous studies that investigated other optical sources of information (shading, specular highlights, etc.) be replicated to control for the effects of the boundary contour (e.g., Norman, Todd, & Phillips, 1995). It then will be possible to isolate the various sources of information to understand the role of each in the perception of 3-D shape independent of the contributions made by the boundary contour.

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