Journal of Experimental Psychology:
Human Perception and Performance
1996, Vol. 22, No. 3, 695–706

0096-1523/96/$3.00

Effects of Changing Viewing Conditions on the Perceived Structure of Smoothly Curved Surfaces

James T. Todd
Ohio State University

Jan J. Koenderink, Andrea J. van Doorn, and Astrid M. L. Kappers
Helmholtz Instituut, Universiteit Utrecht

Observers' perceptions of a male and a female torso were investigated using monocular and stereoscopic images under varying conditions of illumination. Observers judged the shapes of these torsos by adjusting a gauge figure to estimate the local slant and tilt at numerous probe points arranged in a lattice over the torso's surface. The results revealed that the judged surfaces in the monocular and stereoscopic conditions were related by an affine stretching transformation in depth that accounted for approximately 95% of the between-condition variance. There was also a strong affine component between the judgments obtained for the different illumination directions, although a further analysis of the residuals indicated that changing the direction of illumination influenced perceived structure in a piecewise manner.

When visible objects are viewed in a natural environment, they are often seen from different vantage points, or with different conditions of illumination. Visible objects may be moving or stationary, and they can be observed either monocularly or stereoscopically. The experience of most observers is that the three-dimensional (3D) structure of objects appears to remain stable despite these changing viewing conditions—what is often referred to as the phenomenon of shape constancy. It is important to keep in mind, however, that there are many different aspects of an object's 3D structure, and it is not at all obvious that they must all contribute equally to our perceptual awareness of environmental stability. Indeed, when observers are probed using psychophysical procedures to quantitatively measure their perceptions of specific aspects of metrical structure, the results often demonstrate that these properties do not remain invariant over changing viewing conditions.

Consider, for example, an early experiment by Heine (1900). He had observers adjust three vertical rods at varying viewing distances in a well-illuminated room, so that they appeared to form an equilateral triangle in depth. The results demonstrated that at a viewing distance of 50 cm, observers' judgments were reasonably accurate, but that the physical depths were systematically underestimated at farther distances (i.e., between 1 and 2 m) and systematically overestimated at closer distances. These effects were quite large, so that the observers' depth settings varied by a factor of two across the different viewing conditions. Similar results have more recently been obtained by numerous other investigators under full cue conditions (e.g., see Baird & Biersdorf, 1967; Harway, 1963; Loomis, Da Silva, Fujita, & Fukusima, 1992; Norman, Todd, Perotti, & Tittle, 1996; Thouless, 1931; Wagner, 1985).

Although observers typically do not notice such effects in natural vision, they can be quite compelling if one pays careful attention. A particularly salient example can be experienced while driving on a divided highway on which dashed lines have been painted to divide the individual lanes. If one looks out at a distance of several meters, the dashed line segments will appear relatively short, but as they become closer and closer to the point of observation their perceived lengths can increase dramatically by a factor of three or four. However, in the absence of attention, this effect is generally not noticed, so that the visual ground surface usually appears perfectly rigid and stable.

There are several other violations of shape constancy that seldom intrude on our perceptual awareness, yet can be reliably measured using appropriate psychophysical procedures. Consider, for example, the effects of changing object orientation. Tittle, Todd, Perotti, and Norman (1995) have recently investigated this issue for the visual perception of structure from motion (see also Reichel & Todd, 1990; Todd & Reichel, 1989, for similar results in the perceptual analysis of shading and texture). They asked observers to adjust the eccentricity of a simulated rotating cylinder until its cross section appeared circular, or to adjust the angle between two rotating planar facets until they appeared to be orthogonal. These surfaces rotated back and forth over a 10° angular extent, and the mean orientation of the object's

James T. Todd, Department of Psychology, Ohio State University; Jan J. Koenderink, Andrea J. van Doorn, and Astrid M. L. Kappers, Helmholtz Instituut, Universiteit Utrecht, Utrecht, The Netherlands.

This collaboration was supported in part by NATO Scientific Exchange Grant CRG 92065. It was also supported by the Air Force Office of Scientific Research (F49620-93-1-0116), the Human Frontiers Scientific Program Organization, and the Netherlands Organization for Scientific Research.

Correspondence concerning this article should be addressed to James T. Todd, Department of Psychology, 142 Townshend Hall, Ohio State University, Columbus, Ohio 43210. Electronic mail may be sent via Internet to jtodd@magnus.acs.ohio-state.edu.

central axis was varied from trial to trial. The results revealed that the perceived eccentricity of these surfaces varied dramatically with their orientation. The perceived surface relief was greatest when their axes were aligned in the frontoparallel plane, and decreased by as much as 33% when the axes were slanted in depth by 30°. Despite these large changes in perceived metrical structure with a 30° change in orientation, the surfaces appeared perfectly rigid when they rotated continuously over a comparable angular extent.

Still another example of unnoticed failures of constancy can occur when changing from monocular to binocular viewing, or vice versa. If an observer with stereoscopically normal vision opens or closes one eye in a natural environment, there will usually be little or no change in its phenomenal appearance. However, if an observer focuses attention on the apparent distances in depth of relatively near objects, they will appear to flatten out when switching to one eye and to expand in relief when switching to two eyes. The opposite effect can be experienced when looking at pictorial displays. That is to say, objects depicted in pictures appear to flatten when viewed binocularly and to expand in relief when viewed monocularly (e.g., see Koenderink, van Doorn, & Kappers, 1995).

One final example of a failure of shape constancy that deserves to be highlighted involves changes in the pattern of an object's illumination. It is a well-known trick among expert photographers that they can manipulate the apparent shape of an object by altering the direction of illumination. This is especially common in portrait photography. It is possible, for example, to diminish the apparent size of a large nose using direct frontal illumination, or to accentuate its size by illuminating it from the side to produce visible cast shadows.

Little is known at present of how perceived structure is influenced by the direction of illumination. One possible hypothesis to account for these effects is that the human visual system is biased to interpret an object's structure as if it were illuminated from above. Reversals of apparent relief from convex to concave (or vice versa) that can occur when an image is viewed upside down are often taken as evidence for such a bias (e.g., see Brewster, 1826; Rittenhouse, 1786; von Fieandt, 1938, 1949), although Reichel and Todd (1990) have argued that many of these inversion phenomena are due to other factors unrelated to shading. Unfortunately, there have been only a few systematic attempts to measure perceived 3D shape (as opposed to the sign of relief) under varying conditions of illumination (e.g., Johnston & Passmore, 1994; Mingolla & Todd, 1986), and those studies have all been limited to monocular viewing of very simple surfaces such as spheres or ellipsoids.

The research described in the present article was designed, therefore, to investigate the effects of illumination direction on the perceived shape of surfaces that may be more representative of those encountered in natural vision. The human torso was chosen for this purpose because it is one of the most intricately structured and familiar surfaces observed in the environment. We were particularly interested in whether we could measure quantitatively the local partwise effects of oblique illumination that seem to be possible in portrait photography, and we were also curious about how these effects might vary between monocular and stereoscopic viewing conditions.

Method

Stimuli

The stimuli depicted a posterior view of a male or a female mannequin, which were composed of a textured plastic material with a relatively diffuse reflectance. These mannequins were photographed on monochrome film under two different conditions of illumination with a localized light source: In the *frontal condition*, the light source was placed near the camera lens, while in the *oblique condition*, it was positioned at approximately a 45° angle to the right of the line of sight. This particular angle was chosen so that there would be clearly discernible cast shadows on the body's surface from its more prominent parts.

The camera lens had a focal length of 24 cm. Because the mannequins were of different sizes, they were photographed from different distances—258 cm for the male, and 222 cm for the female—to approximately equate their sizes in the photographic images. To obtain stereoscopic images, two photographs, separated by a horizontal distance of 7 cm, were taken for each condition. The prints were scanned using a Hewlett-Packard Scanjet plus scanner to produce 8-bit gray tone images that were displayed on a Macintosh 24-bit color monitor. When presented on the screen, they each had a height of 18 cm and a width of 11.7 cm. The resulting images for all four monocular conditions are shown in Figures 1 and 2, where the effects of varying the direction of illumination are clearly visible.

The displays were viewed at a distance of 50 cm from the monitor screen, and head movements were restricted by using a chin rest. In the monocular conditions, the observer's nondominant eye was covered with an eye patch. In the stereoscopic conditions, the displays were viewed through a standard mirror stereoscope with a convergence angle of zero (i.e., the eyes were converged at infinity). The depicted torsos in each image were triangulated with a regular grid composed of 256 vertices, 688 edges, and 433 faces, which defined the probe points for the observers judgments.

Procedure

The task on each trial was to adjust the slant and tilt of a circular gauge figure centered at a given probe point so that it appeared to be within the tangent plane of the surface at that point (see Koenderink et al., 1992, 1995). Slant is defined in this context as the angle between the surface normal and the line of sight, whereas tilt is the direction of the surface depth gradient within the frontoparallel plane (see Figure 3). The gauge figure simulated a small circle in 3D space with a perpendicular line at its center, whose length equaled the radius of the circle. These appeared in the image as a red ellipse with a small line along the minor axis, whose lengths and orientations could be manipulated using a trackball or a handheld mouse. When adjusted appropriately, all of the observers were able to perceive this configuration as a circle oriented in depth in the tangent plane with a line perpendicular to it in the direction of the surface normal. In the stereoscopic conditions, the gauge figures were presented to one eye only, but they still appeared as circles oriented in depth at the depicted probe point.

There were eight different experimental conditions involving all possible combinations of the three basic stimulus manipulations:

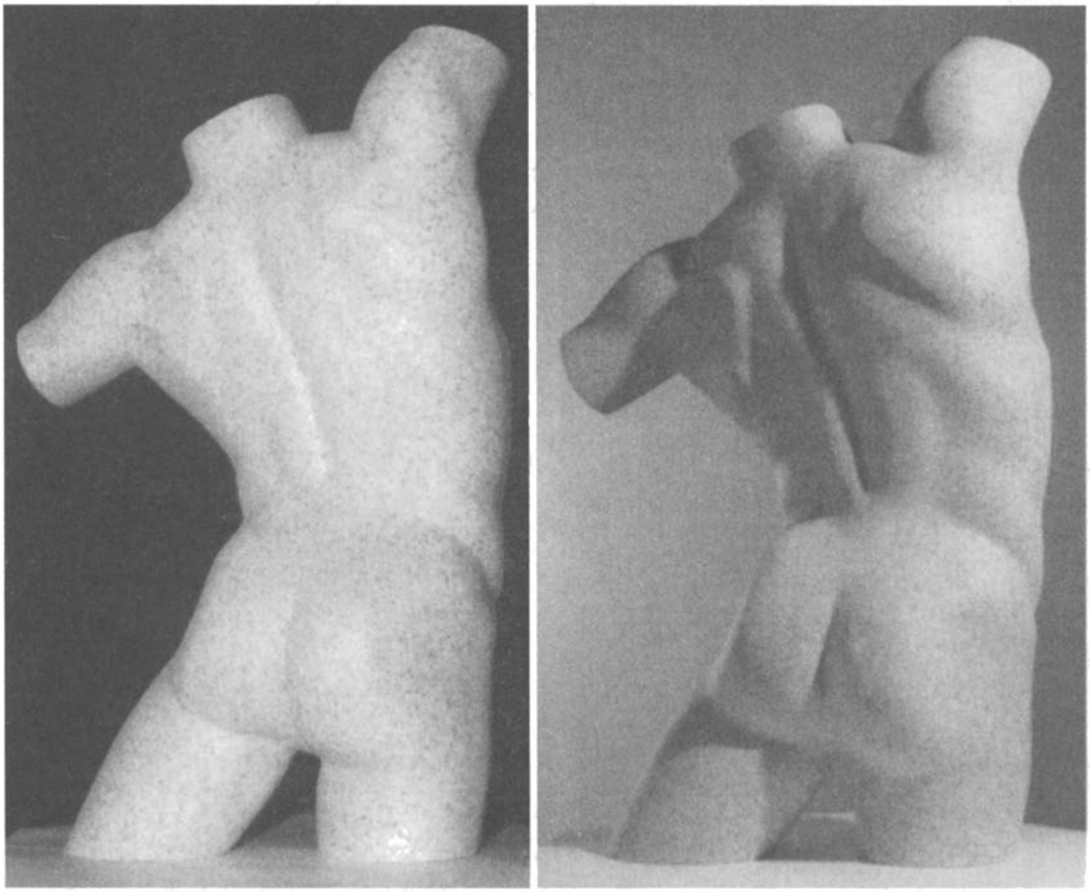

Figure 1. The shaded image of a male torso from two different directions of illumination.

The displays could be presented monocularly or stereoscopically; the depicted torso could be male or female; and the depicted direction of illumination could be either frontal or oblique. During a single experimental session, all of the torso vertices for a single condition were probed three times each in a random sequence, which took approximately 1 hr. The vector average of these three repeated measurements was then used to estimate the judged surface orientation at each probe point.

Observers

The four authors participated as observers. All had normal or corrected to normal vision and extensive experience with the gauge figure adjustment task. Each observer performed the sessions in a different random order.

Results

The method for reconstructing the pictorial relief of a surface from a set of local attitude measurements has been described in detail by Koenderink et al. (1992). The basic procedure is as follows: For each vertex V_i in the lattice of probe points, a gradient vector $\mathbf{G}_i$ is computed from the observer's slant and tilt settings (σ_i and τ_i) using the following equation:

$$\mathbf{G}_i = (\cos \tau_i, \sin \tau_i) \tan \sigma_i.$$

Similarly, for each pair of adjacent vertices ($i = n, m$), a two-dimensional connection vector is computed so that

$$\mathbf{C}_{nm} = (X_n - X_m, Y_n - Y_m).$$

The depth difference D_{nm} between the two probe points can then be determined from the scalar product

$$D_{nm} = \mathbf{C}_{nm} \cdot (\mathbf{G}_n + \mathbf{G}_m)/2.$$

The individual depths Z_n and Z_m are estimated—up to a translation in depth—from the least squares error solution of the overdetermined set of simultaneous equations ($Z_n - Z_m = D_{nm}$) defined by the depth differences for all pairs of adjacent vertices. This also provides a simultaneous confirmation that the overall set of judgments has a consistent interpretation as a smoothly curved surface. The interpretation is consistent if the least squares error is no larger than the standard deviation over multiple judgments for individual probe points, which is typically around 15% or 20% for

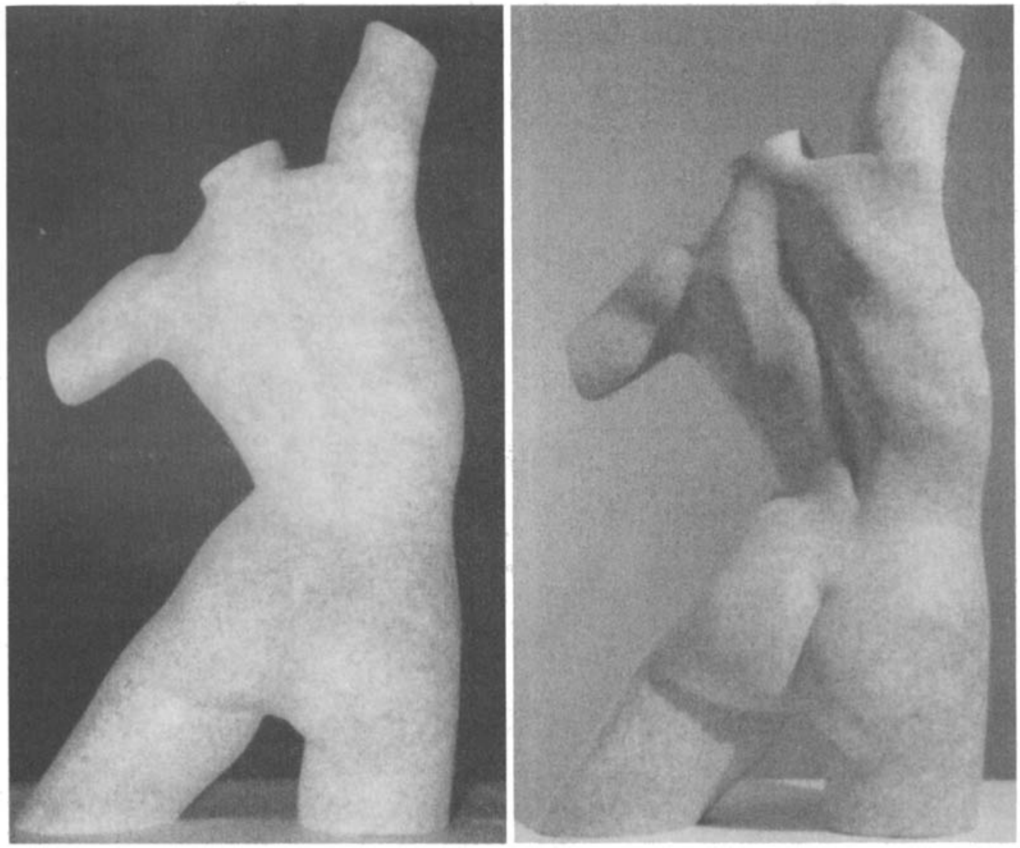

Figure 2. The shaded image of a female torso from two different directions of illumination.

the slant component and about one half that for tilt. Table 1 shows the standard deviation of the slant components in the present experiment as a proportion of their mean, averaged over all probe points in all conditions. Note that the overall level of test–retest reliability is approximately 81%, which is similar to values obtained in previous investigations (see Koenderink et al., 1992, 1995).

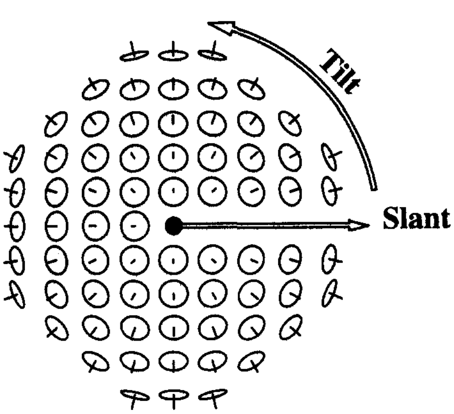

Figure 3. The 3-dimensional (3D) orientation of any surface patch can be decomposed into two components: its slant, which is the angle between the surface normal and the line of sight, and its tilt, which is the direction of its depth gradient in the frontoparallel plane. These components can easily be distinguished in the optical projection of a circular gauge figure in 3D space. The shape of this projection in the image plane is an ellipse, whose eccentricity is determined by the circle's slant and whose orientation is determined by its tilt.

The results of this analysis can be represented in several different ways. Figures 4 and 5 show the isodepth contours obtained from the judgments of observer Andrea van Doorn, for the female torso, and of observer Astrid Kappers, for the male torso in all of the different conditions. The local depth gradients are revealed in these figures by the spacing between the contours, but the overall pattern of judged pictorial relief can be seen more clearly when the reconstructions are viewed in profile. Figures 6 and 7 show the profile reconstructions of the female torsos for observer James Todd and of the male torsos for observer Jan Koenderink. For the sake of comparison, the actual torso profiles are shown in Figures 8 and 9. Note that in these Figures the reconstructions for both observers are bent forward at the waist relative to the depicted posture of the actual mannequins, and that there are large differences in the relative size of the buttocks.

Although all of these reconstructions are qualitatively similar, there were several systematic differences between the different observers and between the different viewing conditions that deserve to be highlighted. Table 2 shows the

Table 1
Standard Deviation of the Slant Components of Observers' Judgments to Individual Probe Points as a Proportion of Their Mean, Averaged Over All Probe Points in All Conditions

Observer	Frontal monocular	Oblique monocular	Frontal binocular	Oblique binocular	Total
		Female torso			
A.V.	0.09	0.12	0.19	0.11	0.13
A.K.	0.11	0.14	0.20	0.13	0.15
J.K.	0.17	0.12	0.14	0.30	0.18
J.T.	0.27	0.18	0.14	0.18	0.19
Total	0.16	0.14	0.17	0.18	0.16
		Male torso			
A.V.	0.12	0.21	0.19	0.15	0.17
A.K.	0.19	0.25	0.17	0.21	0.21
J.K.	0.18	0.21	0.17	0.18	0.19
J.T.	0.20	0.18	0.20	0.17	0.19
Total	0.17	0.21	0.18	0.18	0.19

Pearson product–moment correlation squared (r^2) values obtained for the correlations between all pairs of observers in all of the different conditions. A high linear correlation in this context indicates that the judged pictorial relief between two observers is similar up to an affine stretching transformation along the line of sight. In Table 2, note that for observers Astrid Kappers, Jan Koenderink, and James Todd, the linear trend accounts for approximately 85% of the variance in their respective judgments, but that the correlations are much lower when these observers are compared with those of Andrea van Doorn. The primary reason for this difference is that the reconstructions of the back and shoulder regions for observer Andrea van Doorn were rotated in depth about the vertical axis to a much greater extent than was evident for the other observers.

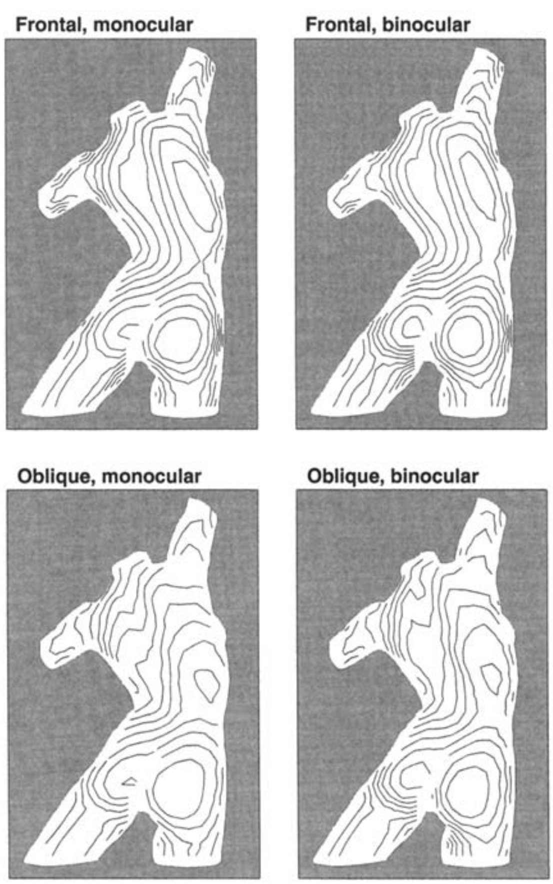

Figure 4. The isodepth contours computed for the judgments of the female torso by observer Andrea van Doorn for four different viewing conditions.

Table 3 shows the r^2 values and slopes of regression for the correlations between the monocular and stereoscopic conditions for all of the different observers and illumination directions. Note that in this case the linear trend accounts for approximately 95% of the variance, indicating that the addition of binocular disparity produces an affine stretching transformation in depth relative to the pictorial relief obtained in the monocular conditions. In general, the regression lines had slopes greater than one, indicating that stereoscopic viewing increases the magnitude of pictorial relief. It is interesting to note, however, that the opposite effect was obtained by all four observers for the female torso with oblique illumination (i.e., the slopes in that condition were all less than one). We do not have a convincing hypothesis as yet for why the effects of stereoscopic viewing should vary for different stimulus objects, although perhaps it could be due to misleading disparity information from the surface's highlights and occlusion boundaries (see Norman & Todd, 1994).

Table 4 shows the r^2 values and slopes of regression for the correlations between the oblique and frontal illumination conditions for all of the observers with both monocular and stereoscopic viewing. Again, there was a strong linear trend in the data that accounted for approximately 84% of

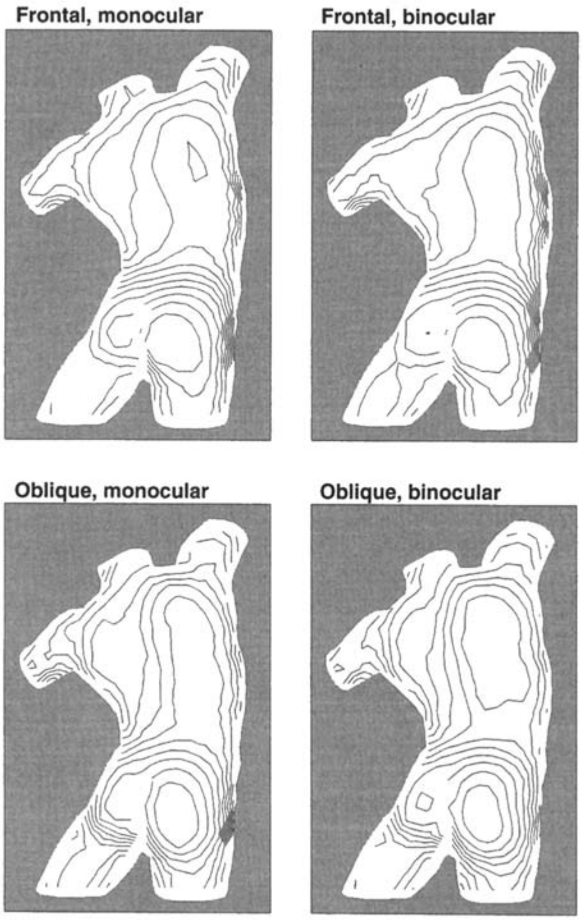

Figure 5. The isodepth contours computed for the judgments of the male torso by observer Astrid Kappers for four different viewing conditions.

the variance. Note that most of the regression lines had slopes less than one, which indicates that oblique illumination produced a greater amount of pictorial relief than did the frontal illumination. This was especially true for the female torso in the monocular condition, where the judged depth for oblique illumination was as much as twice that for the frontal illumination (e.g., see Figure 6).

In examining the scatter plots between different observers and different conditions, we noticed in many instances that the data points were not distributed at random around the best-fitting regression lines. Rather they seemed to be grouped in perceptually distinct clusters with different slopes and intercepts. Consider, for example, the scatter plot shown in the left panel of Figure 10, which compares observer Astrid Kappers's judgments of the monocular male torso with oblique and frontal illumination. In an effort to reveal the underlying component structure of this pattern, we attempted to isolate different subgroups of probe points that appeared perceptually to form distinct clusters in the scatter plot. When we examined where these clustered probe points were located on the depicted torso, we found that they corresponded to distinct anatomical regions, which are shown in the left panel of Figure 10. In general, the individual correlations for these different regions considered separately were much higher than the r^2 values obtained when the entire data set was treated as a single population. Table 5 shows the different body parts that emerged from these clusters, together with the slopes, intercepts, and r^2 values for the best-fitting regression line for each part. From the wide range of slopes and intercepts of Table 5, it is clear that changing the direction of illumination from an oblique to a frontal direction had varying effects on different body

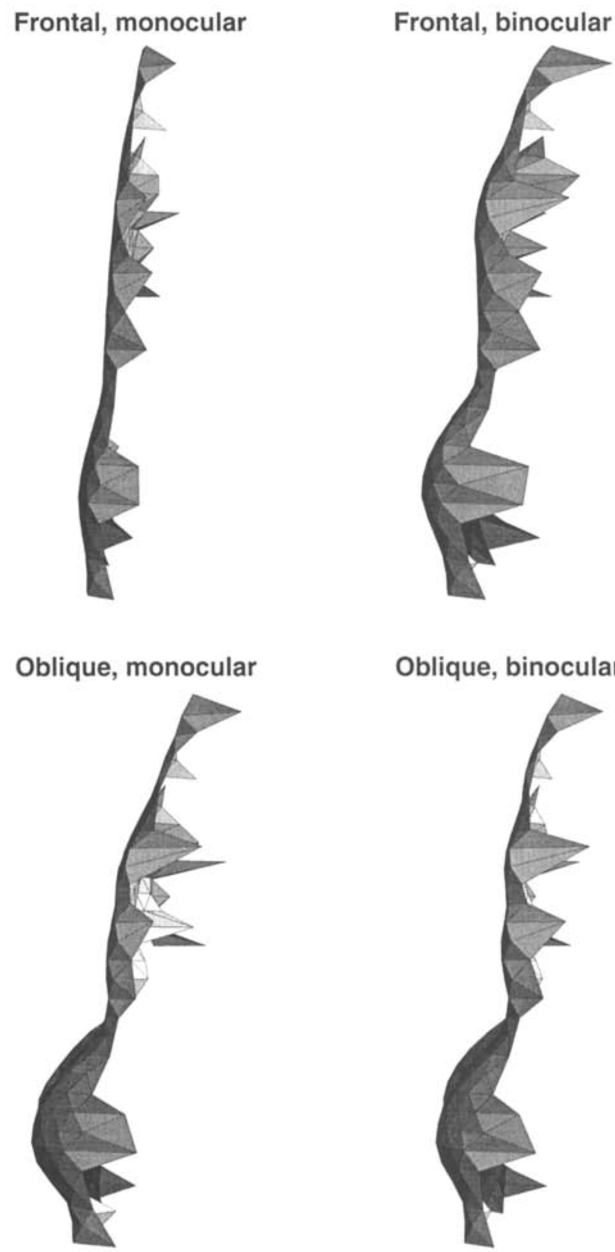

Figure 6. The profile reconstructions computed for the judgments of the female torso by observer James Todd for four different viewing conditions.

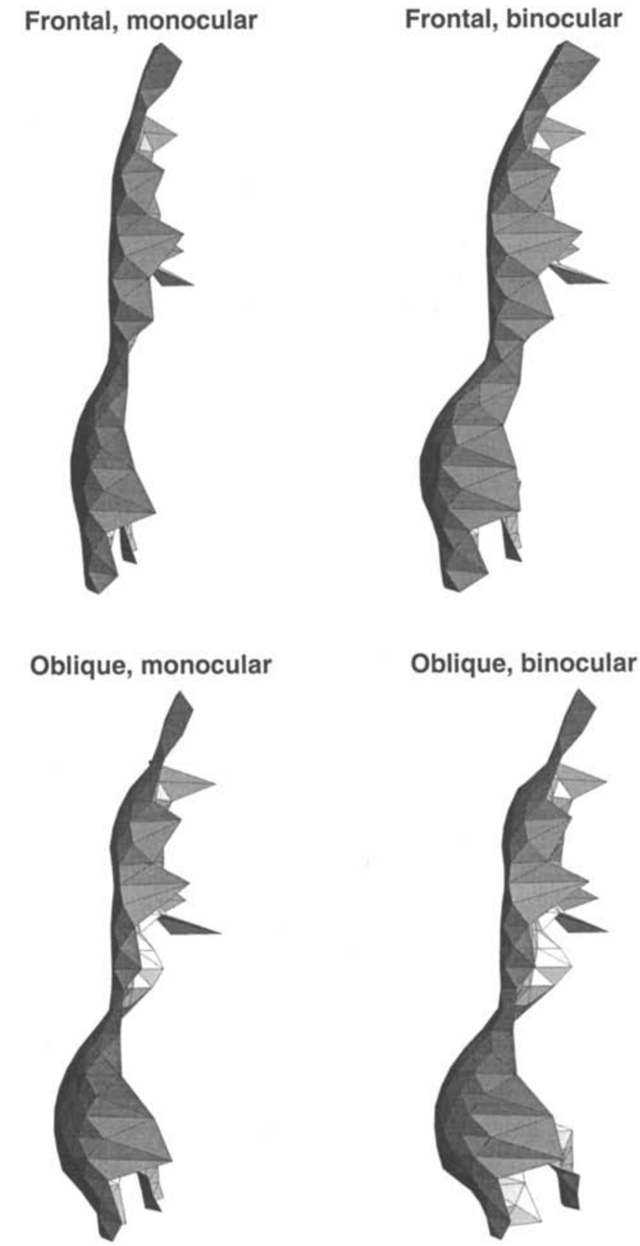

Figure 7. The profile reconstructions computed for the judgments of the male torso by observer Jan Koenderink for four different viewing conditions.

parts. For example, it increased the judged relief of the waist region by 34%, but it decreased the judged size of the left buttock by 22%. These effects can be seen more clearly in Figure 4 by examining the density of isodepth contours for the oblique and frontal monocular conditions in the regions of the waist and just below the left buttock.

A similar distinction among different body parts can be seen in the comparisons among different observers. The left panel of Figure 11 shows a scatter plot comparison of judged depths between observers Andrea van Doorn and James Todd for the stereoscopically viewed female torso with frontal illumination. As in the previous example, the points appear in distinct clusters, which correspond to contiguous bounded regions on the depicted torso. These are shown in the right panel of Figure 11. Table 6 lists the different regions in this figure, together with the slopes, intercepts, and r^2 values for their best-fitting regression lines. Note that the differences between the judgments made by Andrea van Doorn and James Todd vary dramatically among the different parts. Although their judgments were quite similar for the left buttock, the reconstructions made by Andrea van Doorn had twice as much relief in the back region, whereas those made by James Todd had twice as much relief in the breast region. Both of these effects are probably due to the twisting of the back and shoulder

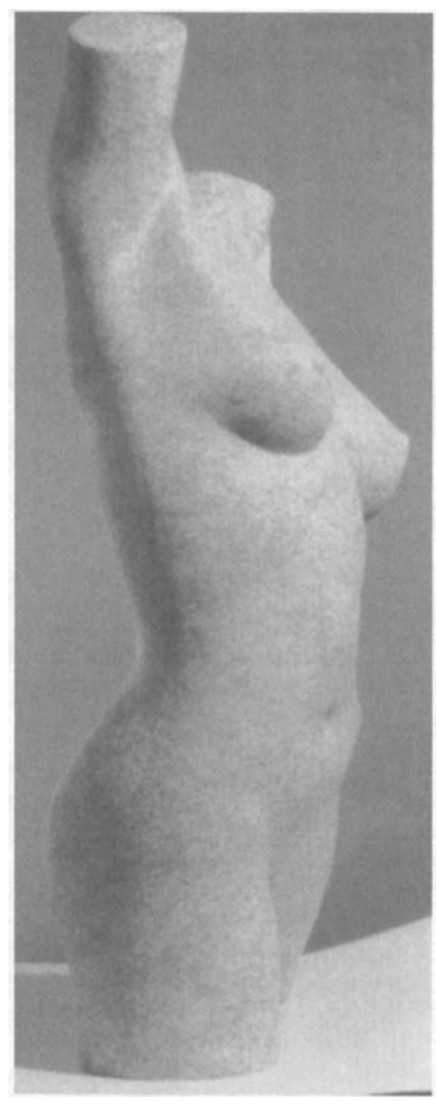

Figure 8. A profile view of the female torso. Although this image was not presented during the actual experiment, it is included to allow a comparison with the profile reconstructions shown in Figure 6.

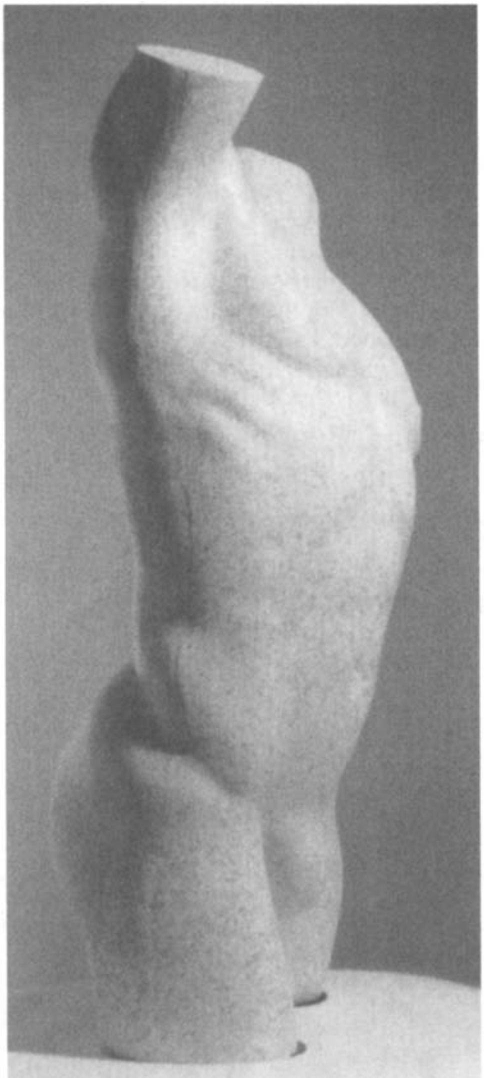

Figure 9. A profile view of the male torso. Although this image was not presented during the actual experiment, it is included to allow a comparison with the profile reconstructions shown in Figure 7.

regions about the vertical axis that is characteristic of Andrea van Doorn's judgments of the female torso. Similar part distinctions were also evident in the comparison made by Andrea van Doorn's judgments with those made by Astrid Kappers and Jan Koenderink.

Discussion

The research described in the present article was designed to examine observers' perceptions of complex, smoothly curved surfaces for a variety of conditions. The stimuli consisted of photographic images of a male and a female torso with either frontal or oblique illumination, which could be presented either monocularly or stereoscopically. Observers judged the shapes of these torsos using a gauge figure adjustment task to estimate the local slant and tilt at numerous probe points arranged in a lattice over the torso's surface. These local attitude judgments were then used to approximate the best-fitting surface to the data in a least squares sense, using an analysis described previously by Koenderink et al. (1992, 1994).

There is a growing amount of evidence to suggest that the reconstructed surfaces obtained with this procedure provide a reasonably valid measure of the perceived surface relief of visible objects in 3D space. One source of evidence to support this conclusion is that there is a strong correlation between the reconstructed surfaces and the actual physical structure of the depicted stimulus objects (e.g., see Koenderink et al., 1994; Koenderink, Kappers, Todd, Norman, & Phillips, 1995; Norman, Todd, & Phillips, 1995), although the slopes of these correlations are seldom one, indicating the presence of a systematic affine distortion of the surface relief along the line of sight. Second, there is also a strong correlation among the judgments obtained for different observers, as was demonstrated in the present experiment and in the previous findings of Koenderink and van Doorn (1995) and Koenderink, et al. (1992, 1994, 1995). Finally, the results obtained using this technique have been confirmed using multiple converging operations, including judgments of ordinal depth (Koenderink & van Doorn, 1995) and adjustments of a stereoscopic depth probe (Koenderink, Kappers, Todd, Norman, & Phillips, in press). The reconstructed surfaces obtained by all of these techniques are remarkably similar, although the attitude probe task appears to be the most reliable.

The results obtained with this task in the present experiment provide clear evidence that observers' perceptions of 3D structure do not exhibit constancy for the different viewing conditions we investigated. That is to say, there were systematic distortions in the perceived 3D structures of the depicted torsos as a function of whether they were viewed monocularly or stereoscopically and whether they were illuminated from a frontal or oblique direction. The specific nature of these distortions differed, moreover, for the different types of stimulus manipulations. For all of the observers, the judged surfaces in the monocular and stereoscopic conditions were related by an affine stretching transformation in depth that accounted for approximately 95% of the between-condition variance. There was also a strong affine component between the judgments obtained for the different illumination directions, although the percentage of variance accounted for in that case was significantly smaller—approximately 84% on average. A further analysis of the residuals of this correlation revealed that changing the direction of illumination influenced the perceived structure of the torsos in a piecewise manner.

One plausible hypothesis for this latter effect is that the magnitude of perceived relief is significantly influenced by the presence of cast shadows, which are essentially local in nature. Other things being equal, a part that casts a prominent shadow will be perceived to have greater relief than a part that does not. Because there are no visible cast shadows with frontal illumination, we would predict from this hypothesis that the overall perceived surface relief should

Table 2
r^2 Values Obtained for the Correlations Between All Pairs of Observers

Condition	Observers						Total
	A.V.–A.K.	A.V.–J.K.	A.V.–J.T.	A.K.–J.K.	A.K.–J.T.	J.K.–J.T.	
Female							
Frontal, mono	.73	.67	.68	.78	.86	.90	.77
Oblique, mono	.86	.73	.74	.77	.92	.76	.80
Frontal, stereo	.60	.72	.60	.87	.91	.93	.77
Oblique, stereo	.84	.72	.55	.90	.80	.89	.78
Male							
Frontal, mono	.78	.78	.57	.88	.90	.75	.78
Oblique, mono	.85	.74	.68	.93	.84	.89	.82
Frontal, stereo	.67	.85	.53	.87	.90	.71	.76
Oblique, stereo	.83	.62	.54	.88	.81	.83	.75
Total	.77	.73	.61	.86	.87	.83	.78

Note. r^2 = Pearson product–moment correlation squared; mono = monocular; stereo = stereoscopic.

increase as the direction of illumination becomes more and more oblique, which is generally consistent with the empirical results. There are several other testable implications of this hypothesis that would be interesting to consider in future research. It suggests, for example, that perceived relief should vary as a function of a part's orientation, relative to the direction of illumination. It also suggests that it may be possible to manipulate the relative relief of different parts by using a localized spot illumination to enhance or attenuate the relative contrast of their cast shadows.

It is a widely accepted view among many theorists that the perceptual representation of objects in space may involve a hierarchical organization of distinct parts, and there have been several hypotheses proposed in the literature for how these parts might be defined (e.g., see Beusmans, Hoffman, & Bennett, 1987; Biederman, 1987; Hoffman & Richards, 1984; Hummel & Biederman, 1992; Marr & Nishihara, 1978; Richards, Koenderink, & Hoffman, 1987). Despite this general consensus, however, there is relatively little hard empirical evidence to support the psychological validity of these theories. The best evidence to date for the existence of parts in perceptual representations comes from the work of Biederman and his colleagues (e.g., see Biederman, 1987; Biederman & Cooper, 1991), using reaction time and priming techniques for line drawings of objects with various parts deleted. The results of the present experiment suggest an alternative methodological approach that may prove useful in future investigations. This approach is based on a general operating assumption that structural relations within a given part should remain more stable to changes in viewing conditions than should the structural relations among different parts.

It is interesting to note, in considering our analysis, that the parts it revealed were intuitively quite natural, and they all corresponded to regions of the body that have distinct names, such as the arms, legs, waist, back, neck, shoulder blades, breast, and buttocks. Although this provides some degree of confidence that the suggested part decomposition is reasonable, it is best to be circumspect about its specific details. There are several important issues in this regard that need to be considered by future research. It remains to be determined, for example, whether object parts will remain

Table 3
r^2 Values and Slopes of Regression for the Correlations Between the Monocular and Stereoscopic Conditions for All of the Observers and Illumination Directions

Observer/ condition	Female r^2	Male r^2	Female slope	Male slope
A.V.				
Frontal	.96	.98	1.13	1.06
Oblique	.95	.94	.86	1.20
A.K.				
Frontal	.96	.95	1.47	1.20
Oblique	.86	.96	.83	1.20
J.K.				
Frontal	.94	.98	1.30	1.57
Oblique	.94	.96	.90	1.17
J.T.				
Frontal	.90	.94	1.54	1.05
Oblique	.95	.98	0.74	0.70

Note. r^2 = Pearson product–moment correlation squared.

Table 4
r^2 Values and Slopes of Regression for the Correlations Between the Oblique and Frontal Illumination Conditions for All of the Observers With Both Monocular and Stereoscopic Viewing

Observer/ condition	Female r^2	Male r^2	Female slope	Male slope
A.V.				
Mono	.88	.86	0.49	0.82
Stereo	.94	.85	0.67	0.71
A.K.				
Mono	.92	.76	0.70	1.17
Stereo	.74	.64	1.05	1.08
J.K.				
Mono	.82	.92	0.64	0.69
Stereo	.91	.86	0.97	0.89
J.T.				
Mono	.89	.84	0.74	0.91
Stereo	.89	.76	1.20	1.02

Note. r^2 = Pearson product–moment correlation squared.

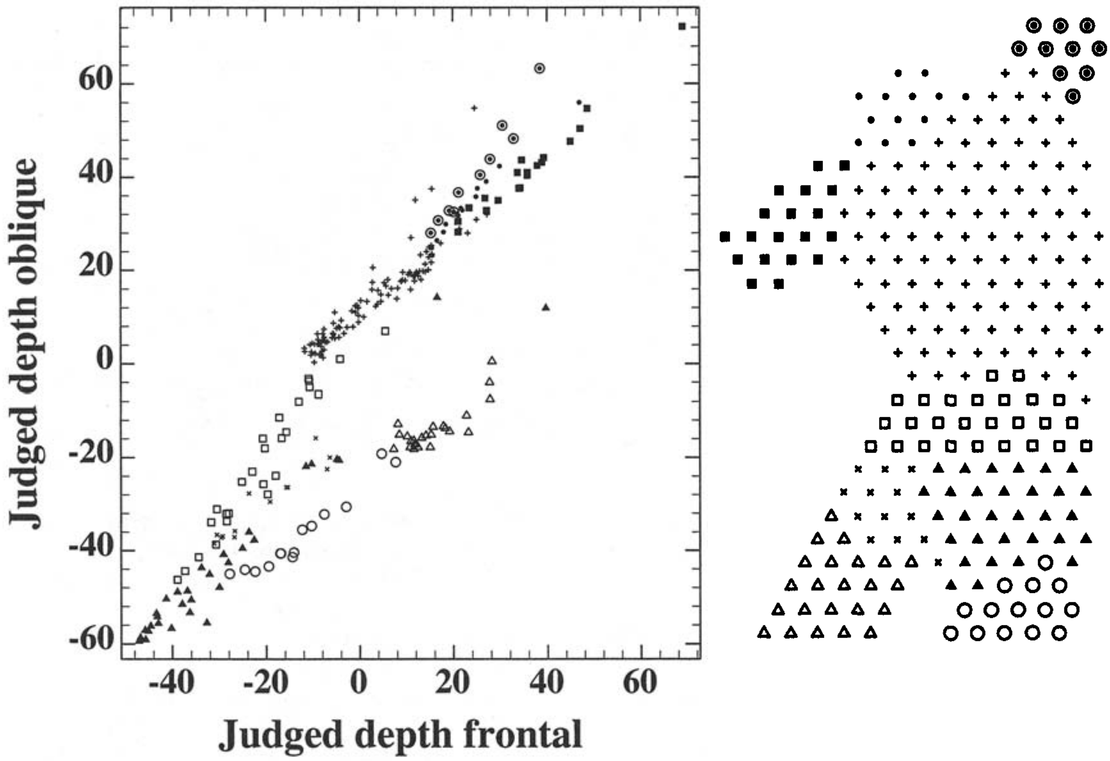

Figure 10. A scatter plot comparing the judgments of Astrid Kappers for the monocular male torso with oblique and frontal illumination (right). The data points in this graph are organized in distinct clusters represented by different symbols, whose corresponding locations on the depicted torso are shown in the left panel.

stable over changes in viewing position, whether the process of part decomposition may vary for different types of objects such as plane-faced polyhedra and smoothly curved surfaces, and whether the perceived parts of complex jointed objects such as a human torso may vary as a function of their specific configuration. There is some anecdotal evidence to suggest that object parts can be context dependent. For example, it is well-known among graphical artists that in drawing the human body, the knee must sometimes be depicted as part of the upper leg, whereas for other poses, it must be depicted as part of the lower leg (e.g., see Hogarth, 1970).

One final issue that deserves to be considered is the extent to which these findings can be generalized to the perception of real objects in a natural environment under full cue conditions. Although the stimuli used in the present experiment were restricted to monocular shaded images and stereograms, these same effects can be obtained when viewing real objects in a natural environment. The distortions observed between monocular and binocular viewing have been reported previously by Koenderink et al. (in press), and can easily be experienced under more natural conditions by carefully attending to the perceived relief of a picture or a real scene while successively opening and closing one eye. The distortions produced by changing the direction of illumination can also be observed with real objects, although the demonstration is a bit more difficult to set up. This can be achieved most compellingly by carefully attending to the perceived relief of an object with two different directions of illumination that can be rapidly switched back and forth.

For both of the demonstrations described above it is important to pay careful attention to the overall magnitude of perceived relief. Although the perceived metrical struc-

Table 5
Slopes, Intercepts, and r^2 Values for the Best-Fitting Regression Line for Each of the Distinct Body Parts Identified in Figure 10

Body part	r^2	Slope	Intercept
Back	.97	0.86	11.30
Left arm	.87	0.87	10.34
Right arm	.96	1.43	5.24
Neck	.97	1.03	10.35
Waist	.94	1.34	6.44
Left buttock	.90	0.78	−13.78
Right buttock	.95	0.94	−15.23
Left leg	.66	0.59	−23.24
Right leg	.94	0.78	−26.74

Note. r^2 = Pearson product–moment correlation squared.

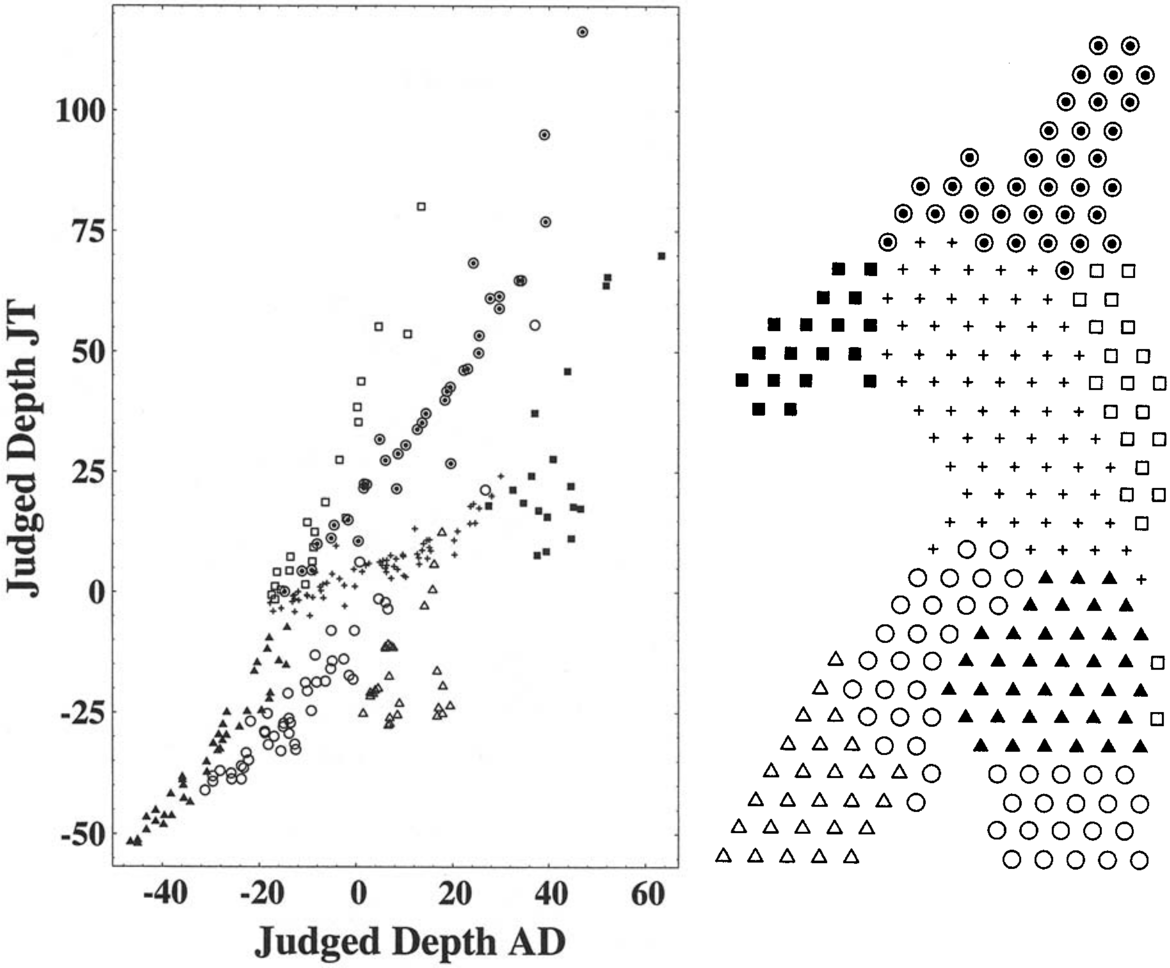

Figure 11. A scatter plot comparing the judgments of Andrea van Doorn and James Todd for the stereoscopic female torso with frontal illumination (right). The data points in this graph are organized in distinct clusters represented by different symbols, whose corresponding locations on the depicted torso are shown in the left panel.

ture of an object may be systematically distorted by changing viewing conditions, there are many other aspects of 3D form that will remain invariant. It would appear to be the case that these invariant nonmetrical properties may be the primary components of our phenomenal awareness in most natural circumstances. When naive observers are asked to describe the appearance of a scene with a moving light source or when opening and closing one eye, they will inevitably report that its 3D structure remains perfectly rigid and stable. The systematic effects of these manipulations on an object's perceived shape will be noticed only when observers are specifically instructed to attend to its metrical structure.

Table 6
Slopes, Intercepts, and r^2 Values for the Best-Fitting Regression Line for Each of the Distinct Body Parts Identified in Figure 11

Body part	r^2	Slope	Intercept
Back	.83	0.45	3.54
Left arm	.51	1.71	−43.43
Right arm	.91	1.57	16.62
Left leg	.1	0.56	−22.3
Breast	.91	2.37	35.96
Right buttock	.94	1.3	6.36
Left buttock and right leg	.91	1.23	−7.41

Note. r^2 = Pearson product–moment correlation squared.

All of this has important theoretical implications for the computational analysis of 3D form from various aspects of optical information. A fundamental assumption of many existing models is that visible surfaces are perceptually represented as point-by-point mappings of local metrical properties such as depths or orientations (e.g., Marr, 1982; Marr & Nishihara, 1978). Given the growing evidence that these properties do not exhibit constancy over changes in viewing distance, orientation, or the direction of illumination, yet the perception of shape remains stable over these changes, it seems reasonable to conclude that the computational analysis of local metrical structure may have little relevance to human vision under most natural circumstances.

References

Baird, J. C., & Biersdorf, W. R. (1967). Quantitative functions for size and distance judgments. *Perception & Psychophysics, 2,* 161–166.

Beusmans, J. M. H., Hoffman, D. D., & Bennett, B. M. (1987). Description of solid shape and its inference from occluding contours. *Journal of the Optical Society of America A. 4,* 1155–1167.

Biederman, I. (1987). Recognition-by-components: A theory of human image understanding. *Psychological Review, 94,* 115–147.

Biederman, I., & Cooper, E. E. (1991). Priming contour deleted images: Evidence for intermediate representations in visual object recognition. *Cognitive Psychology, 23,* 293–419.

Brewster, D. (1826). On the optical illusion of the conversion of cameos into intaglios and of intaglios into cameos, with an account of other analogous phenomena. *Edinburgh Journal of Science, 4,* 99–108.

Fieandt, K. von (1938). Uber das sehen von tiefengebilden bei wechselnder beleuchtungsrichtung [Improvements in depth perception by changes in lighting]. Helsinki, Finland: Psychologisches Institut Universitat Helsinki.

Fieandt K. von (1949). Das phanomenologische problem von licht und schatten [The phenomenological problem of light and shaddow]. *Acta Psychologica, 6,* 337–357.

Harway, N. I. (1963). Judgment of distance in children and adults. *Journal of Experimental Psychology, 65,* 385–390.

Heine, L. (1900). Ueber Orthoskopie oder ueber die Abhaengigkeit relativer Entfernungsschaetzungen von der Vorstellung absoluter Entfernung. [On orthoscopic vision, or on the dependence of relative distance judgments on perceived absolute distance]. *Albrecht von Graefe's Archiv fuer Ophthalmologie, 51,* 563–572.

Hoffman, D. D., & Richards, W. A. (1984). Parts of recognition. *Cognition, 18,* 65–96.

Hogarth, B. (1970). *Dynamic figure drawing.* New York: Watson-Guptil.

Hummel, J. E., & Biederman, I. (1992). Dynamic binding in a neural network for shape recognition. *Psychological Review, 99,* 480–517.

Johnston, A., & Passmore, P. J. (1994). Shape from shading. I: Surface curvature and orientation. *Perception, 23,* 169–190.

Koenderink, J. J., Kappers, A. M. L., Todd, J. T., Norman, J. T., & Phillips, F. (in press). Surface range and attitude probing in stereoscopically presented dynamic scenes. *Journal of Experimental Psychology: Human Perception and Performance.*

Koenderink, J. J., & van Doorn, A. J. (1995). Relief: Pictorial and otherwise. *Image and Vision Computing, 13,* 321–334.

Koenderink, J. J., van Doorn, A. J., & Kappers, A. M. L. (1992). Surface perception in pictures. *Perception & Psychophysics, 52,* 487–496.

Koenderink, J. J., van Doorn, A. J., & Kappers, A. M. L. (1994). On so-called "paradoxical monocular stereoscopy." *Perception, 23,* 583–594.

Koenderink, J. J., van Doorn, A. J., & Kappers, A. M. L. (1995). Depth relief. *Perception, 24,* 115–126.

Loomis, J. M., Da Silva, J. A., Fujita, N., & Fukusima, S. S. (1992). Visual space perception and visually directed action. *Journal of Experimental Psychology: Human Perception and Performance, 18,* 906–921.

Marr, D. (1982). *Vision.* San Francisco, CA: Freeman.

Marr, D., & Nishihara (1978). Representation and recognition of the spatial organization of three-dimensional shapes. *Proceedings of the Royal Society of London, B. 207,* 187–217.

Mingolla, E., & Todd, J. T. (1986). Perception of solid shape from shading. *Biological Cybernetics, 53,* 137–151.

Norman, J. F., & Todd, J. T. (1994). The perception of rigid motion in depth from the optical deformations of shadows and occlusion boundaries. *Journal of Experimental Psychology: Human Perception and Performance, 20,* 343–356.

Norman, J. F., Todd, J. T., Perotti, V. J., & Tittle, J. S. (1996). The visual perception of three-dimensional length. *Journal of Experimental Psychology: Human Perception and Performance, 22,* 173–186.

Norman, J. F., Todd, J. T., & Phillips, F. (1995). The perception of surface orientation from multiple sources of optical information. *Perception & Psychophysics, 57,* 629–636.

Reichel, F. D., & Todd, J. T. (1990). Perceived depth inversion of smoothly curved surfaces due to image orientation. *Journal of Experimental Psychology: Human Perception and Performance, 16,* 653–664.

Richards, W. A., Koenderink, J. J., & Hoffman, D. D. (1987). Inferring three-dimensional shapes from two-dimensional silhouettes. *Journal of the Optical Society of America A. 4,* 1168–1175.

Rittenhouse, D. (1786). Explanation of an optical illusion. *Transactions of the American Philosophical Society, 2,* 37–42.

Thouless, R. H. (1931). Phenomenal regression to the real object. *British Journal of Psychology, 21,* 339–359.

Tittle, J. S., Todd, J. T., Perotti, V. J., & Norman, J. F. (1995). Systematic distortion of perceived three-dimensional structure from motion and binocular stereopsis. *Journal of Experimental Psychology: Human Perception and Performance, 21,* 663–678.

Todd, J. T., & Reichel, F. D. (1989). Ordinal structure in the visual perception and cognition of smoothly curved surfaces. *Psychological Review, 96,* 643–657.

Wagner, M. (1985). The metric of visual space. *Perception & Psychophysics, 38,* 483–495.

Received September 12, 1994
Revision received March 13, 1995
Accepted April 19, 1995 ■