INTEGRATION OF SHADING AND TEXTURE CUES IN THE PERCEPTION OF SOLID SHAPE

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Dedicated to Maureen & Francis Curran.
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ABSTRACT.

In constructing a three-dimensional perception of our environment the visual system draws on a number of different sources of information available in the image. It is often assumed that, at the early stages of this process, these cues to three-dimensional shape are processed independently, and are later integrated to form the three-dimensional percept. The experiments in this thesis address a number of issues relating to the integration of shading and texture cues. These include 1) At what level of representation are shading and texture cues integrated? 2) Is the integration of these cues a linear or non-linear process? 3) What factors influence the weights assigned to cues? 4) Is shape from shading and texture a local or global process? 5) What texture properties do subjects use to extract curvature information? and, finally, 6) What factors influence the perceived degree of curvature of a convex surface. Two main paradigms, perturbation analysis and 3D curvature contrast, were employed in an attempt to answer these questions.

The results of the experiments described in this thesis lead to the following conclusions: a) the locus of integration for the shading and texture cues used in these experiments is more likely to be a curvature map than a depth map; b) the integration of these cues is not best described by a linear model, but by a non-linear model; c) although the shading and texture cue weights are robust across a number of different viewing conditions, they are influenced by some context manipulations as well as by the cues' availability and reliability; d) 2D line curvature appears to be the primary source of texture curvature information used by subjects in these experiments; e) the processing of shape from shading and texture cannot be a purely local operation, but appears also to include global operations; and, finally, f) although the perceived curvature sign of a convex surface defined by shading may be disambiguated with the inclusion of other cues, it is demonstrated that subjects' perception of the surface's degree of curvature may be influenced by other factors. These include light source position and the curvature of the background in which the surface is embedded.
CHAPTER ONE

INTRODUCTION

Humans have evolved several sensory systems which are employed in guiding our behaviour in a potentially hazardous environment. These include the haptic, visual, gustatory, auditory and olfactory systems. It could be argued that the visual system is one of the more complex of our sensory repertoire; up to one third of the cerebral cortex in humans is given over to visual perception. A core task of the human visual system is to build up a three-dimensional representation or percept of the visual scene from a paired sequence of two-dimensional retinal images of the scene in question. To create a representation of depth the visual system makes use of several cues, including occluding contours (of which Marr (1982) identifies three classes), relative size, relative height, familiar size, linear perspective, motion parallax, blur, shading, texture gradients, and binocular disparity. All, except binocular disparity, are monocular depth cues. Two additional depth cues, convergence and accommodation, provide information not from the retinal image but from the muscles of the eye.

The past few decades have witnessed a growing interest in how the brain processes individual cues to depth. Investigators typically test subjects’ perception of depth using images in which a single depth cue can be manipulated in isolation. This approach to depth perception has been adopted in the investigation of the perception of shape from
stereopsis (Julesz, 1971), shape from shading (Ramachandran, 1988; Todd & Mingolla, 1983), shape from motion (Sperling, Landy, Dosher & Perkins, 1989; Wallach & O'Connell, 1953), and shape from texture gradients (Cutting & Millard, 1984; Stevens, 1981; Todd & Akerstrom, 1987; Witkin, 1981) amongst others. Research of this type is based on the assumption that the visual perception of objects is achieved by a visual system made up of largely independent modules.

1.1 A MODULAR APPROACH TO VISION.

A system which is structurally modular contains distinct modules that are located at different physical sites within the system. The modules in such a system may or may not process information independently of each other. If its modules are autonomous in their computations, then such a system would also be considered to be functionally modular. Just as a structurally modular system can exist without being functionally modular, so too can a functionally modular system exist in the absence of modular structures.

Fodor (1983) proposes a view of modularity in which he defines a module as a subsystem characterized by the following set of properties; 1) it is informationally encapsulated, having access to only a very restricted amount of information contained in the system as a whole; 2) it is computationally autonomous, that is it does not share any general-purpose processes (such as memory) with other modules; 3) it is domain specific, innately specified, hard-wired, and is not assembled from more basic elements. Fodor argued that only input systems are modular, and that central processing is carried out by a diffuse equipotentially organised system. For Fodor the main criterion of modularity is that, given a particular input, an operation is mandatory; if an operation is not mandatory, then
it is carried out by equipotential central systems rather than modular input systems. Fodor's theory that central processing systems, those processes that occur beyond the "observation-inference" interface, are not modular has been challenged in recent years by neuropsychologists (see Shallice (1990) for possible examples of central modular systems). His proposal that input systems are modular, however, has been very influential and widely accepted.

For Marr (1982), the primary advantage of a modular system in which a large computation is split up and implemented as a collection of small, autonomous sub-parts is that a small change in one place will not seriously compromise the activities in other places. However, if a process is not designed in this way, a small change in one place will have consequences in many other places. Therefore, from an evolutionary perspective, a non-modular system would be less adaptive than a modular one.

Thus there is a clear adaptive advantage in having inherited a visual system which has evolved in a modular fashion. However, regardless of its advantages, is there any evidence that the human visual system is functionally and/or structurally modular? There is evidence to suggest that this is indeed the case. This evidence has been contributed, in the main, from two fields of science - neurophysiology and neuropsychology.

1.1.1 Neurophysiological Evidence Of Modularity.

Neurophysiological and anatomical research of primate visual systems over the past twenty years has provided clear evidence that the visual cortex is divided into areas that
can be functionally and anatomically differentiated. This division of the visual system into specialized pathways begins at the retina and continues through the lateral geniculate nucleus (LGN) to the visual cortex. There are two identifiable specialized pathways projecting from the retina to different destinations in the visual cortex, known as the M and P pathways (Zeki & Shipp, 1988). P α retinal ganglion cells project, via the magnocellular layers (M pathway) of the LGN, to layers 4Ca and 4B of striate cortex. The M pathway then seems to split into two pathways, one concerned with orientation and the other concerned with direction selectivity. From here, the M pathway projects to areas V3 and V5 directly, and indirectly to V5 through the thick stripes of V2. The chief functions of V3 are thought to be orientation selectivity, suggesting that it receives its inputs from the orientation pathway which arises in layer 4B of V1, and processing dynamic form; the primary function of V5 is motion processing (Zeki, 1993).

P β retinal ganglion cells project, via the parvocellular layers (P pathway) of the LGN, to the blobs and interblobs of layers 2 and 3 of V1. The blobs contain cells that are responsive to wavelength, and are thus suited to extracting information about colour; interblobs cells, on the other hand, are mainly orientation selective and respond to contours generated by differences in wavelength or luminance (Hubel & Livingstone, 1985; Zeki & Shipp, 1988). Thus the P pathway divides into two pathways in layers 2 and 3 of V1; one pathway, which is concerned with colour, and a second pathway concerned with detecting form. Both pathways project, via V2, to V4.

The segregation of function briefly described above allows different regions of the visual cortex to process motion, form and colour with a large degree of autonomy. The M
system appears to be more concerned with the form of moving objects and with
generating structure from motion, whereas the P system is more concerned with colour
perception (Zeki & Shipp, 1988). However, the presence of orientation selective cells in
both these systems suggests that both pathways are, to a greater or lesser extent, involved
in form perception. Just as neurons responsive to orientation and motion have been
isolated in several areas of the striate cortex in primates, so too have binocularly driven
neurons (Zeki, 1979) and neurons tuned to different disparities (Poggio, 1984). Such
neurons have also been isolated in the thick stripes of area V2; and in area V5 where they
have been found to be tuned to both binocular disparity and direction of motion
(Maunsell, 1988). While the above studies suggest that the signals projecting from the M
and P pathways continue to be segregated in visual cortex, more recent studies suggest only
a partial correspondence between the subcortical and cortical pathways (Maunsell, 1992;
Nealey & Maunsell, 1994; Ferrera, Nealey & Maunsell, 1994).

There is now extensive evidence from primate studies demonstrating that the visual
system segregates information about the visual world. Recent research (Zeki, et al., 1991)
has demonstrated the existence of functionally specialised areas in the human visual cortex
reflecting those observed in the macaque monkey. Given that we perceive the visual
world as a unified whole, with all the various properties of objects being perceived in
exact spatio-temporal registration, one would expect to find anatomical and physiological
evidence of the integration of visual information. Zeki and Shipp (1988) describe two
types of integration or convergence as an anatomical means of assembling information,
topical and confluent, both of which are found in all types of cortical projections -
backward, forward and lateral. Zeki and Shipp define topical convergence as occurring
within a specialized pathway and involves integration of an attribute across space;
confluent convergence, on the other hand, occurs between pathways and involves
integration between different attributes. An example of forward topical convergence is
seen in the colour pathway of the P pathway, where many blobs in V1 project onto one thin stripe in V2, which, in turn, is only one of several thin stripes that project to a small part of V4. An example of confluent convergence between pathways is seen in the connections between the separate zones in the temporal lobe, that receive inputs from V4 and V5, where neurons selective for faces are found in juxtaposition with neurons which respond to body movements.

Zeki (1993) acknowledges that the integrative processes described above result in the loss of important information which must be recovered. For example, the enlargement of receptive fields as a consequence of forward topical convergence results in an imprecise topographic map and, consequently, in higher cortical areas these cells are not as able to locate the exact position of a stimulus. Zeki proposes that the visual cortex has evolved "re-entrant pathways" that overcome this and other problems of functional specialization, such as compiling two or more signals from different stages of different parallel pathways.

By re-entrant pathways Zeki is referring to the diffuse return input from the various specialized visual areas to V1 and V2. Unlike the inputs reaching a specialized visual area, re-entrant input from that area is not segregated, nor is it restricted to the area of V1 or V2 that projects to the specialized region.

A good example of this is the re-entrant input to layer 4b of V1 from V5, which distributes to the territory of cells projecting to areas other than V5 as well as to the territory of cells projecting to area V5. Zeki proposes that the consequence of this particular re-entrant pathway is the integration of the two different branches of the M system - V5 and V3 - which are concerned predominantly with motion and form,
respectively. A similar re-entrant pathway connecting area V4 with area V2 is described by Zeki (1993); it is thought that this pathway unites signals belonging to form, motion and colour. Unlike the projections from V1 and V2 to the specialized visual areas, the re-entrant pathways are not easily localizable and seem to lack modularity. Thus although attributes of the visual scene, such as form or colour, are almost certainly processed by distinct modules, the integration of such information appears to be executed by a non-modular system.

1.1.2 Neuropsychological Evidence Of Modularity.

Neuropsychological research provides evidence that concurs with neurophysiological findings suggesting that the visual system is structurally and functionally modular. Much of this evidence has originated from clinical studies demonstrating dissociations between disorders of visual perception. Since the turn of the century there have been reports of patients suffering from specific deficits in the perception of shape (Efron, 1968; Warrington, 1986), colour (Mollon, Newcombe, Polden & Ratcliff, 1980), movement (Zihl, Von Cramon & Mai, 1983), and in the visual information necessary for the accurate visual guidance of actions. These deficits have been found to exist independent of visual acuity. By testing a group of patients with bilateral occipital lobe lesions, Warrington (1986) obtained every possible pair-wise combination of intact and impaired dimensions for perception of location, colour, and of shape; thus demonstrating that these impairments are distinct, and supporting the idea that the visual system has a modular architecture. These and other clinical findings that very specific visual abilities can be selectively compromised in half or even all of the visual field provide strong evidence that different
visual functions are carried out in separate brain regions.

If, as the above evidence suggests, the human visual system comprises autonomous modules involved in the independent analysis of visual information such as colour, shape, and movement, it is possible that there exists within the visual system other subsystems for the independent processing of visual features such as shading and texture. Such a proposition is supported by the fact that we readily recognise images of objects defined by either of these two cues in isolation. The ability of the visual system to discern images generated by just shading or texture has led to attempts at identifying the critical characteristics of these cues that the visual system exploits. The following two sections give an overview of the progress to date in these two areas of research.

1.2 SHAPE FROM SHADING:

Although there has been a growing experimental interest in form perception over the past few decades, work on shape from shading was largely neglected until the late seventies. This was despite the fact that artists have made effective use of shading in their execution of paintings for several centuries. This late development was partly a consequence of the unavailability of an appropriate technology for the systematic manipulation of shaded images with mathematical precision. These methodological difficulties have, however, been largely overcome by the increasing availability of computer graphic systems. The increasing availability of such technology was accompanied by the rapid development and growth of another field of research - computer vision research. Thus over the past fifteen
years technological developments have provided valuable tools with which to investigate and/or to simulate the visual processing of images defined by shading (or, indeed, any other visual cues).

A major problem encountered by those who wish to mathematically model or simulate how the visual system processes shading information is often referred to as the "many-to-one mapping" problem (Todd & Mingolla, 1983). This describes how the specific intensity of any given point on an observed surface can be generated by an infinite number of possible combinations of several variables, including surface orientation and position, surface reflectance, light-source intensity, and light source position. To overcome this problem of image analysis, researchers in artificial intelligence adopt simplifying assumptions that are designed to constrain the number of possible solutions to just one. These include the assumptions that the observed surface is sufficiently far from the observer and source of illumination such that its image approximates an orthographic projection, each image point intensity is unaffected by cast shadows or specularities, the "observer" has prior knowledge about the direction of illumination, and that the observed surface is smooth (Horn, 1975; Horn, 1977; Horn, 1981; Ikeuchi & Horn, 1981; Pentland, 1982).

Some of the assumptions adopted by machine vision researchers clearly have no psychological validity. For example, objects need not be far away for us to correctly perceive their form; not all surfaces are perfectly smooth; surfaces often lie partially or completely in cast shadows; and an observer may be unaware of a surface’s reflectance properties. However, in the case of some other assumptions, it is not always immediately
apparent whether they have psychological validity or not. In such instances it is important that these assumptions be tested empirically.

Psychophysical research (Mingolla & Todd, 1986; Todd & Mingolla, 1983) has demonstrated that the process of representing shading-defined objects by the human visual system is unlikely to be constrained by several of the assumptions employed by machine vision researchers. These include the assumptions that the environment is composed of relatively homogenous Lambertian surfaces, that illuminant direction must be known before shape detection can proceed, and that surface orientation is detected locally. Todd and Mingolla (1983) report that, when given the task of judging the curvature of shaded cylinders that had their occluding contours masked, subjects performed more accurately to stimuli that had specular highlights than to stimuli with dull surfaces. They also found that subjects could accurately judge the position of the light source, and that their performance on this task was independent of ability to judge surface curvature. These results suggest that, when processing shaded images, the human visual system is not constrained by the assumptions that all surfaces have Lambertian reflectance characteristics or that explicit knowledge of the illuminant direction is a necessary prerequisite to form detection. Similarly, Mingolla and Todd (1986) reported that subjects’ performance on illuminant direction and surface orientation judgment tasks was affected differently by the manipulation of three variables - cast shadows, highlights and object shape, thus suggesting a dissociation of the two processes. This dissociation is contrary to what would be predicted by those models that assume knowledge of an illuminant direction is necessary for analyzing shape.
The suggestion that knowledge of illuminant direction is not essential for surface orientation estimation is supported by the recent research of Erens and colleagues (Erens, Kappers & Koenderink, 1993a). These researchers demonstrated that, when estimating the orientation of a Gaussian perturbation (in the form of either a bump or a dent) set against a spherical background, observers did not seem to use the information about light direction which was provided by the global shading of the background sphere. However, knowledge of light source position has been shown to be important in distinguishing between concave and convex ellipsoids (Berbaum, Bever & Sup Chung, 1983; Erens, Kappers & Koenderink, 1993b; Kleffner & Ramachandran, 1992; Ramachandran, 1988), but not in distinguishing between elliptic and hyperbolic surfaces1 (Erens, et al., 1993a; Erens, et al., 1993b).

The assumption that the perception of solid shape from shading is a local process has been challenged by several investigators (Mingolla & Todd, 1986; Ramachandran, 1988). Ramachandran (1988) reported that, when they are presented with two rows of shaded ellipses, with the intensity gradients of one row mirroring that of the other, observers simultaneously perceive one row as convex ellipsoids and the other row as concave ellipsoids. This, asserts Ramachandran, is evidence that deriving shape from shading cannot be a strictly local operation. The idea that shape from shading is a global process is indirectly supported by the experimental results reported by Mingolla and Todd (1986), in which subjects were required to make slant and tilt judgements of local points on pairs of computer-generated ellipsoids. Although the ellipsoids differed in their "eccentricity"
(the ratio of the lengths of the longest and shortest axes), the local intensity patterns and gradients for the two shapes had similar distributions. Yet, subjects' performances differed dramatically for the two ellipsoids; slant and tilt judgements were relatively accurate for the low-eccentricity shapes, but very poor for the high-eccentricity shapes. A local approach to shape-from-shading, argue Mingolla and Todd, would not predict such performance differences. However, it is plausible that the visual system uses some other metric, rather than local slant and tilt, for local shape detection; if so, then, one would expect the above result. Similarly, Erens, et al (Erens, et al., 1993a; Erens, et al., 1993b) report that subjects are unable to distinguish elliptic and hyperbolic surfaces on the basis of local surface orientation even when illuminant direction is specified by the presence of a cast shadow on the surfaces. Even when subjects were presented with stimuli simulating a light source moving in a given direction about a shape of fixed orientation, they were unable to distinguish between the two classes of surface shapes.

Thus, although machine vision researchers have made laudable progress in developing solutions to the shape-from-shading problem, psychophysical investigations have challenged the psychological validity of several of the underlying assumptions and demonstrated the psychological implausibility of other assumptions.

The machine-vision community plays a valuable role in terms of developing computational theories of vision that are accessible to testing for psychological validity. This relationship between the machine vision and psychophysics communities is a reciprocal one, in that psychophysical research is a valuable tool for identifying key components of human visual processing. Psychophysical research is an invaluable source
of information for those machine-vision researchers who wish to simulate human vision.

Although it has been demonstrated through psychophysics that it is not necessary to have explicit knowledge of the illuminant direction in order to derive the form of an object defined by shading, it has been suggested that the human visual system processes shaded images in accordance with an assumed illuminant position. The well known phenomenon of the ambiguity of protuberances and indentations defined only by shading and viewed in the frontal plane was commented on as early as the 4th century B.C. (Plato, 375 B.C.), and has led several researchers to conclude that, when the light position is not in view, observers assume overhead lighting (Benson & Yonas, 1973; Brewster, 1826; Gibson, 1950; Kleffner & Ramachandran, 1992; Ramachandran, 1988). However, it has been demonstrated that this assumption can be overridden or vetoed when the subject obtains explicit "knowledge" of an apparent light source's position prior to, but not during, stimulus presentation (Berbaum, et al., 1983). It has also been reported that shadows attached to unambiguous objects and cast shadows may compete with the light-from-above assumption in interpreting the shape of ambiguous objects in the same scene (Berbaum, Bever & Chung, 1984). Reichel and Todd (1990) have argued that, while there is considerable evidence that an overhead illumination bias is employed by the visual system, this explanation is applicable to a relatively narrow range of shaded images. They reported that, even after neutralising the supposed perceptual bias for overhead illumination by placing the light source at the point of observation, inversion effects due to changes in image orientation persisted. Furthermore, these inversion effects were also perceived for surfaces depicted by texture or motion. Reichel and Todd argue that their observed effects are better accounted for by a bias to perceive surfaces as slanted
backwards in depth. Thus, while not denying the possible existence of a perceptual bias for overhead illumination, Reichel and Todd suggest that it is "probably of only marginal significance in natural vision".

The effects on perception of systematically manipulating shaded images has led Ramachandran (1988) to propose a number of rules for the early visual processing of shaded images. He suggests that, as well as invoking the light-from-above assumption, the visual system's extraction of information about "above" and "below" is based on a retinal, rather than a gravitational, frame of reference. He also argues that the visual processing of shading is a global process which occurs in the early stages of vision, and suggests that when the single light source assumption cannot be satisfied it is replaced by a "pointing" rule - a rule which states that shapes with similar orientations are in fact parallel surfaces. Howard, Bergstrom and Ohmi (1990) point out that, although Ramachandran provides evidence that the assumption of a light source coming from above is based on a retinocentric rather than a gravitational frame of reference, the same evidence can be used to support the view that the light-from-above assumption is based on a headcentric frame of reference. Like Ramachandran (1988), these authors demonstrated that a gravitational frame of reference was unlikely, but they did not attempt to dissociate the effects of the two egocentric frames. Oberle (cited by Howard, Bergstrom and Ohmi (1990)) approached the problem by having subjects view images of convex and concave stimuli with upright head such that the part of the picture that was "top" with respect to gravity and to the head was "bottom" with respect to the retina. The results supported Ramachandran's view that the visual system employs a retinocentric frame of reference.
There is also some support for the view that the extraction of information from shading occurs at the early stages of visual processing, thus lending support to the possible existence of neural channels designed specifically for the processing of shape from shading. This possibility is highlighted by Lehky and Sejnowski's (Lehky & Sejnowski, 1988; Lehky & Sejnowski, 1990) work on a neural network model of shape from shading. These researchers trained a neural network to accurately associate shaded images with their three-dimensional axes of curvature. The network comprised an input and an output layer of units, with a hidden layer between the two. The hidden units were trained, by a back-propagation learning algorithm, to provide a transform between the retinotopic space of the input units and the 2D curvature magnitude and orientation parameter space of the output units. It was reported that the hidden units had developed receptive fields similar to those in the cat's visual system that had been previously identified as "edge" or "bar" detectors (Hubel & Wiesel, 1962; Hubel & Wiesel, 1965); this was despite the fact that Lehky and Sejnowski had purposely omitted any edge information from the stimuli used. This, of course, is not unequivocal evidence for the existence of shape-from-shading neurons in the human visual system. Lehky and Sejnowski acknowledge this, suggesting that we should be cautious when attempting to deduce neuronal function solely from determination of their receptive fields.

1.2.1 What Level of Representation Mediates Shape From Shading?

A common assumption adopted by vision researchers is the idea that three-dimensional structures of smoothly curved surfaces are perceptually represented by point-by-point metric depth and/or orientation maps that are observer-centred (Horn, 1975; Horn, 1977;
Marr & Nishihara, 1978; Pentland, 1984; Stevens, 1984; Stevens, 1981; Witkin, 1981). It has been argued that, if this view of shape representation is correct, it should be possible to estimate the effectiveness of a given cue to shape by giving subjects tasks that involve local surface orientation and depth judgments (Mingolla & Todd, 1986; Todd, Reichel & Mingolla, 1986). If this is the case, then, one would expect shading, which does not provide information about absolute depth, to be a poor cue to depth and orientation.

There is evidence to suggest that shading is a poor cue to depth in comparison with binocular disparity (Bulthoff & Mallot, 1988). Yet, artists find chiaroscuro to be a very effective means of depicting surface shape. This raises the question of whether tasks involving local orientation and depth judgments require subjects to make decisions about surface attributes that are not explicitly encoded by visual mechanisms (Todd & Reichel, 1989; Johnston & Passmore, 1994a), and casts doubt on the view that the primary form of representation for the visual perception of surfaces is local mappings of depth or orientation.

Recent research suggests that surface curvature is encoded explicitly in the early stages of visual processing, and that this "primary representation" is not mediated by a local orientation map. Rogers (1986) has demonstrated that observers are able to match accurately the curvature of two parabolic surfaces viewed stereoscopically from different distances. Furthermore, observer ability to perform this task is influenced by the orientation of surface markings (Rogers & Cagenello, 1989), with thresholds being higher when surface lines on a vertically oriented cylinder were oriented at 0° or 90° than when they were oriented at 45°. Rogers and Cagenello point out that this result is consistent with the fact that there is no curvature disparity in the former case, thus suggesting that
observers were using curvature disparity in the curvature discrimination task. Stevens, Lee and Brookes (1991) suggest that surface curvature features are detected separately by stereo and mono processes. They further suggest that it is these surface curvature features, rather than local, pointwise values such as depth or surface orientation, which constitute a "common language" or representation. Recent work by Johnston and Passmore (1994a; 1994b) provides evidence that curvature information may be represented by the visual system in the form of an explicit description, rather than being represented implicitly as changes in the topography of surface normals from which orientation may be derived. Using a surface alignment task for a range of surface curvatures defined only by shading, Johnston and Passmore measured curvature discrimination thresholds. Considerable precision was reported for this task, and was evidenced by reported Weber fractions of around 0.1. Johnston and Passmore point out that, as a measure of discrimination performance, their results compare well with a Weber fraction of around 0.1 found by E. Johnston (1991) for curvature discrimination using cylinders defined by binocular disparity. This is strong evidence that shading is as effective a cue to surface curvature as binocular disparity. Johnston and Passmore also reported that, whereas rotating the light source towards the viewer resulted in increased discrimination thresholds, slant discrimination thresholds declined. Similar results were reported when the above experiments were run using stimuli presented stereoscopically (Johnston & Passmore, 1994b). These results are similar to the results reported by Rogers and Cagenello (1989), who tested subjects curvature discrimination thresholds for parabolic stimuli presented stereoscopically. It was found that the disparity range of their displays at curvature discrimination threshold levels was one third of that required to detect a change in surface slant over the same spatial extent. This dissociation between slant and curvature
discrimination thresholds is compelling evidence that surface curvature is not represented by a surface orientation map; rather, it supports the notion that surface curvature encoding is primary and does not depend upon the prior encoding of surface orientation. Similarly, when subjects were given a shape index\(^2\) (Koenderink, 1990) discrimination task, De Vries, Kappers and Koenderink (1994) found that varying the slant angle of a range of object shapes had no effect on discrimination thresholds.

A further series of experiments by Johnston and Passmore (1994c) also undermine the notion that the visual system constructs a dense orientation map, from which higher order geometric properties such as curvature are derived. Subjects' precision at making three-dimensional spatial judgments was assessed through their performance on two spatial judgment tasks, arc length bisection along geodesics and geodesic alignment, with reference to a sphere. It was argued that, if arc length is computed on the basis of a surface orientation map, subjects' performance should improve as a function of increasing the sources of information about surface orientation. However, when compared with a control condition in which only minimal information about the surface orientation was available, it was reported that the presence of shading and texture in the displays had no effect on subjects' performance in the above tasks.

Thus, until recently, shading was regarded as a poor cue to shape perception; this is

\[^2\] Koenderink's shape index (S) is a quantity describing objects in \(K_{\text{max}}, K_{\text{min}}\) space; where \(K_{\text{max}}\) and \(K_{\text{min}}\) are the maximum and minimum principal curvatures at any given point on a surface. The shape index is defined by Koenderink as

\[ S = -\frac{2}{\pi} \arctan \frac{K_{\text{max}} + K_{\text{min}}}{K_{\text{max}} - K_{\text{min}}} \]

Thus the shape index ranges from -1 to 1, and parametrizes a continuous family of shapes which runs from concave elliptical (-1 to -1/2), through hyperbolic (-1/2 to 1/2), to convex elliptical (1/2 to 1).
supported by the relatively poor performance of subjects when making local orientation
and depth judgements of surfaces defined by shading. The implications of such findings
are surprising in light of the fact that we readily interpret objects in which shading is
virtually the sole cue to shape; for example pictures of sculptures. Consequently, the
notion that we derive higher order geometric features from an orientation map has come
under scrutiny. Recent developments suggest that the visual system does not construct
an orientation map for the purpose of extracting higher order geometric properties, such
as curvature. There is also a growing body of evidence that the recovery of surface
curvature from shading is primary, rather than being mediated by the construction of a
dense surface orientation map.

1.3 SHAPE FROM TEXTURE.

When compared with the shape from shading problem, the problem of deriving a
representation of shape from surface texture has attracted relatively more attention from
vision researchers. A large proportion of the research in this area has concentrated on the
problem of perceiving slanted surfaces from texture. This tendency of the study of slant
perception to be closely tied to the study of shape perception is, in part, a consequence
of the shape-slant invariance hypothesis (Koffka, 1935; cited in Braunstein (1976)), which
states that a given retinal projection is perceived as a particular 2D shape at a particular
slant; if, through the manipulation of experimental variables while keeping the retinal
projection constant, the perceived slant is altered the perceived shape is held to change
accordingly.
Much of the research into the perception of shape from texture evolved from the initial work of Gibson (1950), who proposed that a texture density gradient was a sufficient stimulus for the perception of surface slant. A texture gradient is a systematic variation in projected surface texture (Stevens, 1981); more specifically, texture density gradients describe how the density of projected texture elements vary as a function of surface slant and texture element distance from the observer. Gibson demonstrated a positive correlation between slant judgements and displayed slant in an experiment in which subjects viewed photographs of slanted surfaces, which were projected onto a translucent screen through an aperture arrangement restricting the field of view to a small circular area within the photograph. Gibson found that subjects consistently underestimated a surface's slant by as much as 50%, with subjects' accuracy being greater for surfaces with regular texture than for those with irregular texture.

Gibson's finding that subjects were better able to judge the slant of regularly textured surfaces prompted other investigators to identify what types of texture regularities are important in the perception of slant. For example, it has been suggested that size and shape regularity are more important than the regular distribution of texture elements (Flock & Moscatelli, 1964; Phillips, 1970). Gruber and Clark (1956) report that texture density is an influential variable in slant judgments; they found an inverted U-shaped function relating judged slant to mean separation of texture elements.

Gibson suggested that the important texture measure is density, and that its gradient specifies slant. However, demonstrating that slant is equated with a surface's texture gradient is not proof in itself that the human visual system derives slant from texture.
gradients. Although he successfully isolated the texture density gradient from other slant cues, such as stereo, motion, and accommodation, Gibson did not isolate it from other possible texture measures. These include decreasing texture size (scaling) and increasing foreshortening, both of which occur with distance (Stevens, 1981). Stevens (1984; 1981) has shown it is possible that the visual system uses the geometrical transformations scaling and foreshortening in deriving surface distance and orientation, respectively; and that surface shape may then be derived from these measurements. He identified a texture measure for computing surface distance, which he called the characteristic dimension or CD of surface texture. The CD varies only with scaling, and thus is considered to be an appropriate cue to distance or depth. Thus Stevens argues that local surface depth values can be estimated directly from such texture measures, rather than through the mediation of texture gradients as proposed by Gibson.

The approaches of Gibson and Stevens have in common the underlying assumptions that a surface texture comprises texture elements of uniform density and of uniform size. However, the former assumption is not strictly true of natural textures (Cumming, Johnston & Parker, 1993; Witkin, 1981), and it has been reported that random variations in the sizes of individual surface elements does not affect observers’ surface curvature judgments (Cumming, et al., 1993; Todd & Akerstrom, 1987). Stevens adopts the further assumption that surface texture elements have an approximately circular symmetry. However, Todd and Akerstrom (1987) report that observers’ performance on a shape-judgment task was unaffected when a surface texture composed of irregularly-shaped elements was substituted for one composed of regularly-shaped texture elements; this was despite the fact that using the "irregular-element" surface significantly
diminished the correlations between optic element length and depth, and between optic element compression and orientation. This, argue Todd and Akerstrom, also undermines the notion that observers draw on point-by-point depth maps or orientation maps derived from optical texture when constructing a representation of surface shape. Instead, they argue that the perception of shape from texture by human observers is probably based on a more global level of analysis. This is supported by the recent work of Cumming, Johnston and Parker (1993), who reported that randomly varying the aspect ratios of surface texture elements, thus controlling for the possibility that subjects could calculate local surface orientation from the elongation of the texture element in the image, did not affect subjects’ performance on the "apparent circular cylinder" (ACC) task.

Witkin (1981) argues that, although some assumptions about texture geometry are necessary to successfully recover surface shape and orientation from texture, the unpredictability of natural textures precludes the use of highly restrictive assumptions. He proposes that emphasis should be placed on the regular nature of projective distortion rather than on the assumption of perfectly regular textures; he also advocates the assumption that natural textures do not usually mimic or cancel projective effects. This approach to perceiving shape from texture ensures that as much as possible of the observed variation in an image is attributed to projection. Witkin proposes that the visual system resolves the problem of projective distortion by separating the projective component of the image from a component intrinsic to the unprojected texture. Using this strategy, a machine vision system demonstrated considerable success at reconstructing

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3The ACC task describes an experimental procedure in which subjects decide if a computer-generated cylinder is more or less extended in depth than a cylinder of circular cross section.
images of planar and curved surfaces. However, Witkin's strategy fails for natural textures that violate the assumption that texture geometry does not mimic projection, such as wood grain. This problem is overcome, argues Witkin, by drawing on additional sources of information in the image, such as shading.

Witkin, like many machine-vision researchers, employs the simplifying assumption that the image is formed through orthographic projection. However, in the real world, most objects under our scrutiny are relatively near to us, with variation in nearness being captured by perspective projection. Orthographic projection, on the other hand, simulates infinite viewing distance, and is "unnatural" in terms of human vision. Orthographic projection also nullifies the usefulness of particular texture gradients, such as perspective and density; cues that have been shown to be effective in the perception of slant. Cutting and Millard, for example, have demonstrated that perspective and density are probably the primary cues to perceiving flat surfaces. This underlines the importance of choosing the appropriate form of image projection for the study of human vision. Witkin's approach further assumes that surface texture is isotropic, and that the projection of such a surface texture generates an anisotropic image texture (if the surface is not fronto-parallel). Support for this assumption is provided by recent psychophysical research (Cumming, et al., 1993), in which it was found that surface texture isotropy is an important contributing factor in perceiving curvature from texture.

Much of the research addressing the question of what projective properties of surface texture are used in deriving shape representations has typically relied on the cue-conflict
paradigm, in which one texture cue is varied while the others are held constant. It is possible that the mechanism employed by the visual system to resolve the cue-conflict condition in a psychophysical experiment differs from the mechanism used to interpret naturally occurring images, which, typically, are not composed of conflicting cues. However, Blake, Bulthoff and Sheinberg (1993) report that the results of such experiments are similar to those predicted by an ideal observer model for estimating shape from texture. Their model predicted that, as well as density being a texture cue to shape, optical texture compression is an important texture cue to shape; and that compression dominates density for the family of parabolic cylinders. The model's predictions agreed with the results of psychophysical experiments reported by Blake et al, as well as those of other investigations of texture as a cue to surface curvature (Cumming, et al., 1993; Cutting & Millard, 1984; Todd & Akerstrom, 1987). Thus the practise of employing the cue-conflict paradigm to assess the relative importance of visual cues in shape perception appears to be justified.

The results of Blake et al's ideal observer model and psychophysical experiments showed that the relative dominance of compression over density increased as a function of increasing elongation of portrayed cylinders. This is in general agreement with the earlier work of Cutting and Millard (1984). These researchers tested subjects' ability to assess the three-dimensional character of projections of flat and curved surfaces receding in the distance. They reported that, for flat surfaces, the compression gradient accounted for only 6% of the total variance. However, for curved surfaces, the compression gradient accounted for a mean of 96% of the variance. Similarly Cumming, Johnston and Parker (1993) found that, when textured surfaces were viewed under stereoscopic conditions,
compression was the strongest cue to perceived surface curvature, and that changes in texture size and density had relatively little effect. Furthermore, they reported that the effectiveness of the compression gradient as a cue to surface curvature was mediated by the level of surface texture isotropy; as surface texture becomes more anisotropic, the effectiveness of the compression gradient is markedly reduced.

1.4 CUE INTEGRATION.

The previous sections on shape-from-shading and shape-from-texture attest to the fact that, until relatively recently, a great deal of research has focused on how the visual system extracts three-dimensional information from single cues; an approach which reflects the current view that the visual system is essentially modular in nature. However, over the past decade, a number of researchers have turned their attention to the question of how the visual system integrates the three-dimensional information from each module to form a unified three-dimensional depth percept. Although there had been earlier empirical attempts at addressing this question (eg: Gillam (1968)), any possibility of rapid progress was hampered by the lack of appropriate technology. It was only with the advent and accessibility of computer graphics systems that progress in this area of research became a reality.

Several possibilities for cue interactions which are not mutually exclusive are generally considered. These are veto, disambiguation, accumulation and cooperation.
1.4.1 Classification of Cue Integration.

1.4.1.1 Veto: This occurs when unequivocal information from one or more "strong" cues completely overrides the information from another "weaker" cue. Several instances of vetoing have been reported. As early as 1925 Schriever found that there was no perceived depth inversion when the pairings between the viewing eye and stereo photographs of complex scenes were switched. This demonstrates that when several consistent pictorial cues are present in the images, stereo can be vetoed if the depth information it conveys is incongruent with that of the pictorial cues. Similarly, other researchers (Bulthoff & Mallot, 1990; Bulthoff & Mallot, 1988; Gregory, 1970; Stevens & Brookes, 1988; Youngs, 1976) have found that stereo is vetoed when it is placed in direct opposition to monocular information, such as linear perspective and edge information. For instance, Bulthoff and Mallott (1990; 1988) report that when edge information is present in images of ellipsoids it vetoed both shape-from-shading and disparate shading. Stevens, Lees and Brookes (1991) found that when a wireframe surface was generated by two conflicting cues, stereo disparity and monocular surface contours, the local dominance of either cue over the other was dependent on the form of the local surface area depicted by each cue. Thus disparity information dominated the monocular information when the former indicated curvature and the latter indicated planarity, and the monocular interpretation was dominant where the disparity information suggested planarity.

Veto has also been reported for other cue combinations. Braunstein et al (1982) reported that when conflicting motion parallax and dynamic occlusion cues were used to simulate a rotating sphere, dynamic occlusion always dominated. Rogers and Graham (1983), however, report the opposite effect when these two cues are placed in conflict. These
conflicting results have been shown to be related to the magnitude of the depth separation of the dynamic occlusion and motion parallax cues (Ono, Rogers, Ohmi & Ono, 1988), with motion parallax determining the perceived depth order for small depth separations and dynamic occlusion dominating for large depth separations.

1.4.1.2 Disambiguation: Quite often the information from a single cue, say shading or texture, is ambiguous in that there is no one unique interpretation. The inclusion of a second cue can disambiguate the percept by indicating which one of two opposing interpretations is correct. A good example of this is the use of occluding contours by the visual system to disambiguate shading information (Ramachandran, 1988). Ramachandran found that when two identical shading patterns were enclosed by different outlines, one pattern was perceived as three cylinders lit from above and the other suggested a corrugated metal sheet lit from the side (although it should be noted that the perceived shape of the latter stimulus and the perceived position of the light source were bi-stable).

Several other authors report instances in which the inclusion of a specific cue serves to disambiguate a percept. For example, when viewing a transparent 3D object under orthographic projection conditions, dynamic occlusion has been used to disambiguate the depth order of the object's surfaces (Andersen & Braunstein, 1983; Braunstein, Andersen & Reifer, 1982). Proffitt, Bertenthal and Roberts (1984) found that appropriate occlusion information served to reduce the multistability of point-light "walker" displays, and increased the likelihood of recognising such a display as a walking person. Rogers and Rogers (1992) report that nonvisual information, in the form of proprioceptive and vestibular signals, can disambiguate the direction of depth in motion parallax displays.
It has been suggested that the 3-D appearance of a surface specular reflection may be used by the visual system to disambiguate an ambiguous concave-convex figure (Blake & Bulthoff, 1990). Similarly, several authors have reported that, following adaptation to an unambiguous structure-from-motion stimulus, a motion aftereffect was reported by observers when presented with a previously ambiguous kinetic depth (KD) display (Nawrot & Blake, 1991; Petersik, Shepard & Malsch, 1984; Rogers & Graham, 1984). Thus the unambiguous information in the former display biased observers’ perception of the ambiguous motion in the KD display.

1.4.1.3 Cooperation: A cooperative interaction between visual processes or modules occurs when information from one process/module facilitates the functioning of another process/module. Tittle and Braunstein (1990) found what they believed to be cooperative interaction between stereo and shape-from-motion (SFM). These authors presented subjects with computer-generated, transparent cylinders defined by conflicting depth values of the above two cues (stereo-defined-depth was three times that of motion-defined-depth). When stimuli motion was halted, leaving stereo as the only cue to depth, subjects reported that the display looked flat. However, when both cues were presented simultaneously, subjects’ perceived depth was greater than that depicted by the SFM cue alone. The observed five-fold increase in judged depth from the separate to the combined conditions, argue Tittle and Braunstein, is evidence that the SFM cue facilitated the use of stereo information. Similarly, for a shape-matching task in which the standard was defined by stereo-disparity, Bulthoff (1991) found that subjects underestimated the depth of an ellipsoid defined by either one of two pictorial cues (texture or shading); but their depth percept was more veridical when both cues were present. Bulthoff and Yuille
(1991) interpreted this as evidence of cue cooperation, which they term "strong coupling".

A further example of one cue facilitating another is reported by Buckley, Frisby and Mayhew (1989), who demonstrated the influence that texture boundaries have over the perception of discontinuities between neighbouring 3-D surfaces defined by stereo cues. They found that, in the absence of a monocularly visible texture boundary in the area between two stereo-defined surfaces, perceived depths of the monocular texture elements are in part determined by the adjacent stereo-defined surfaces. This may be interpreted as an example of texture information facilitating the construction of a 3-D surface section which effectively bridges the gap between the stereo-defined regions. Furthermore, it was shown that this effect could be removed by adding a distinct monocular texture boundary; in such cases the stereo-defined regions were perceived as being separated by sharp surface discontinuities.

1.4.1.4 Accumulation: Information from different cues could be accumulated in a number of ways, one of the simplest methods being a weighted linear combination rule. Evidence has accrued in recent years to suggest that the visual system may employ such a strategy in the integration of information from a number of different cue combinations (Bruno & Cutting, 1988; Dosher, Sperling & Wurst, 1986; Johnston, Cumming & Landy, 1994; Johnston, Cumming & Parker, 1993; Landy, Maloney & Young, 1990; Maloney & Landy, 1989; Rogers & Collett, 1989; Tittle & Braunstein, 1990; Young, Landy & Maloney, 1993).

Dosher, et al (1986) investigated the integration of stereo rotation disparity (SRD) and
proximity luminance covariance (PLC), PLC being a technique first adopted by Schwartz and Sperling (1983) in which line intensity co-varies with depth. They reported that a simple linear model accounted for the results of their experiment. It was found that more weighting was given to the stereo cue than to the proximity luminance covariance (PLC) cue when subjects were presented with a still preview of a Necker-cube stimulus. However, in the absence of a still preview, more weighting was given to the PLC cue, thus emphasising the role of context in the assignment of weights to depth cues.

Bruno and Cutting (1988) obtained statistical support for a linear combination rule encompassing four depth cues - relative size, height in the projection plane, occlusion and motion parallax. A magnitude estimation procedure, in which subjects judged the relative distance between three square panels, was employed to assess subjects' perceived exocentric distances. Each depth cue was either present or absent in a given stimulus (an "absent" cue provided no relative depth information), resulting in sixteen different combinations. They found effects of relative size, height in plane and motion parallax. More importantly, the absence of significant interactions between the depth cues provided support for the argument that a linear combination strategy was adopted by the visual system in the processing of these depth cues. Their analysis, however, was dependent on the assumption that each cue was either present or absent. Massaro (1988) argues that, with the technique adopted by Bruno and Cutting it was not possible to eliminate these depth cues, if eliminating them means to make them uninformative, and emphasises the importance of distinguishing between a cue's presence or absence and whether the cue simply supports one depth or another.
As noted earlier, Tittle and Braunstein (1990) reported a cooperative interaction between stereo and shape-from-motion cues when these cues depicted transparent cylinders. However, when the cues depicted opaque cylindrical surfaces the experimental results were consistent with an additive combination of the two sources of information. This is supported by the observation that judged depth increased monotonically as a function of both sources of information, and that there was no significant interaction between the two cues. The results of their experiments led Tittle and Braunstein to speculate that stereopsis and SFM integration might be a two-step process, in which SFM facilitates the resolution of the stereo correspondence problem prior to the depth estimates derived from the two cues being integrated in a simple additive manner. This explanation is similar to the concept of cue promotion (Landy, Maloney, Johnston & Young, submitted) discussed below.

Johnston et al (1993) report that, when a texture depth cue is added to stereograms portraying a range of surfaces (ellipsoids, cylinders and 'roofs'), subjects' perception of depth is increased (although not necessarily made more veridical). When both cues portrayed incongruent depth information, the data were well accounted for by a weighted linear rule, with stereo being more heavily weighted than texture. As in the experiments of Dosher et al (1986) Johnston et al reported that the weight assigned to the depth cues employed appeared to be somewhat dependent on context; as viewing distance was increased beyond one metre, the weight assigned to texture increased and the weight assigned to stereo decreased. Similarly, Rogers and Collett (1989) report contextual effects on the weight assigned to motion parallax when combined with binocular disparity, with parallax affecting subjects' perceived depth only when the disparity gradients for a
depicted corrugated surface were shallow. Furthermore, their data were consistent with a weighted linear model.

The classes of integration or "fusion" of 3-D information discussed above can be considered as belonging to two broader categories; these are strong and weak fusion (Clark & Yuille, 1990). The primary feature of strong fusion is that the operation of one or more modules can be affected by the outputs of other modules prior to integration of their outputs; in other words, the modules are not independent. In contrast to this, the main feature of weak fusion is that the modules are to a lesser or greater extent independent. Clark and Yuille distinguish three classes of weak fusion. In class I weak fusion each module is stable and provides a unique solution, and a weighted combination of their outputs is performed. The weighting of each information source is derived from the relative reliabilities of the information sources or cues. A characteristic of classes II and III weak fusion is that any module in isolation does not provide a unique solution; however, these two classes of fusion differ in the strategies used to obtain a unique solution. In the case of class II weak fusion the additional information required to derive a unique solution is provided solely by other modules; however, in the case of class III weak fusion information is also derived from prior constraints added in the fusional process. Three of the four classes of integration discussed above, veto, disambiguation and accumulation, are consistent with a modular conceptualization of processing, and, thus, belong to the weak fusion category (although disambiguation may also be achieved using a strong fusion strategy). In the case of a cooperative interaction, on the other hand, strict modularity does not hold (Tittle & Braunstein, 1990). Thus cooperation belongs to the strong fusion category of integration strategies.
Because most cues in isolation do not provide a unique solution (e.g., texture does not uniquely determine distance) it is unlikely that the visual system would employ a class I form of weak fusion when integrating information from different modules. However, because the modules in the visual system are considered to be largely independent, it has been suggested that the visual system may use a modified version of class I weak fusion (Landy, et al., unpublished; Landy, et al., 1990; Maloney & Landy, 1989; Young, et al., 1993), which is described below in detail.

### 1.4.2 The Modified Weak Fusion Model.

The modified weak fusion (MWF) model proposed by Young and colleagues is characterised by several assumptions. A central assumption of the model is that the visual system comprises depth modules that are largely independent in their processing of different sources of depth information in the scene. However, because a single cue may provide depth information dependent on one or more undetermined parameters (i.e., it does not provide a unique solution), and because the data computed independently from two different sources may differ in their parameterization, it would be meaningless to combine the output from independent modules. This problem is addressed by the MWF model, which deals with it by proposing that promotion occurs between the "depth-maps-with-parameters" computed by each module. Promotion describes the process in which information from one depth map is used to specify the missing parameters for another depth map, thereby promoting that cue to the status of an absolute depth cue. This process of cue promotion constitutes an interaction among different cues, and, as such, the MWF model may be considered to have a strong-fusion stage built into it. Johnston et al (1994) describe an example of cue promotion, in which stereo is
promoted by KDE information. In their experiments subjects were given the ACC task, in which they had to decide whether a computer-generated cylinder extended more or less in depth than a cylinder of circular cross-section. Stimuli contained either just texture, just motion, or both cues. When viewed from 200 cms cylinder depth, and therefore curvature, was under-estimated when stereo was the only cue available\(^4\), and was veridical when KDE was the only cue available. Depth perception was still veridical when both cues were present in the image, suggesting that stereo was promoted by using the motion information to overcome the stereo viewing distance scaling problem. When the KDE cue was reduced to two frames, depth perception was no longer veridical when stimuli consisted of either cue in isolation. Yet, when the cues were both present in the image, perception was veridical, thus providing further evidence of promotion between these two cues.

In line with weak fusion models, the MWF model assumes that the outputs of the depth modules are combined using a weighted average rule. The weights assigned to depth cues are considered to be malleable in the sense that a given cue's weight is determined by a number of factors; including availability of the cue in the image, cue reliability, the number of other cues present, and whether the information derived from the cue is commensurate with the other cues in the scene. The reliability of a cue is determined by what Young and colleagues refer to as ancillary measures (see Figure 1.1); that is "conditionally sufficient statistics that serve to reduce the variability of estimate of a

\(^4\) This is contrary to the results reported by Rogers (198\(^3\)), who found that observers could accurately match the perceived curvature of two parabolic surface stimuli that differed in their distance from the observer. However, it should be noted that the curvature-matching task given to observers is quite different from that used by Johnston et al. The subjects in Johnston et al's experiments were required to decide if the cylinder was more or less extended in depth than a cylinder of circular cross section.

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parameter, but whose distribution is independent of the values of the parameter being estimated" (Maloney & Landy, 1989). Thus the role of ancillary measures is to provide information about the likely performance of different depth modules, without themselves providing information about depth in a scene. Examples of possible ancillary measures are proprioceptive and vestibular signals. Rogers and Rogers (1992) report that these two sources of information are used by observers to help disambiguate the structure of a surface defined by motion parallax. A further assumption of the modified weak fusion model is that the output following depth fusion is represented in a depth map of surface points in the scene; that is the locus of integration is assumed to be a depth representation.

Maloney and Landy demonstrate that the weights assigned to depth cues can be assessed psychophysically using perturbation analysis. If a subject is presented with a stimulus composed of inconsistent depth cues, then the weight assigned to a given cue may be obtained by varying the cue in question while allocating a fixed depth value for the other cues. The weight assigned to the cue is simply the ratio between the change in the subject’s estimate of overall depth and the change in the cue.

To test the validity of their model, Landy et al (1990) estimated the weights given to two depth cues, texture and motion. The stimuli used were computer-generated, vertically orientated, textured cylinders rotating back and forth about a centrally placed horizontal axis. With the motion depth cue being assigned a constant value and the texture cue varying in depth, Landy et al estimated the weight of the texture cue by measuring the slope of a line fitted to the plotted data of perceived depth as a function of the value of
Figure 1.1. A schematic representation of the modified weak fusion model (after Landy et al, unpublished). Each depth cue produces both a depth map $d$ and, using ancillary cues, a reliability map $r$. 
the texture cue. They estimated the weight of the motion cue by subtracting the weight of the texture cue from 1, rather than independently determining the weight of the motion cue by reversing the roles of the cues in a second experiment and determining whether the weights of the two cues did in fact sum to one; a strategy recommended by Maloney and Landy (1989) as a rigorous test of the model. If cue integration does conform to a linear model, then this strategy would be considered a redundant test; however, its usefulness in uncovering evidence of non-linear integration justifies using this strategy. Thus Landy et al’s experimental results were in agreement with their proposal that depth may be integrated in a linear manner by the visual system.

1.5 OUTLINE OF THESIS.

It is clear from the discussion on the integration of cues that the work in this area is still at the relatively early stages. Although the modified weak fusion model proposed by Young and colleagues finds support in research suggesting that cue combination is a linear process, there are also a number of studies pointing to non-linear processes being employed by the visual system. The experiments in this thesis are designed to investigate the integration of two monocular cues to shape, texture and shading. The following chapter provides a detailed account of the methodology employed in these experiments. The five subsequent chapters (3-7) report on the experimental work carried out in this thesis. The experiments in chapter three address two questions: 1) At what level of representation are shading and texture cues integrated? and 2) Is the integration of shading and texture best described by a linear model? The results of these experiments suggest that, firstly, a curvature representation is a likely locus of integration for shading and
texture cues, and, secondly, that the linear model does not generalize to the integration of shading and texture.

Chapter four describes a series of experiments that investigate further the processing of the texture cue used in the previous experiments. Experiments three and four address the notion that a cue’s weight is partly determined by its reliability and its availability; assumptions that are an integral part of the modified weak fusion model. This issue is addressed by manipulating the texture contrast and the extent of surface area visible to the observer, and looking at the effect these manipulations have on the texture weight. The results demonstrate that the texture cue’s weight is, indeed, partly determined by these factors. Experiments five to seven attempt to isolate those features of the checkerboard texture used in the previous experiments that are relevant to curvature perception. It is concluded that the primary source of curvature information being utilised by the visual system in these experiments was line curvature.

Chapter 5 describes the effect that varying the light-source position has on the shading and texture weights. Although changing the light source has no effect on the weights of these cues, it was found that it did have a marked effect on the perceived curvature magnitude of surface stimuli; thus highlighting the effect of context on curvature perception.

The experiments in chapter six further investigate contextual effects on curvature perception. They are designed to investigate a previously unreported illusion, here referred to as 3D-curvature contrast. The results of these investigations show the illusion
to be quantifiable, and also suggest that 3D curvature contrast is not simply reducible to brightness contrast induced effects. Finally, the experiments in chapter seven investigate the effect of context on the weight assigned to shading by using the perturbation analysis technique in the presence of 3D-curvature contrast. The results described in chapter seven demonstrate that, while the weights of both cues were unaffected by the sign of 3D curvature contrast, manipulating the background in terms of the cues present did affect the texture and shading weights; thus demonstrating that context has a role to play in the assignment of cue weights.
CHAPETR TWO

METHODOLOGY

2.1 INTRODUCTION.

Detailed investigations of contour-curvature perception provide important lessons for those researching surface curvature perception. Hyperacuity for curved contours was demonstrated as early as 1967 (Ogilvie & Daicar, 1967) and has been shown to be a robust finding (Watt & Andrews, 1982; Wilson, 1985). Although the limits of line curvature discriminability are well established, those investigating the geometric cue for contour-curvature discrimination have yet to produce unequivocal findings. This is because, as Watt (1984) points out, there are several geometric parameters that co-vary with contour curvature, and it is not a simple matter to identify that cue used by the mechanism involved in curvature perception. Proposed cues have included curvature itself, height or "sag", orientation range, chord length, and the area enclosed by the curve (Foster, Simmons & Cook, 1993).

Watt (1984) measured subjects’ relative efficiency (as compared to an ideal observer) for curvature discrimination under a number of conditions in which one of a pair of parameters was fixed while the other co-varied with curvature. Watt discounted height and chord length as candidate cues, by identifying under which condition subjects’ performance least resembled that of a statistically ideal observer. Subjects’ relative
efficiency was greatest when the parameter under manipulation was curvature itself, suggesting that this was the cue most likely to have been used by subjects for the experimental task. Foster, et al (1993) considered seven candidate cues: curvature, orientation range (turning angle), arc-length, arc-length-divided-by-chord-length, sag, mean sag, and area. Contour-curvature discrimination was defined by the increment threshold and its standard deviation, and the efficiency of the cues was defined in terms of the amount of variance associated with the cue in a number of curvature-discrimination tasks. Subjects' increment thresholds were obtained for curved contours ranging in their orientation and proximity to the observer. Foster, et al reported that sag accounted for the most variance across all experiments, suggesting that this is the relevant cue for contour-curvature discrimination. This contrasts sharply with the findings of Watt (1984) and demonstrates that, even in the case of 2D curvature perception, possible confounding factors have not been ruled out.

Investigations into contour curvature have highlighted the geometrical complexity of a seemingly simple stimulus. While it is true that a curved line can be described in many different geometric ways, it is equally true for a curved 3D surface. Thus, when investigating the latter it is important that the appropriate metric is being used in measuring subjects' performance. As pointed out in chapter one, there is good evidence suggesting 3D surfaces are not represented primarily as a local mapping of depth or orientation (Johnston & Passmore, 1994a; Todd & Reichel, 1989; De Vries, et al, 1994); rather, curvature may be directly represented by the visual system (Rogers & Cagenello, 1989; Johnston & Passmore, 1994b; Stevens, et al., 1991). This would suggest that curvature is the appropriate metric for measuring subjects' performance in a
2.2 PSYCHOPHYSICAL TECHNIQUES.

The primary goal of psychophysical experiments is to describe and explain the nature of human perception. Such experiments require that data are collected under well controlled conditions if the results are to be interpretable, and that subjects can confidently and reliably perform a given experimental task. It is to this end that psychophysical methods have been developed.

There are three basic psychophysical methods which can be used to estimate a sensory discrimination or increment threshold and a point of subjective equality (PSE). In the method of adjustment, or method of average error, the subject is asked to match a variable test stimulus with a standard stimulus along a dimension specified by the experimenter. The PSE is determined by the mean of the settings, and the probable error of the adjustment provides an estimate of the sensory threshold for the parameter under investigation. This approach is highly subjective, since it is impossible to control for criterion shifts the subject may make. In contrast to the method of adjustment, in the method of limits control of the test stimulus is placed in the hands of the experimenter. The subject is presented with a test stimulus which clearly differs from the standard stimulus along a specified dimension, and is asked to state in which direction the test stimulus differs from the standard. The difference between the two stimuli is reduced by small steps until the subject reports that both stimuli are 'equal'. A common problem
with this method is that subjects tend to perseverate their responses, so that a descending
series of test stimuli will give a systematically lower estimate of the threshold and PSE
than will an ascending series. The systematic differences between these estimates suggest
that the subject’s judgment when comparing a test stimulus with the standard is to some
extent determined by those test stimuli the subject has recently experienced. As Laming
(1986) points out, a sequential constraint of this kind is incompatible with the notion of
a threshold as a physiological constant.

The method of constants overcomes the sequential constraint problem associated with the
method of limits by presenting stimuli in a randomized sequence. The subject makes a
forced choice between the test and standard stimuli, the test stimulus being selected at
random from a predetermined set of stimulus levels. Another advantage that the method
of constants has over other psychophysical methods is that the same procedure may be
used to measure simultaneously the threshold and the point of PSE. The classical method
of constant stimuli, however, is inefficient. This is because, in choosing those stimulus
levels that are worth testing, the psychometric function must first be known with a
reasonable degree of accuracy. This necessitates running pilot studies with the
consequence that much data and energy are wasted. However, these problems have been
largely overcome through the use of adaptive regimens. For example, Adaptive Probit
Estimation or APE (Watt & Andrews, 1981) is based on the procedure of re-determining
the set of stimulus levels to be tested by the method of constant stimuli at intervals during
an experimental run. The set of stimulus levels chosen each time is determined by the
subject’s recent response history. APE fits a psychometric function, in the form of a
cumulative normal sigmoid curve, to the data obtained from each experimental run. By
calculating the standard deviation and mean of the underlying error distribution, APE is able to estimate the subject’s discrimination threshold and PSE for the task at hand. The discrimination threshold and the PSE correspond to the 84% and 50% points on the psychometric functions, respectively.

All the data in the following experiments were collected using the method of constant stimuli, because it is arguably the most accurate and widely useful of the psychophysical methods (Guildford, 1954). The APE adaptation of the method of constants was used, thus avoiding unnecessary pilot studies to identify stimulus levels worth testing.

2.3 GENERAL METHODS.

2.3.1 Subjects. At least two subjects were tested in each experiment. Because most of the experiments were quite prolonged, requiring subjects to complete many sessions lasting up to three hours each, it was not possible to enlist only naive subjects for each experiment. However, at least one naive subject took part in each experiment. The author, who was stereo-blind, was a subject in all experiments. Otherwise, all subjects had normal or corrected-to-normal vision.

2.3.2 Stimuli used. Images of spherical patches were used in all the experiments (see Figure 3.4). There are several advantages to using such stimuli. Firstly, using spherical patches ensures that curvature is invariant across the stimulus surface; this would not be
the case if the stimuli were non-spherical, curved patches. This is important when we consider that subjects were required to discriminate between pairs of stimuli on the basis of their curvatures. Secondly, because no part of a sphere falls within its own cast shadow, shape from shading processes can be investigated independently of cast shadows. Similarly, because the spherical patches are displayed in a void, the illumination of one part of a sphere by light reflected off another area(s) of the sphere (mutual illumination) does not occur. The amount of spherical surface area visible was constrained by the occluding edge of a circular aperture centred on each patch. The curvature of a patch was defined by at least one of two shape cues - shading and texture. The patches were set against either a random noise surround or a uniform black surround in most experiments, and were derived from spheres with radii equal to or greater than the radius of the aperture. Thus the generated displays gave the impression of an opaque screen with two apertures through which only a centrally positioned patch of surface on each sphere was visible.

It is possible to vary the curvature of the surface stimuli and thus run curvature-matching experiments. However, in varying the curvature of a spherical surface, other parameters which might provide subjects' with an unwanted cue to the matching task also vary. Figure 2.1 shows a normal cross-section through a spherical surface, highlighting the relevant geometrical parameters in these experiments. The cross-section has an arc length \( L \), a chord length \( C \), radius \( R \), and a depth range \( \Delta D \). The curvature, \( K \), is given by \( 1/R \).

Because they co-vary with curvature, these parameters will act as potential confounding variables in a curvature matching task (see Figure 2.2). One of the potential cues is available when the curves are positioned relative to each other. An increasing curvature
Figure 2.1. A normal cross-section through a spherical surface highlighting the parameters that co-vary with curvature, $K (1/R)$. $L =$ arc length; $R =$ radius; $D =$ viewing distance; $C =$ chord length; $\Theta =$ orientation range; $\Delta D =$ depth range.
Figure 2.2. Normal cross-sections through spherical surfaces illustrating the parameters that could act as cues in a curvature discrimination task (after Johnston, 1990). Figure A illustrates the depth parameter caused by a difference in the proximinity of the surfaces to the observer. This is eliminated by setting parameter $D'$ to zero. The size cue, depicted in figure B, was controlled for by fixing the chord length at less than the stimuli diameters. Figure C depicts the depth range parameter. Although it is not possible to control for this while controlling for the other two cues, the experimental results in chapter three suggest that this parameter was not employed by subjects when making curvature judgements.
difference between the curves is accompanied by an increasing difference in their proximity to the observer, the parameter D' (Figure 2.2A). This difference in absolute distances would clearly be a highly salient cue if stereo cues were available (Johnston, 1990). However, because the shape cues used in these experiments do not provide information about absolute distance, it is unlikely that this is a salient cue in these experiments. Nevertheless, to reduce the likelihood of it being used as a cue, the stimuli were aligned in depth at the point closest to the observer, the mid-point of the arc. Keeping parameter D constant results in an obvious difference in the sizes of stimuli that differ in their curvature. This size cue was eliminated by keeping the chord length fixed across trials and identical for each of the stimuli pair (Figure 2.2B). With this control, however, the difference in depth between the arc midpoint and the point of intersection with the chord (the depth range parameter, ΔD) co-varies with curvature (Figure 2.2C). It is not possible to control for this depth range cue while controlling for the other two, with the consequence that it may inadvertently provide subjects with an unwanted cue in the matching task. However, it is unlikely, for the reasons given above in the case of the parameter D', that this would be a particularly salient cue in these experiments. This is supported by the results of two sets of experiments, discussed later.

2.3.3 Stimulus generation. The spherical surface patches were constructed by ray tracing (Foley, van Dam, Feiner & Hughes, 1990). Ray tracing describes a computer graphics technique for determining the visibility of surfaces by tracing imaginary rays of light from the viewers eye to the last object in the scene from which each ray was reflected. To do this, a window on an arbitrary view plane and a centre of projection (the viewer’s eye) are selected. Rays are fired from the centre of projection through the centre of each pixel
Figure 2.3 A ray is fired from the centre of projection through each pixel to which the window maps, to determine the closest object intersected.
in the window. The colour of a given pixel is set to that of the first object to be struck by the eye ray passing through that pixel (see Figure 2.3). The stimulus-generation software allowed control over the curvature of the patches, their location in the modelling space, the viewpoint, and the location of a single point light source. The stimulus surfaces were rendered using a Phong illumination model,

\[ p = sI_a + sI_p(N \cdot L) + gI_p(H \cdot N) \]

where \( p \) is the computed brightness, \( s \) is the albedo, \( I_a \) is the intensity of ambient illumination, \( I_p \) is the intensity of direct illumination, and \( g \) is the proportion of light reflected specularly. \( N \) and \( L \) are the surface normal and light source direction unit vectors and \( H \) is the unit vector which bisects \( L \) and the line of sight. The spread of specular reflection is controlled by the parameter \( n \).

The illumination model can be used to simulate surfaces with reflectance functions varying from perfectly diffuse to perfectly specular. A surface which exhibits diffuse reflection, also known as Lambertian reflection, reflects light equally in all directions, and thus will appear equally bright from all viewing angles. The brightness depends only on the angle \( \theta \) between the light source \( L \) and the surface normal \( N \) (see Figure 2.4), with the amount of light seen by the viewer being proportional to \( \cos \theta \). In contrast to matte surfaces, shiny surfaces reflect light unequally in different directions and, thus, exhibit specular reflection. Specular reflection can be observed on any shiny surface; on a perfectly shiny surface, such as a perfect mirror, light is reflected \textit{only} in the direction of reflection \( R \), which is \( L \) mirrored about \( N \). In the case of a perfect mirror the viewer
Figure 2.4. A surface exhibiting diffuse reflection reflects light equally in all directions, thus appearing equally bright from all viewing angles. Its brightness depends only on the angle $\theta$ between the light source $L$ and the surface normal $N$, with the surface brightness seen by the observer being proportional to $\cos \theta$. 

\[ N_0 = 45 \]
\[ N_0 = 22.5 \]
Figure 2.5. A surface with a specular reflection function is one which reflects incident light unequally. A perfectly specular surface, such as a perfect mirror, reflects light travelling from a light source \( L \) only in the direction of reflection \( R \), which is \( L \) mirrored about \( N \). In the case of a perfectly specular surface the viewer would see reflected light from \( L \) only when the angle \( \alpha \) between \( R \) and the direction to the viewer \( V \) is zero.
would see reflected light from the mirror only when the angle $\alpha$ between $R$ and the direction to the viewer $V$ is zero (see Figure 2.5). For most of the experiments surfaces were modelled as diffuse Lambertian reflectors.

Texture was added to the spherical patches using a texture mapping technique. The plane cannot be mapped onto a doubly curved surface without distortion, the nature of the distortion depending upon the mapping function. An equidistant azimuthal mapping, which preserves radial distances (Horn & Brooks, 1989; Johnston & Passmore, 1994a), was chosen. We can think of the equidistant azimuthal mapping as the result of positioning the north pole of the sphere from which the surface patch is derived on the origin of the texture map and then transferring the texture onto the sphere by rolling along lines passing through the origin. In this projection there is no distortion of the texture along meridians of longitude, although there is some compression of the texture along parallels of latitude. Compression is minimal near the central point of the display and maximal at the occluding boundary. The scale factor which describes this compression is

$$\sin (\pi/2 - \theta) / (\pi/2 - \theta),$$

where $\theta$ is the elevation, in radians. Texture compression was less than 10% for most of the stimuli used. The texture map provides the albedo value for any point on the visible hemisphere. For a given ray through a pixel on the screen the surface normal at the intersection point of the ray and the sphere was computed and specified in terms of elevation and azimuth. Those parameters were used to index the texture map. Since in
general the specified location in the texture map would lie between grid points, the albedo values were calculated using bilinear grey level interpolation. In all but one series of experiments to be reported the texture of choice was a grey-level checkerboard texture.

The stimuli-generating program used for these experiments was adapted such that the curvature value of each cue could be set independently, allowing the adoption of the cue-conflict paradigm and perturbation analysis (Landy, et al., 1990) which provides a means of assessing the relative importance of individual curvature cues.

The stimuli were displayed on a 19" Sony trinitron monitor screen under the control of a SUN Sparcstation 330. The grey level display provided 8 bit resolution per pixel. In order to linearise the display a lookup table of luminance values was determined with a micro-photometer and used to control stimulus brightness. Subjects viewed the screen from a distance of 75cm. The position and direction of the light source are specified with reference to a coordinate frame centred on the patch. The z-axis extends out from the centre of the patch. The light source slant describes the angle between the light source vector and the z-axis and the light source tilt specifies the direction of slant, with 0 deg of tilt referring to the upper quadrant of the yz-plane.

Stimuli were displayed under polar (perspective) projection. By displaying the stimuli under polar projection, which is equivalent to viewing such an object in the real world from a point of observation, texture cues available to us when viewing real objects are also available in the computer-generated image. These cues include variations in texture element compression, area and density, and linear perspective. If, however, stimuli were
displayed under orthographic (parallel) projection, which approximates viewing an object from a great distance, some potential cues, such as perspective information, are lost. Stimuli were displayed under polar projection, because it is more typical of our everyday visual environment.

2.3.4 Procedures. A number of aspects are common to all the experimental procedures employed. These include the task required of subjects and the viewing conditions under which the task was carried out. Subjects were told that they would be presented with a series of computer-generated images depicting pairs of spheres viewed through circular apertures, and that the spheres would always be partially occluded by the apertures’ borders. They were given a curvature discrimination task in which they were asked to indicate which one of the spheres appeared more curved. They were instructed to respond by pressing one of two buttons - the left one if the left spherical patch appeared the more curved of the two, or the right button if the right spherical patch appeared the more curved. The spatial positions of the standard and test stimuli were altered between the left and right side of the display in a random fashion throughout any experimental run; thus for approximately 50% of presentations the standard stimulus and the test stimulus were positioned on the left and right side of the display, respectively, and for the remaining presentations these positions were reversed. Each stimulus pair remained on view until the subject made a response.

Subjects viewed the stimuli monocularly, with the dominant eye, from a distance of 75cms, and were positioned such that the dominant eye was aligned perpendicular to the midpoint between each pair of stimuli (see Figure 2.6). During a given experimental run
Figure 2.6. The layout of the apparatus during experiments. The subject was seated 75 cms from the display and viewed the stimuli monocularly in a darkened room. A head and chin rest was employed to prevent head movements during experimental runs.
comprising 64 stimuli presentations subjects' heads were immobilised with a chin and headrest; eye movements were not restricted. All experiments were carried out in a darkened room, the only light being that emitted from the computer screen.

The above is a description of the general procedure employed for all the experiments. A description of the procedural aspects peculiar to any individual experiment (or series of experiments), and the reason for using them, is given in the appropriate chapter.
CHAPTER THREE

INTEGRATION OF SHADING AND TEXTURE CUES: TESTING THE LINEAR MODEL

3.1 INTRODUCTION.

Work on the integration of shape cues has covered a wide range of cue combinations. Most studies on cue integration have used combinations of either motion and other monocular cues (Andersen & Braunstein, 1983; Braunstein, et al., 1982; Landy, et al., 1990; Maloney & Landy, 1989; Ono, et al., 1988; Rogers & Rogers, 1992), or stereopsis and monocular cues (Blake, Zisserman & Knowles, 1985; Bradshaw, Rogers & Frisby, 1991; Buckley, et al., 1989; Bülthoff & Mallot, 1988; Dosher, et al., 1986; Johnston, et al., 1994; Johnston, et al., 1993; Rogers & Cagenello, 1989; Rogers, 1986; Stevens & Brookes, 1988). Only a few studies have addressed the question of pictorial cue integration. For example, Ramachandran (1988) investigated the disambiguating role of occluding contours when combined with shading information. Similarly, Bülthoff’s (1991) work focused on the integration of two monocular cues, texture and shading; although it should be noted that subjects’ depth judgements were made by comparing stimuli against a stereo-defined standard.

The experiments in this chapter are designed to address two issues. Recent developments suggest that shape cues may not be integrated at the level of a depth representation (He & Nakayama, 1994; Todd & Reichel, 1989) but at some other representational level, such
as curvature (Johnston & Passmore, 1994a; Stevens, 1992; Stevens, et al., 1991). Experiments one and two attempt to identify the locus of integration for two monocular shape cues, shading and texture. Experiment one investigates whether subjects performing a curvature-matching task base their responses on information about depth or distance, or curvature. The results of this experiment, while not unequivocal, suggest that the information extracted from shading and texture is more likely to be integrated at the level of a curvature representation than a depth representation. Support for this conclusion is found in the results of experiment two. When the data from this experiment were expressed in curvature units they provided a better fit to a number of models tested than the same data expressed in depth-range units. Experiment two also provides the opportunity to test whether a linear model best describes the integration of these two cues. The results of this experiment suggest that this is not the case; instead, a non-linear model, which provides a better fit to the data, is proposed.

3.2 EXPERIMENT ONE: INVESTIGATING DEPTH RANGE AS A CUE TO CURVATURE.

Chapter two identified those parameters that co-vary with curvature and, consequently, are potential cues for subjects performing a curvature-matching task. These are the depth parameter, caused by a difference in the proximity of the surfaces to the viewer; the size cue; and the depth-range cue. It is possible to ensure that the first two cues are not available to subjects making a curvature matching judgement (see chapter two). However, it is not possible to eliminate the depth range cue while controlling for the size and depth cues. Consequently, in a curvature-matching task using these controls, one cannot rule out the possibility that subjects' decisions are based on the depth-range cue. The present
Figure 3.1. An example pair of spherical patch stimuli used in experiment one. Both patches are identical in their curvature (0.66 cm⁻¹), and differ only with respect to the size of their occluding boundaries. The spherical patch on the left is bounded by a 1.25 cm radius aperture, and the spherical patch on the right is bounded by a 1 cm aperture.
experiment was designed to investigate that possibility. In this experiment subjects were presented with pairs of spherical surface patches which differed in the spatial extent of their bounding contours (see Figure 3.1). Thus the diameter of the aperture bounding each stimulus was fixed at 70 pixels (2cms) for one of the stimuli, and at 88 pixels (2.5cms) for the other stimulus. The curvature of the stimulus bounded by the larger of the two windows was fixed at .66 cm⁻¹. Subjects were given a curvature discrimination task, in which they had to decide whether the test surface appeared more curved than the standard. The standard stimulus was the one with the larger bounding aperture, and the test stimulus was the one with the smaller bounding aperture. Subjects were given two blocks of trials, with each block consisting of 64 trials.

Using the above paradigm provides the opportunity to observe directly whether subjects are using the depth-range cue when carrying out curvature-discrimination tasks. For each stimulus curvature value there is a corresponding depth-range value

\[ \Delta D = r - \sqrt{r^2 - a^2} \]  

where \( r \) is the radius of the spherical surface, and \( a \) is the aperture radius in the image plane (see Figure 3.2). Thus, in the case of a spherical surface with a radius of 1.5cm (curvature = .66 cm⁻¹) and bounded by a 1.25cms radius aperture, the depth range is 0.67cms. If we set the aperture radius to 1cm, the depth range for the same surface will now be 0.38cms. If subjects' judgements in this experiment were based on the depth range parameter, the surface surrounded by the smaller of the two apertures would require a curvature
Figure 3.2. A normal cross-section of a spherical patch and occluding aperture. The patch's curvature can be expressed in depth-range units as

$$\Delta D = r - \sqrt{r^2 - a^2}$$
\[
\frac{2 \Delta D}{\Delta D^2 + a^2} \text{ cm}^{-1}
\]  \hspace{1cm} (3)

(which, in this case, is equal to .93 cm\(^{-1}\)) for both surfaces to appear equally curved.

The data for three subjects are plotted in Figure 3.3. Figure 3.3a shows the curvature of the small-aperture stimulus when the two surfaces appeared equally curved; Figure 3.3b is a plot of the same data plotted on a depth-range scale. If subjects were basing their responses on the depth-range cue, the small-aperture stimulus should have a curvature of .93 cm\(^{-1}\) and a depth range of .67 cm when both stimuli appear equally curved. If, on the other hand, responses were based on the curvature cue, the small-aperture stimulus should have a curvature of .66 cm\(^{-1}\) and a depth range of .38 cm at subjects’ points of subjective equality. Although the results are equivocal regarding this issue, the plotted data in figures 3.3a and 3.3b suggest that, of the two cues tested, subjects’ responses were more likely to have been based on the curvature cue than the depth-range cue. This suggests that, for the task in experiment one, the locus of integration was more likely to have been a curvature map than a depth-range map. This issue of the locus of integration is further addressed in experiment two.
Figure 3.3. a) The curvature of the small-aperture patch when the two surfaces appeared equally curved. b) A plot of the same data plotted on a depth-range scale. If subjects were basing their responses on the depth-range cue, the small-aperture stimulus should have a curvature of .93 cm$^{-1}$ and a depth range of .67 cm when both stimuli appear equally curved. If, on the other hand, responses were based on the curvature cue, the small-aperture stimulus should have a curvature of .66 cm$^{-1}$ and a depth range of .38 cm at subjects' points of subjective equality. Although the results are equivocal regarding this issue, the plotted data in figures 3.3a and 3.3b suggest that, of the two cues tested, subjects' responses were more likely to have been based on the curvature cue than the depth-range cue.
3.3 EXPERIMENT TWO: THE INTEGRATION OF SHADING AND TEXTURE; TESTING THE LINEAR MODEL.

Chapter one included a discussion on recent developments in the field of 3D shape cue integration and the evidence that some cues are integrated in a linear manner (Bruno & Cutting, 1988; Dosher, et al., 1986; Johnston, et al., 1993; Landy, et al., submitted; Landy, et al., 1990; Maloney & Landy, 1989; Young, et al., 1993), whilst other cue combinations appear not to follow a simple additive rule (Bulthoff & Mallot, 1990; Stevens, et al., 1991; Tittle & Braunstein, 1990). One of the first attempts to develop a formal model of depth cue integration is to be found in the Modified Weak Fusion (MWF) model, proposed by Landy and colleagues, and which is reported to provide a good account of the integration of motion and texture depth cues. The MWF model proposes that shape cues are integrated in a linear manner, and that the locus of this integration is at the level of a depth representation.

The following experiment was designed to test whether the linear model generalises to the integration of shading and texture cues, or whether some other, as yet unspecified, combination rule better describes their integration. The experiment also provides the opportunity to follow up the results of experiment one, by further investigating the locus of integration. This can be done by showing that a simple model, like the linear model, holds for one kind of 3-D shape representation but does not hold for another. Thus by comparing the ease with which a simple model is fitted to data described in terms of depth and curvature descriptors, we can infer which of the two representations was more likely to have been employed by the visual system.
Figure 3.4. An example pair of stimuli used in experiment two. Subjects were told to treat each display as though viewing two spheres protruding through two apertures. The diameters of the spheres were never smaller than the diameters of the apertures. For the pair of stimuli shown the inconsistent-cues stimulus (on the left) has a shading curvature value of .83 cm$^{-1}$ and a texture curvature of .7 cm$^{-1}$; the consistent-cues stimulus has a curvature value of .7 cm$^{-1}$.
3.3.1 Procedure.

The cue-conflict paradigm was employed in this experiment, and perturbation analysis used to estimate the weights of the shading and texture cues. The spherical surfaces were bounded by apertures measuring 2cms in diameter (see Figure 3.4). One stimulus comprised texture and shading cues with identical curvature values and the second comprised texture and shading cues with different curvature values. These stimuli were labelled the consistent-cue and inconsistent-cue stimuli, respectively. The inconsistent-cue stimuli were generated as follows. The shading was calculated on the basis of each surface normal for the shading cue surface. As stated earlier, the texture map provides the albedo value for each point on the surface. For discrepant surfaces, those stimuli for which the shading and texture curvatures differed, the texture map was indexed by the azimuth and elevation of the normal at the intersection of each ray and the texture cue surface. This procedure is equivalent to painting the texture for one curved surface onto another, appropriately shaded, curved surface. The texture was scaled with curvature to ensure that the texture element size, as defined on the texture cue surface, remained constant. The consistent and inconsistent-cue surfaces were the test and standard stimuli, respectively.

One cue in the inconsistent-cues stimulus (the "anchor cue") remained fixed. The perceived curvature of the inconsistent-cues stimulus was measured as a function of the curvature of the second cue, which was assigned one of eight curvature values in a given block of trials. These values were 0.25, 0.33, 0.50, 0.58, 0.67, 0.75, 0.83, and 1.0 cm\(^{-1}\). In each experiment the curvature value of the "anchor cue" of the inconsistent-cues stimulus was fixed at one of three settings: 0.4, 0.7, or 0.9 cm\(^{-1}\). There were two parts to the experiments. In the texture condition the shading cue of the inconsistent-cues
stimulus was anchored and the curvature value of the texture cue was allowed to vary. In the shading condition the roles of the two curvature cues in the inconsistent-cues stimulus were reversed.

If the integration of texture and shading is best accounted for by a simple weighted linear model, as proposed by Maloney and Landy (1989), then the data obtained from the above experimental conditions should fall on a plane defined by the formula:

$$c_p = w_t c_t + (1 - w_t) c_s$$

where $c_p$ is perceived curvature, $w_t$ and $1 - w_t$ are the texture and shading weights, and $c_t$ and $c_s$ are the portrayed texture and shading curvature values. Note that the above model has only one parameter. This is because there are only two cues and the linear model, as proposed by Maloney and Landy, is constrained by the assumption that the weights of the available depth cues in a given scene must add to one. Thus, the appropriate linear model under the conditions of this experiment has only one free parameter. The weight of the given cue, say texture, can then be estimated by calculating the slope of the line fitted to the data obtained from the experimental conditions in which a given shading curvature is combined with a range of texture curvatures.

3.3.2 Results.

Figures 3.5a to 3.5f plot subjects’ results for both experiments. Figures 3.5a, 3.5b and 3.5c plot subjects’ perceived curvature as a function of the value of the texture curvature cue, with the shading cue remaining fixed at one of three curvature values - 0.4, 0.7, and 0.9. Figures 3.5d, 3.5e and 3.5f plot subjects’ perceived curvature as a function of the
value of the shading curvature cue, with the texture cue remaining fixed at one of the above three curvatures. The data were similar across subjects; thus the data from each experiment were summed and averaged across subjects to produce one set of results (see Figures 3.6a and 3.6b).

The data in figures 3.5a to 3.5f demonstrate that the texture cue had practically no effect on curvature judgments for images with low curvature values, whereas the shading cue had a large effect. This is well illustrated by the 0.4 condition, in which shading curvature remained constant at 0.4 and texture curvature was varied. When the texture cue was assigned a curvature value of between 0.25 and 0.58, subjects' curvature judgments are equivalent to a surface curvature value of 0.4. Thus, varying the texture cue in the range 0.25 to 0.58 had no noticeable effect on subjects' perceived curvature. However, when the texture curvature value remained fixed at 0.4 and shading was varied across the above range, there was a clear effect on curvature perception; changes in perceived curvature were in the same direction as the changes in shading curvature. In contrast, as the curvature value of either cue increased beyond 0.58 in the 0.4 condition, the perceived curvature of the inconsistent-cues stimulus also increased. Furthermore, as the texture anchor cue curvature value is increased perceived curvature appears gradually to become more influenced by the texture cue than by the shading cue. This is demonstrated in Figure 3.5(d-f); as the texture anchor cue is increased, the effect of the shading cue on perceived curvature is reduced. Consequently, the slope of the plotted data decreases as a function of increasing the texture anchor cue.

Figures 3.5a to 3.5f can be thought of as representing cross-sectional views of the
Figure 3.5(a-c). Perceived curvature as a function of the curvature represented by the texture cue with the value of the shading cue fixed at one of three levels. Curvature is expressed as the inverse of the radius. a) subject P.P.; b) subject W.C.; c) subject C.F. Each data point is the average of at least three separate PSEs. The bars show ± one standard error of the measurement.
Figure 3.5(d-f). Perceived curvature as a function of the curvature represented by the shading cue with the value of the texture cue fixed at one of three levels. Curvature is expressed as the inverse of the radius. d) subject P.P.; e) subject W.C.; f) subject C.F. Each data point is the average of at least three separate PSEs. The bars show ± one standard error of the measurement.
three-dimensional surface generated for each subject by the data combined from all the experimental conditions (see Figure 3.6b). Because a consistent-cues stimulus with $c_t = c_s = c_p$ must match an "inconsistent-cues" stimulus with $c_t = c_s = c_p$, the surfaces generated by each subject's data are constrained to lie on the line in $c_t, c_s, c_p$ space described by this relationship. Landy and Young (personal correspondence) point out that such surfaces are well described by a general quadratic model incorporating the above constraint,

$$c_p = ac_t^2 + bc_s^2 - (a+b) c_t c_s + dc_t + (1-d) c_s$$

(5)

This reduces the number of free parameters to three.

To test how much variance in the data was accounted for by a linear model the following procedure was applied to each subject's set of data. The six sets of data generated by each subject (three sets each from the texture and shading conditions) were treated as estimates of points on a continuous surface. If the integration of the texture and shading cues conforms to a simple linear rule, we should expect that the slope of each of the three sections of the surface generated by the texture conditions will be both constant and equal. Similarly, the slopes of the three surface sections generated by the three shading conditions should also be both constant and equal. If this is the case, then the resulting surface will be best described by a planar function of the form

$$c_p = dc_t + (1-d) c_s$$

(6)

where $c_t$ and $c_s$ are texture and shading curvature values, and $d$ is a parameter. Note that this model meets the theoretical constraint discussed earlier, and is a subset of the above
Figure 3.6. Because of the similarity of performance between subjects, the data for all subjects were summed and averaged. These mean responses are represented in a three-dimensional bar plot (above), and surface plot (overleaf), of perceived curvature as a function of shading and texture curvature. The blue bars in the above bar plot indicate perceived curvature when the shading cue was anchored at curvature values of 0.4, 0.7 and 0.9 cm$^{-1}$ and the texture curvature was varied between 0.25 and 1 cm$^{-1}$. The yellow bars indicate perceived curvature when the texture cue was anchored at the above three curvature values and the shading cue’s curvature was varied between 0.25 and 1 cm$^{-1}$. 
Figure 3.6b. A surface plot of the mean responses across subjects, with texture curvature and shading curvature plotted along the X and Y axes, respectively, and perceived curvature plotted along the Z axis.
three-parameter quadratic model. It is clear from figures 3.5a to 3.5f that, for most of the experimental conditions, the obtained data do not fall on a straight line, suggesting that the shading and texture cues were not combined in a linear fashion.

The planar function (with $d=0.499$) accounted for 90.4%, 81.6% and 90.9% of the variance in WC’s, PP’s and CF’s data, respectively. However, fitting a six-parameter general quadratic function to the subjects’ data and removing coefficients close to zero suggested the following one-parameter non-linear model may provide a better fit to the data

$$c_p = a c^2 - a c c_s + c_s$$  \hspace{1cm} (7)

with the parameter $a = 0.757$. Note that this model is a subset of the three-parameter quadratic model, and also incorporates the diagonal constraint discussed above. The non-linear model accounted for more variance in the data than the linear model, accounting for 94.3%, 88.8% and 93.4% of WC’s, PP’s and CF’s data, respectively.

Although the two models clearly accounted for different amounts of variance, it is not possible to test directly whether this difference is statistically significant. Instead, both models were compared with the three-parameter quadratic model

$$c_p = a c^2 + bc^2 - (a+b) c c_s + d c + (1-d) c_s$$  \hspace{1cm} (8)

of which both models are subsets. Thus the linear model was set with $a=b=0$ and with $d$ being fit to the data, and the non-linear model was set with $b=d=0$ and with $a$ being fit to the data. The strategy was to attempt to show that the three-parameter model was
not significantly different from the non-linear model, but was significantly different from
the linear model. Preliminary exploration indicated that the proposed non-linear model was
appropriate for these data, whereas the linear model was not. T-test analysis (Table 3.1)
demonstrates that $b$ and $d$ are not significantly different from zero, although $d$ was just
significantly different for CF, and that $a$ is significantly different from zero for all
subjects. This indicates that the linear model is inappropriate for these data. Furthermore,
when the standardized residuals are plotted against texture curvature for the linear model
fit, there is evidence of systematic curvature for all subjects, as opposed to the random
scatter that is typical of good model specification (see Figure 3.7), indicating a quadratic
term is needed. In the case of the non-linear model there is no apparent systematic
pattern when standardized residuals are plotted against the squared texture curvature.
Regression analysis (Chatterjee & Price, 1977)\textsuperscript{3} shows that, for all subjects, the non-linear
model accounted for significantly less variance in the data than the three-parameter model
[WC: $F(2,43)=5.4$, $p<0.05$; CF: $F(2,44)=19.48$, $p<0.001$; PP: $F(2,44)=8.048$, $p<0.001$], as
did the linear model [WC: $F(2,43)=21.5$, $p<0.001$; CF: $F(2,44)=30.68$, $p<0.001$; PP:
$F(2,44)=22.98$, $p<0.001$]. Although the results of the regression analysis are inconclusive,
in each case the F-values are considerably higher for the linear model than the non-linear
model, suggesting that the linear model may be a poorer fit to the data than the non-linear
model. Furthermore, the pattern of residuals and the results of the t-tests suggest that the

\textsuperscript{3}Chatterjee and Price show that this test can be expressed directly in terms of the sample multiple correlation coefficient.
Let $R_p$ denote the sample multiple correlation coefficient obtained by fitting the full model with all the $p$ variables to a set
of data, and let $R_q$ denote the sample multiple correlation coefficient obtained by fitting the reduced model with $q$ number
of variables to the data. The F statistic for testing the null hypothesis that ($p$-$q$) specified variables have zero regression
coefficient is

$$
P = \frac{(R^2_p - R^2_q)}{\frac{(p-q)}{(n-p-1)}(1-R^2_p)}
$$

with d.f. = $p - q$, $n - p - 1$. 

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Figure 3.7. a, b and c show the standardized residuals plotted against squared texture curvature values for the non-linear model for each subject. d, e and f (overleaf) show the standardized residuals plotted against texture curvature values for the linear model for each subject. While there is random scatter of the points in figures 7a-7c, there is clearly systematic curvature in figures 7d-7f suggesting that a quadratic term is needed.
non-linear model provides a more parsimonious representation of the data than the Maloney-Landy model.

<table>
<thead>
<tr>
<th>Subject</th>
<th>a</th>
<th>b</th>
<th>d</th>
</tr>
</thead>
<tbody>
<tr>
<td>W.C.</td>
<td><em>p&lt;0.05</em></td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>C.F.</td>
<td><em>p&lt;0.05</em></td>
<td>NS</td>
<td><em>p&lt;0.05</em></td>
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<tr>
<td>P.P.</td>
<td><em>p&lt;0.05</em></td>
<td>NS</td>
<td>NS</td>
</tr>
</tbody>
</table>

*Table 3.1: The results of T-test analysis testing if either of the parameters a, b or d is significantly different from zero. Note that parameter a is significantly different from zero for all subjects, indicating that the linear model is inappropriate for the data from experiment two.*

The data suggest that the weight of the texture cue varies as a function of that cue's curvature value. Although the linear model does not provide the best fit to the data, we can consider the use of a local linear approximation. Since, from elementary calculus,

\[
dc_p = \frac{\partial c_p}{\partial c_t} dc_t + \frac{\partial c_p}{\partial c_s} dc_s
\]

we can see that the change in perceived curvature \(dc_p\) is a linear function of increments in shading and texture cues weighted by the values of the partial derivatives of the surface. For the Maloney and Landy model the weight of a given cue, defined by the slope of the function relating perceived curvature and the value of the cue, is equal to the
value of the parameter which scales that cue,

\[ w_t = \frac{\partial c_p}{\partial c_t} = d \quad (10) \]

However, this is not true of the non-linear model. In order to make explicit the changes in the perceived curvature for a change in a given cue, the local slope values were estimated by means of the partial derivatives of the perceived curvature with respect to shading curvature and texture curvature. Thus the weight of the texture cue, that is the influence that changing the texture cue has on perceived curvature, is given by the equation

\[ w_t = \frac{\partial c_p}{\partial c_t} = 2ac_t - ac_s \quad (11) \]

and the weight of the shading cue was estimated from the equation

\[ w_s = \frac{\partial c_p}{\partial c_s} = 1 - ac_t \quad (12) \]
In the Maloney and Landy model (1989) the weights scale the absolute values of the depth cues to derive a value for perceived depth. However, in the differential model

\[ dc_p = w_t dc_t + w_s dc_s \]  

(13)

the weights scale increments in 3D cues to derive a value for the change in perceived 3D shape. In other words, the weights describe how changes in shading or texture determine the change in perceived curvature.

Figures 3.8a and 3.8b are plots of the weights assigned to texture and shading, respectively, for the 0.4, 0.7 and 0.9 conditions. We can see from figure 3.8a that as the curvature value of the texture cue increases there is a proportional increase in the influence of texture on subjects’ perception of surface curvature. However, in the case of the shading cue, figure 3.8b shows that, as the value of the shading cue increases, the influence that shading has on subjects’ perception of surface curvature remains constant.

To assess the likelihood of subjects using depth measurements rather than curvature measurements in making their judgments, the data were transformed into depth values and tested with both models described plus the three-parameter model. Scaling the axes in this way rather than in terms of curvature results in a reduced fit for all three models. The amount of variance accounted for by the linear model was reduced from 90.4%, 81.6% and 90.9% to 76.6%, 78.8% and 82.9% for subjects WC, PP and CF, respectively. The amount of variance accounted for by the three-parameter model was reduced from 95.4%, 91.8% and 96.5% to 89.4%, 82.3% and 91.9% for subjects WC, PP and CF, respectively. Thus the non-linear model in the curvature domain was a better fit than the
Figure 3.8. The weights of the texture cue (above) and shading cue (overleaf) for each of the eight levels tested within each "anchor" condition. The weights scale increments in the texture and shading cues to derive a value for the change in perceived three-dimensional shape. The weights were calculated from the mean responses across subjects.
three parameter model in the depth domain for all subjects (WC, PP and CF: 94.3%, 88.8% and 93.4% for the non-linear model in the curvature domain as compared to 89.4%, 82.3% and 91.9% for the three-parameter model in the depth domain). The better fit of the non-linear model in the curvature domain when contrasted with the three-parameter model in the depth domain suggests that it is likely subjects were deriving information about surface form from a curvature map rather than from a range map.

3.4 DISCUSSION.

The experiments described in this chapter served two purposes. Experiment one was designed to investigate which of two cues, depth-range or curvature, is used by subjects carrying out the curvature-matching task employed in these experiments. While the primary aim of experiment two was to test whether the linear model of cue integration applies to the integration of texture and shading information, it also provided the opportunity to investigate whether the integration of these cues is more likely to result in a curvature representation than a depth-range representation. The results of experiment one suggest that subjects performing the curvature-matching task were more likely to have been basing their responses on the curvature cue than the depth-range cue. The conclusion of experiment one is supported by the results of the second experiment; it was demonstrated that the data expressed in curvature units provided a better fit to a range of models than the same data expressed in depth-range units. These results are in agreement with experimental results reported by Johnston and Passmore, (1994a; 1994b), and those reported by Koenderink et al (Koenderink, Van Doorn & Kappers, 1994) suggesting that the primary representation of pictorial relief is not a depth map, but more likely to be a curvature map.
As stated above, the primary goal of experiment two was to test whether the linear model proposed by Maloney and Landy (1989) applies to shading and texture. In the Maloney and Landy model of depth cue integration the percept results from the process of combining the outputs of independent depth modules in a specified proportion; a procedure which they refer to as weak fusion (Young, et al., 1993). The technique of perturbation analysis allows one to estimate the relative weights of individual depth cues by varying one cue and measuring its influence on the combined percept. If the change in the combined percept is proportional to the change in the level of the cue for all increments in the cue then we can model the combined percept as a planar function of the values of the component cues. This situation conforms to a linear combination rule. However, Maloney and Landy accept that other influences might affect the combined percept, like the separation of the component cues. Under these conditions there will be a departure from linearity. Indeed one interpretation of the non-linear model presented here

$$c_p = c_s + a(c_t - c_s)c_t$$  \hspace{1cm} (14)

is that perceived curvature depends upon shading curvature plus some influence from texture which is weighted by a proportion of the difference between the cues. Other interpretations may also be possible and it should be noted that an explicit implementation of this rule is not assumed. It does however provide a useful description of the data.

Following Maloney and Landy, the weights have been defined as the values of the partial
derivatives of the surface generated by the measured value of the combined percept, with the component cues taken as parameters, although the idea has been generalised to deal with more complex surfaces. This approach involves a local linear approximation and so concurs with Maloney and Landy that locally we can think of the cue combination rule as linear. However, it is clear that any curved surface will appear planar if investigated locally. So, in attempting to test Maloney and Landy’s (1989) proposed model of depth cue integration in the context of shading and texture, the shape of the function was investigated for a wide range of cue combinations.

The results show that a linear model as proposed by Maloney and Landy, that is one in which the weights scale the absolute curvature cue values to derive a value for perceived curvature, does not generalise to the integration of these shading and texture cues. However, for other pairs of cues the weights may not vary with component cue separation. If the integration of shading and texture was best described by a linear model then one would expect that the weight of a given cue would remain constant as the cue varied in its level of curvature. Although the weight assigned to shading was constant within experimental conditions, suggesting that the two cues may be integrated in a simple linear fashion, the weight assigned to texture was shown to vary systematically with texture curvature when the roles of the two cues were reversed. The value of the non-linear model described above is its role in highlighting the way in which the shading and texture weights change as a function of the values of the component cues.

Experiment two also provided the opportunity to test the proposal that the combination of cues results in an integrated representation of surface distance or depth. The data
suggest that, in the above experimental conditions, 3D surface information was more likely to have been derived from a curvature map. This is supported by the poorer fit of all three models (the linear, the non-linear and the three-parameter) to the transformed depth data, and the better fit of the proposed non-linear model in the curvature domain when contrasted with the three-parameter model in the depth domain.

Thus, although several experimenters have reported empirical support for Maloney and Landy's depth cue integration model for the combination of a wide range of depth cues, the results of the experiments reported in this chapter suggest that such a strategy may not be used for the integration of shading and texture cues. Instead, the results lend support to the hypothesis that the visual system may combine such cues in a non-linear fashion, although this is qualified by the observation that, locally, any non-linear combination rule can be approximated by a linear model. It is also suggested that the locus of texture and shading cue integration is a curvature map, rather than a depth or orientation map.
CHAPTER FOUR

FACTORS INFLUENCING TEXTURE WEIGHT

4.1 INTRODUCTION.

One of the findings of experiment two was how ineffectual texture was as a cue to curvature for surfaces with low curvature values. Yet texture was very effective for highly curved surfaces. It seems reasonable to conclude from this that the weight assigned to texture was likely to be a function of the magnitude of the texture gradients present in the test field, which are constrained by a combination of aperture size and surface curvature. Thus as surface curvature increases, more of the surface will become visible within the boundary of the aperture. Young, et al (Young, et al., 1993) report that the weight given to a motion cue to depth varies in a similar fashion. They found that, for stimuli depicted by motion and texture, the weight of the motion cue was reduced when the area of the motion stimulus was reduced (reduced motion availability). In their experiment Young et al presented subjects with cylindrical stimuli composed of inconsistent texture and motion depth cues, and used perturbation analysis to estimate the two cues' weights. It was found that the motion cue weight varied with the rotation amplitude of the inconsistent-cues surface. When the inconsistent-cues surface was viewed rotating through 20-30 degrees, the motion cue was assigned a greater weighting
than when the surface rotation was less than 20 degrees. Young et al argued that greater rotations result in larger sets of 2D measurements being made available for computing structure from motion, and that it was this increased ‘availability’ of 2D measurements which resulted in the motion cue being given more weight when the rotation amplitude of the surface increased. Johnston et al (Johnston, et al., 1994) report similar results when using stimuli comprising stereo and limited, two-frame motion cues. Similarly, it could be argued that the increase in texture weight with increasing curvature, reported in experiment two, may be a result of an increase in the set of 2D measurements being made available.

Just as a cue’s weight is positively correlated with the cue’s availability, a change in the reliability of a cue appears to result in a complementary change in the cue’s weight (Cumming, et al., 1993; Young, et al., 1993). Cumming et al report that disrupting texture isotropy reduced the effectiveness of the compression gradient as a cue to surface curvature, which, in turn, resulted in a reduction in the texture cue weight. Arguably, the reduced effectiveness of the compression gradient may be considered to reflect a disruption of the texture cue’s reliability. Young et al report similar findings. They found that reducing the reliability of either the texture or motion depth cues, by increasing the variability of texture compression or the texture element velocities in the stimulus, reduced the reliability of that cue; this, in turn, resulted in a reduction of the cue’s weight. However, it should be noted that this manipulation of the cues’ reliability applied only to the inconsistent-cues stimulus. Following this manipulation of either one of the two cues, subjects were given the task of matching the depth of the inconsistent-cues stimulus to a consistent-cues stimulus in which cue reliability had not been manipulated. A
consequence of this manipulation is that subjects are no longer comparing like with like, in that the cues combined to construct both stimuli are not drawn from the same sets. The mixed cue surface is no longer constrained to pass through the diagonal $d_p = d_m = d_t$, where $d_p$ is perceived depth, $d_m$ is the inconsistent motion depth, and $d_t$ is the inconsistent texture depth. In other words, when the cues of the inconsistent-cues stimulus depict the same depth value as the consistent-cues stimulus, the inconsistent-cues stimulus will not necessarily be perceived as having the same depth-range as the consistent cues stimulus. Consequently any change of a cue’s weight under these circumstances may be interpreted as either reflecting the cue’s reduced reliability, or reflecting a shift in the point of subjective equality (PSE), or both.

This problem in interpreting the data is demonstrated in Figure 4.1(a-b). Figure 4.1 plots data from an imaginary experiment, in which subjects are presented with pairs of cylindrical stimuli comprising inconsistent and consistent motion and texture cues. The motion cue is anchored at a depth value of 6.6cm while the texture cue is perturbed about this value. Subjects’ perceived depth is plotted as a function of texture depth, with the texture cue weight then being estimated using perturbation analysis. Figures 4.1a and 4.1b plot the data from two different versions of the same experiment. The ‘filled-triangle’ data in Figure 4.1a show a set of results prior to reducing texture cue reliability. The ‘filled-square’ data in Figure 4.1a are taken from an experiment in which the texture cue reliability is reduced in an identical manner for both the inconsistent- and consistent-cues stimuli. Both types of stimuli in the former version of the experiment contain identical cues; consequently an ‘inconsistent-cues’ stimulus with $d_t = d_m = 6.6cm$ is matched to a consistent-cues stimulus with an identical depth - 6.6cm. Similarly, because the
Figure 4.1. Contrasting the effect of reducing texture reliability for both stimuli (a) against the effect of reducing texture reliability in just one stimulus (b). See text for details.
reliability of the texture cue in the latter version of the experiment is reduced in an identical manner for both types of stimuli, the above constraint still applies. Thus the reduced weight of the texture cue, reflected by the shallower slope of the ‘filled-square’ data in comparison to the ‘filled-triangle’ data, may be interpreted as being a consequence of reducing texture cue reliability. Contrast this with the data in Figure 4.1b. As in Figure 4.1a, the ‘filled-triangle’ data in Figure 4.1b are obtained prior to reducing texture cue reliability. In contrast to Figure 4.1a, the ‘filled-square’ data in Figure 4.1b are taken from an experiment in which texture cue reliability is reduced for just the inconsistent-cues stimulus, and not the consistent-cues stimulus. Consequently, an inconsistent-cues stimulus with $d_i = d_m = 6.6\text{cm}$ is no longer constrained to appear equal in depth to a consistent-cues stimulus of the same depth. In other words reducing the reliability of the texture cue in just one of the stimuli also results in a shift in the identity of the stimulus. Therefore any subsequent change in the texture cue’s weight may be a consequence of reducing texture cue reliability, of shifting the identity, or of a combination of both factors. However, if one assumes that the shift in the identity of the stimulus has a simple additive effect and, therefore, does not influence the texture cue’s weight, one could conclude that any change in the texture cue’s weight is a consequence of reducing the texture cue’s reliability. It was decided that this assumption would not be used in the experiments in this chapter that investigate the effect of manipulating cue reliability and availability on a cue’s weight. Instead, identical availability and reliability manipulations were applied to both the consistent- and inconsistent-cues stimuli.

The experiments in this chapter address a number of factors that may affect the texture cue’s weight. Experiment three investigates what effect manipulating the texture
availability, through varying the aperture size, has on the texture cue's weight. Just as increasing surface curvature results in a larger set of 2D measurements being available when viewing the stimulus through a fixed-sized aperture, the same applies when a fixed-curved stimulus is viewed through a larger aperture. The results of the above manipulation support the notion that increasing or decreasing the availability of a cue results in a concurrent increase or decrease in that cue's weight. The data from this experiment were also used as a test of the non-linear model proposed in chapter three. As in experiment two, it was found that the same one-parameter non-linear model provided a better fit to the data than a one-parameter linear model. Experiment four tested the notion that manipulating a cue's reliability results in a complementary change in that cue's weight. In this experiment the change in the texture cue's weight was measured as a function of texture contrast. It is clear that the weighting for texture would be zero for textures with sub-threshold contrast. What this experiment sought to address was how the texture weight would change as contrast varied within a range of supra-threshold levels. The results of experiment four demonstrate that at very low contrast the texture weight is reduced, and that it generally rises rapidly with increasing contrast before levelling out at relatively low contrast levels.

The final series of experiments in this chapter attempt to identify the relevant texture measure being used by subjects to extract information about surface curvature in the previous experiments. The outcome of these experiments suggest that the most likely texture measure that subjects employed was line curvature.

The following section gives a detailed account of experiments three and four. This is
followed by a description of those experiments designed to identify the relevant texture measure used by subjects for the curvature matching tasks.

4.2 INVESTIGATING CUE AVAILABILITY AND RELIABILITY.

Although the next two experiments investigate the effect of very different manipulations, aperture size and texture contrast, the methodology employed is essentially the same. For that reason, the following discussion on methodology applies to both experiments.

4.2.1 METHODOLOGY.

The following two experiments were designed to avoid the potential data-interpretation problem discussed above. The above discussion describes how manipulating an inconsistent cue’s reliability, without an identical manipulation of the same cue in the consistent-cues stimulus, results in the identity no longer being constrained to lie on the diagonal $d_p = d_q = d_m$. Any subsequent change in the cue’s weight could be a result of both this shift in identity and reducing the cue’s reliability. This problem is avoided in experiments three and four by applying identical ‘availability’ and ‘reliability’ manipulations to both the consistent- and inconsistent-cues stimuli. Thus in experiment three the aperture sizes of both stimuli were varied in identical ways, and in experiment four the texture contrast manipulation was identical for both stimuli. This has the result that, when the inconsistent cue curvatures are identical, the identity will lie on the diagonal $c_p = c_s = c_t$, where $c_p$, $c_s$, and $c_t$ are the perceived, shading and texture curvatures, respectively. Thus any change in the texture weight in experiments three or four may be attributed to the manipulation of the aperture size or texture contrast.
4.2.2 EXPERIMENT THREE: VARYING APERTURE SIZE.

As stated earlier, this experiment was run to test the assumption of the modified weak fusion model that a cue’s weight is partly determined by the cue’s availability. Increasing and decreasing the size of the aperture bounding the stimuli leads to a complementary increase and decrease in the magnitude or availability of visible texture gradients. Three aperture sizes were used in this experiment; these were, in radius measurements, 0.6cm, 1cm and 1.5cm (see Figure 4.2). If the above assumption is correct, the texture weight should rise as a function of increasing aperture size. Thus if the 0.4 condition of experiment two were to be repeated for the three aperture sizes, then, as the aperture size increases or decreases the texture weight should depart from zero at lower and higher curvature values respectively. Similarly, because discrimination threshold is taken to be a reliable indication of the difficulty of a task, it is expected that curvature discrimination thresholds should decrease as the availability of the texture cue increases. This is because an increase in texture availability leads to increased curvature information; the more (relevant) information that is available in the scene, the easier the task should be. Thus, if the texture weight rises as a function of increasing the aperture size, it is expected that subjects’ curvature discrimination thresholds will fall with increasing aperture size.

4.2.2.1 Procedure. The shading curvature was anchored at 0.4cm⁻¹ in each aperture condition, and the texture curvature was perturbed. In the 1cm aperture radius condition subjects were tested with identical combinations of inconsistent cues as in the 0.4 condition of experiment two. For two of the three subjects tested, WC and CF, the data for the 1cm condition was obtained from experiment two. The texture curvature values ranged from 0.75cm⁻¹ (r=1.3cm) to 1.43cm⁻¹ (r=0.7cm) in the 0.6cm aperture radius.
Figure 4.2. The three aperture sizes used in experiment three. The radii of the three apertures are, from top to bottom, 0.6cm, 1cm and 1.5cm. The spherical patches in the left-hand column comprise consistent texture and shading cues of identical curvature (0.33cm⁻¹). The same pair of spherical patches are viewed through each aperture. The spherical patches in the right-hand column are comprised of inconsistent cues, with a shading curvature of 0.3cm⁻¹ and a texture curvature of 0.58cm⁻¹. When comparing the stimuli pair one notices that, as aperture size increases, the right hand patch appears to become more curved than the patch on the left, suggesting that the texture cue weight increases with increasing availability. The results of experiment three support this qualitative observation.
condition, from 0.25cm\(^{-1}\) (r=4cm) to 1.0cm\(^{-1}\) (r=1cm) in the 1cm condition, and from .17cm\(^{-1}\) (r=6cm) to .65cm\(^{-1}\) (1.53cm) in the 1.5cm aperture radius condition. Note that there is considerable overlap between the points tested in the 0.6cm and 1cm condition, and between the points tested in the 1cm and 1.5cm conditions.

4.2.2.2 Results. Figure 4.3(a-c) plots subjects' perceived curvature of stimuli defined by the combinations of texture and shading curvature described above. The data from each of the three aperture conditions are included for each subject. The data plotted in Figure 4.3 suggest that, in the case of the 1.5 aperture condition, the texture weight began to increase at a lower texture curvature than was the case in the 1cm aperture condition. This is demonstrated for those texture curvature values tested in both conditions. When texture curvature ranged from 0.5cm\(^{-1}\) to 0.67cm\(^{-1}\), curvature values that were common to both the 1cm and 1.5cm aperture conditions, the inconsistent-cues stimulus appeared more curved when bounded by the 1.5cm aperture than by the 1cm aperture. The data from the 0.6cm aperture condition demonstrate that the texture weight began to rise at higher curvature levels than in the 1cm aperture condition. Thus for texture curvature values from 0.75cm\(^{-1}\) to 1cm\(^{-1}\) subjects' perceived the spherical patches in the 0.6cm aperture condition as being less curved than identically curved stimuli in the 1cm aperture condition.

Figure 4.4(a-c) plots subjects' curvature discrimination thresholds for the three aperture sizes. The data show the same pattern across all the subjects; as the aperture size increases there is a clear lowering of subjects' curvature discrimination thresholds. Thus as the area of visible surface texture increases subjects are better able to discriminate a
Figure 4.3. Perceived curvature of an inconsistent-cues patch as a function of texture curvature and aperture size. The shading curvature was anchored at 0.4 cm\(^{-1}\) (radius = 2.25 cms) for all aperture conditions and texture curvature was perturbed about this value. These plots show that the larger the aperture bounding the stimuli, the lower the curvature value at which the texture weight begins to rise. a) Subject W.C.; b) subject C.F.; c) subject M.F.
Figure 4.4. Subjects' curvature discrimination thresholds as a function of texture curvature and aperture size. It is clear from these plots that, for all subjects, as the aperture size increases there is a lowering of curvature discrimination thresholds. Similarly, increasing the texture curvature leads to a decrease in discrimination thresholds.
given surface curvature from a range of other curvatures. Similar results have been reported by Johnston and Passmore (1994a). In their experiment subjects performed a curvature discrimination task for a spherical patch set against a background sphere. The ratio of the spatial extents of the background sphere and the surface patch remained constant; thus as the background sphere’s curvature increased, the radius of the patch was reduced. Johnston and Passmore found that subjects’ curvature discrimination thresholds rose with increasing curvature of the background sphere (and a concurrent decrease in the patch size).

<table>
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<tr>
<th>Aperture Condition</th>
<th>Subject W.C.</th>
<th>Subject C.F.</th>
<th>Subject M.F.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Linear model</td>
<td>Non-linear model</td>
<td>Linear model</td>
</tr>
<tr>
<td>0.6cm radius.</td>
<td>76.8 (d=.486) 95.2 (a=.408)</td>
<td>88.1 (d=.623) 98.7 (a=.513)</td>
<td>55.4 (d=.366) 78.5(a=.321)</td>
</tr>
<tr>
<td>1cm radius.</td>
<td>86.4 (d=.306) 96.7 (a=.365)</td>
<td>92.0 (d=.588) 98.1 (a=.694)</td>
<td>85.9 (d=.409) 97.2(a=.49)</td>
</tr>
<tr>
<td>1.5cm radius.</td>
<td>88.2 (d=.344) 96.0 (a=.804)</td>
<td>90.2 (d=.42) 93.7 (a=.961)</td>
<td>85.9 (d=.355) 93.8(a=.831)</td>
</tr>
</tbody>
</table>

Table 4.1: The amount of variance accounted for by the one-parameter linear and non-linear models in each aperture condition, with the parameter value in brackets. Note that the non-linear model consistently accounts for more variance across subjects and aperture sizes than the linear model.

The one-parameter non-linear and linear models described in chapter three were fit to the data, and the percentage of variance in the data accounted for by both models was compared. Table 4.1 (above) shows the amount of variance accounted for by the two models in each of the three aperture conditions. In each aperture condition the non-linear
model accounted for more variance in the data than did the linear model for all subjects (see table 4.1).

4.2.3 EXPERIMENT FOUR: VARYING TEXTURE CONTRAST.

This experiment investigates whether varying the texture contrast affects the weight assigned to the texture cue. By reducing surface texture contrast one is effectively reducing the texture cue reliability, which has been demonstrated to be an important factor influencing how a cue is weighted by the visual system (Cumming, et al., 1993; Young, et al., 1993). While it is obvious that the texture cue would have zero weighting when the texture contrast is at some sub-threshold value, it is not clear if and how the texture weight would vary across a range of supra-threshold contrast values. If, as the evidence suggests, a cue’s weight is dependent on that cue’s reliability, this would predict that reducing texture contrast would result in a reduction in the texture weight. However, what is not clear is whether the relationship between changing texture contrast and changing texture weight is a linear or non-linear one. If the relationship is linear, then one would expect the change in texture weight to be directly proportional to the change in the texture contrast.

4.2.3.1 Procedure. Subjects were presented with pairs of stimuli bounded by apertures with radii of 1cm. The shading curvature was anchored at 0.6cm⁻¹ for the inconsistent-cues stimulus, and the texture curvature was set to one of three values - 0.33cm⁻¹ (r=3cm), 0.8cm⁻¹ (r=1.25cm), and 1cm⁻¹ (r=1cm). For each of these three cue combinations the texture contrast was randomly chosen from one of five values; 0.06,
0.12, 0.24, 0.5, and 0.75. These values refer to the Michelson contrast, which is defined as

\[
\frac{L_{\text{max}} - L_{\text{min}}}{L_{\text{max}} + L_{\text{min}}}
\]  

(15)

where L is the surface luminance measure. Note that, for the Phong model, local texture contrast depends only on the albedo, and thus is constant across the patch. As in the previous experiments, subjects were given a curvature discrimination task. For each of the three inconsistent-cue conditions, perturbation analysis was used to map out any change in the texture cue’s weight as a function of changing contrast.

4.2.3.2 Results. Subjects’ combined results for the three cue-combination conditions are plotted in Figure 4.5(a-c). The figure plots perceived curvature as a function of changing contrast for each of the cue-combination conditions. If varying the contrast has no effect on the texture weight, then perceived curvature should remain constant across the contrast range tested. If, on the other hand, varying the contrast does have an effect on texture weight, then subjects’ perceived curvature should move away from the shading curvature (0.6cm\(^{-1}\)) towards the texture curvature as contrast increases.

The pattern of results is similar for all subjects. Varying the texture contrast when texture curvature was set at 0.3cm\(^{-1}\) had only a small effect on subjects’ perceived curvature.
Figure 4.5. Subjects' perceived curvature of a number of inconsistent-cues spherical patches as a function of the stimulus contrast. Shading curvature was fixed at 0.6 cm⁻¹ and texture curvature was fixed at one of three values: 0.33 cm⁻¹, 0.8 cm⁻¹ and 1 cm⁻¹. The texture cue weight is reflected in the extent to which perceived curvature is displaced from 0.6 cm⁻¹ in the direction of the texture curvature. We can see that, in the two higher texture curvature conditions, texture weight increases with increasing texture contrast.
However, when texture curvature was set at either 0.8cm\(^{-1}\) or 1.0cm\(^{-1}\), there was a more pronounced effect on subjects' perceived curvature. From looking at Figure 4.5 we can see that perceived curvature rises rapidly as texture contrast rises; but as texture contrast increases beyond 0.24, the increase in perceived curvature slows down and begins to flatten out. This is especially apparent for data from the more extreme texture curvature condition (0.8cm\(^{-1}\)).

4.2.4 DISCUSSION.

The goals of experiments three and four were to test two common assumptions regarding cue integration; namely, that a cue's weight is partly determined by its availability and reliability. By varying the aperture radius in experiment three it was possible to manipulate the availability of the texture cue. The data in Figure 4.3(a-c) demonstrate that this manipulation had a clear effect on the weight of the texture cue. This is particularly apparent for those inconsistent-cue combinations shared by both the 1cm and 1.5 cm radius aperture conditions, and for the inconsistent-cue combinations shared by the 1cm and 0.6cm conditions. Thus when texture curvature ranged from 0.5cm\(^{-1}\) to 0.67cm\(^{-1}\), the inconsistent-cue stimulus appeared more curved in the 1.5cm aperture condition than in the 1cm aperture condition. This suggests that the increasing availability of the texture cue in the former condition resulted in the texture cue weight beginning to increase at a lower curvature value than in the latter condition. Similarly, when texture curvature ranged from 0.75cm\(^{-1}\) to 1cm\(^{-1}\) the stimulus appeared less curved when bounded by a 0.6cm radius aperture than when bounded by a 1cm radius aperture condition. The reduced availability of the texture cue in the former condition resulted in the texture
weight beginning to increase at a higher curvature value than in the 1cm condition. This increase in texture weight as a function of increasing the availability of the cue is reflected in the concurrent decrease in curvature discrimination thresholds (Figure 4.4(a-c)). Thus the results of experiment three support the assumption that a cue's weight is, in part, determined by that cue's level of availability. Experiment three also provided the opportunity to assess the robustness of the non-linear model proposed in chapter three, by testing it for a wider range of curvature values. Table 4.1 shows that the non-linear model accounted for more variance in the data for all three aperture conditions than did the linear model, and that the better fit of the non-linear model was found for all subjects. This suggests that the non-linear model is an appropriate description of the data, and that it generalises to a wider range of curvatures than that tested in experiment two.

The issue of reliability was dealt with by experiment four, in which the texture cue weight was estimated as a function of varying texture contrast. While it is obviously the case that the texture cue would have zero weighting when given a sub-threshold contrast, this experiment examined whether the texture weight changed across a range of supra-threshold contrast levels, and whether any such relationship between texture weight and texture contrast is linear or non-linear. The results plotted in Figure 4.5 are an indication of texture weight as a function of texture contrast. An increase in the texture cue weight would be reflected in a reduction of the difference between subjects' perceived curvature and the actual curvature of the texture cue. The data from the 0.8cm⁻¹ and 1.0cm⁻¹ demonstrate that texture weight increases rapidly with increasing texture contrast, before starting to level out as texture contrast increases beyond 0.24. This suggests that
the relationship between texture weight and texture contrast is not a linear one, and that the texture cue begins to lose its reliability only after texture contrast drops below some critical point. In the case of the 0.3cm⁻¹ condition, in which the texture curvature was set to 0.3cm⁻¹, varying texture contrast had a minimal effect on the texture weight, which remained close to zero. This is consistent with the results of experiment two, in which it was found that texture was an ineffectual cue to curvature for surfaces with low curvature values. The results of experiment four suggest that texture contrast may affect the reliability of the texture cue, and support the assumption that a cue's weight is partly determined by that cue's reliability.

4.3 WHICH TEXTURE PROPERTIES ARE IMPORTANT FOR CURVATURE PERCEPTION?

A number of authors have suggested that the important texture gradient for extracting information about surface curvature is texture element compression (Blake, et al., 1993; Cutting & Millard, 1984; Todd & Akerstrom, 1987) or the overall gradient of texture compression (Cumming, et al., 1993). While it is possible that texture compression was the information source being used by subjects when making curvature judgements in experiments one to four, there is one other potential source of information in the texture used for these experiments, which was not available in the experiments of Cutting and Millard (1984), Todd and Akerstrom (1987), and Cumming, Johnston and Parker (1993). This other source of information is 2D line curvature. In experiments one to four both compression and 2D line curvature co-varied with surface curvature. Furthermore, both properties would also have been affected in the same way by the manipulations of
aperture size and texture contrast described earlier in this chapter.

The following series of experiments investigate whether 2D line curvature and/or compression was being used by subjects in making curvature discrimination decisions. It is possible to independently manipulate the availability of the two sources of information by using textured surfaces that contain reduced or no 2D line curvature information, but whose images contain texture compression. Similarly, surface textures rich in 2D line curvature information, but with reduced compression, can also be generated. By employing the cue-perturbation paradigm in which shading is combined with different types of texture, one can infer from the weights given to the textures whether 2D line curvature and compression were utilised by subjects in the curvature discrimination tasks. Thus if a texture which has no 2D line curvature information, but is rich in compression information, is assigned a higher weighting than other textures, this would be evidence that compression was the relevant source of information.

4.3.1 PROCEDURE

Apart from the type of texture chosen, the procedure was the same for each experiment. Subjects were presented with pairs of surface patches viewed through a 1cm radius aperture. Perturbation analysis was employed in each experiment. For the inconsistent-cues stimulus the shading cue was anchored at 0.6cm⁻¹, and the texture cue varied between 0.3cm⁻¹ and 1cm⁻¹.
4.3.2 EXPERIMENT FIVE: SURFACE CONTOUR CURVATURE.

The purpose of this experiment was to investigate the role of contour curvature when assigning a weight to the checkerboard texture. Checkerboards have edges that change in sign at each repeat of the pattern. In order to investigate the role of contour curvature without this complication we compared the checker board texture with a simpler stimulus in which the edges were replaced with lines. Because of its appearance, this pattern will be referred to as a "grid" texture (see Figure 4.7). The texture was constructed such that the lines comprising the grid segmented the surface into equally sized squares. The surface areas contained within each grid were identical in size to the checkerboard texture elements. Two subjects, W.C. and M.F., were tested with the range of shading and texture cue combinations for stimuli containing the checkerboard texture and for stimuli containing the grid texture.

4.3.2.1 Results. Figure 4.6(a-b) plots subjects’ perceived curvature as a function of texture cue curvature for both texture conditions. The plotted results demonstrate that the grid texture is almost as effective a cue to curvature as the checkerboard texture.

4.3.3 EXPERIMENT SIX: VARYING SURFACE CONTOUR CURVATURE.

This experiment looks at the effect of manipulating the extent of continuous surface contours. It is known that the discrimination of curved lines is in the hyperacuity range (Watt & Andrews, 1982). Therefore 2D line curvature, which would be present in the image of a 3D surface with straight texture edges, could act as an effective cue to the
Figure 4.6. Subjects' perceived curvature of an inconsistent-cues patch as a function of the texture curvature and the type of texture mapped onto the patch. Shading curvature was anchored at 0.6 cm$^{-1}$ and texture curvature was perturbed about this value. The data show that the grid texture was almost as effective a cue to curvature as the checkerboard texture.
curvature of the underlying 3D surface. We also know that the perceived curvature of an arc decreases as the length of the curve decreases (Smits & Vos, 1987). If 2D line curvature is the most salient source of curvature information in the grid texture, it follows that disrupting the continuity of the lines forming the grid should result in the texture becoming a less effective cue to curvature, which, in turn, will be reflected in a reduction in the texture weight.

4.3.3.1 Textures Used. Three distinct texture patterns were chosen for this experiment. One texture pattern, the grid texture, was composed of continuous 2D lines. The remaining two textures were formed from discontinuous, intersecting line segments (see Figure 4.7). These two textures differed only in the types of intersections formed by the line segments. In the case of the "conjunctive-T" texture the line segment intersections take the form of T-junctions. The "conjunctive-X" texture, on the other hand, is composed of line segments forming X-junctions. Although 2D line curvature is reduced in these two textures, texture compression is unaffected. Reducing the extent of the line segments in the latter two textures results in a change in the first-order texture statistics. The first-order texture statistics of a two grey-level texture describes the frequency with which either grey level occurs in the texture (Julesz, 1981). Thus the first-order statistics of both textures composed of discontinuous line segments was 25%; that is, 25% percent of pixels in both texture images were black. This is considerably lower than the first-order statistics of the grid pattern used in experiment five (35.8%). In order to keep the first-order statistics constant across the textures being compared, the first-order statistics of the grid texture was reduced to 26.8%. This reduction in the grid texture's first-order statistics results in a texture with larger grid elements (see Figure 4.7).
Figure 4.7. The textures used in experiments five to seven. From top to bottom, left column: the checkerboard, conjunctive-X, parallel line, and random-block textures; right column: small grid, conjunctive-T, bandpass, and large grid textures.
4.3.3.2 Procedure. The procedure was identical to experiment five, with the same range of inconsistent-cue combinations being used for each texture type.

4.3.3.3 Results. Figure 4.8(a-b) plots each subject's data for the three texture conditions. The plotted data show that, as the texture curvature increases, the effect on perceived curvature differs for the three texture types, with the grid texture being the more effective of the three textures.

These results support the hypothesis that the relevant texture property in these curvature discrimination experiments is 2D line curvature in the image texture. When the grid pattern was replaced with short, intersecting line segments, the texture weight was reduced; this was reflected in the perceived curvature of the inconsistent-cues stimulus moving closer to the shading curvature. These results suggest that 2D line curvature information was used by subjects in these experiments, but do not rule out the possibility that subjects were also making use of texture compression information. If subjects were using just the 2D line curvature cue in the curvature discrimination task, this would predict that a texture without straight edges/lines would be an ineffective cue for this task, and that a texture composed of continuous line segments would be more effective than the conjunctive-T and the conjunctive-X textures. The results of the last experiment lend support to the latter prediction. However, the effect was, at best, quite weak. This weak effect may be a consequence of the cue combination used for the inconsistent-cues stimulus. This is taken into account in the next experiment, which tests the two predictions above.
Figure 4.8. Subjects' perceived curvature of an inconsistent-cues patch as a function of texture curvature and the type of texture used. The three textures used have the same first-order statistics (see text for details). As texture curvature increases the effect on perceived curvature differs for the three texture types, with the grid texture being the most effective of the three textures. Regression analysis indicated that the data from the 'grid' condition were significantly different from parallel to that from both the 'conjunctive-T' condition (W.C.: df=20, t=-4.75, p<0.05; M.F.: df=20, t=-4.63, p<0.05) and the 'conjunctive-X' condition (W.C.: df=20, t=-2.61, p<0.05; M.F.: df=20, t=-2.52, p<0.05). This suggests that the weight assigned to the grid texture is significantly higher than the weight assigned to the other two textures.
4.3.4 EXPERIMENT SEVEN. INCREASING INCONSISTENT CUES DIFFERENCE

In contrast to the previous two experiments, subjects were tested for just one combination of shading and texture curvature. However, the relative weights of textures may also be estimated using this paradigm. The texture with the greatest weighting will be that one which results in subjects' perceived curvature of the inconsistent-cues stimulus being closest to the texture curvature. As pointed out above, the weak effect of manipulating 2D line curvature in experiment six may have been a consequence of the cue combination used. In this experiment a large curvature difference between the two cues is introduced in an attempt to maximise the effect of manipulating the texture cue. Thus subjects were presented with an inconsistent-cues stimulus which had a shading curvature of 0.4cm\(^{-1}\) and a texture curvature of 0.9cm\(^{-1}\). Subjects' perceived curvature of the inconsistent-cues stimulus were estimated for a range of textures, including the original checkerboard texture, the grid textures from experiment six, the conjunctive-X and conjunctive-T textures, a texture composed of vertical stripes, a random-block texture, and a bandpass texture (see Figure 4.7).

Three of the seven textures tested had not been used in the previous experiments. These were the "random-blocks" texture, the "stripes" texture and the "bandpass" texture. The random-blocks texture was generated by randomly assigning each square in the checkerboard one of two grey levels. This manipulation severely disrupts the line curvature information present in the checkerboard texture, although it should be noted that it also disrupts the even distribution of texture elements. The bandpass texture was generated by passing a random-noise texture through a band-limited filter, with a
bandwidth of 1 octave and a frequency of 57.6 cycles per texture image (256 * 256 pixels). An important feature of the bandpass texture is the total absence of straight line segments. The texture elements are limited in scale and, unlike the random-block texture, evenly distributed. The parallel-lines texture was generated in an attempt to limit sources of curvature information other than 2D lines. Although still present in the image, texture compression is markedly reduced. By removing the horizontal lines compression along the vertical axis is also removed. This manipulation also removes any line intersections that had been present in the grid texture. Unlike the grid and discontinuous-lines textures, whose first-order statistics ranged from 25% to 26.8%, the first-order statistics for the parallel-lines texture was approximately 20%. This was the highest frequency at which subjects felt they could discriminate the lines without difficulty for multiple stimuli presentations over prolonged periods of time.

If 2D line curvature is the primary texture information used by subjects in the curvature discrimination task, then the parallel-lines texture should be more heavily weighted than the other textures in which 2D line curvature has been disrupted. However, texture compression is still available in the parallel-lines texture. The possibility that texture compression was a primary source of information in these tasks would be ruled out, and the case for 2D line curvature would be strengthened, if it were found that the bandpass texture had a lower weighting than the other textures.

4.3.4.1 Results. Figure 4.9(a-c) shows subjects' perceived curvature of the inconsistent-cues stimulus for the seven textures. It is clear from this figure that, of all the textures tested, shading had more influence than texture on perceived curvature. For
Figure 4.9. Subjects' perceived curvature of an inconsistent-cues patch as a function of the texture type mapped onto the patch. Shading and texture curvature were fixed at 0.4 cm\(^{-1}\) and 0.9 cm\(^{-1}\), respectively. The amount that perceived curvature is shifted away from shading curvature towards texture curvature may be considered as a relative measure of the texture cue's weight. Seven texture types were used (see Figure 4.7). It is clear from the data that the checkerboard and grid textures had a greater weight than the other textures. The next most highly weighted texture was the parallel lines texture. The bandpass texture had the lowest weight for all subjects. These results suggest that line curvature, not compression, was the primary source of texture curvature information.
each texture used perceived curvature was closer to the shading curvature than the texture curvature. Furthermore there is a clear difference between the weights of the different textures. The checkerboard and grid texture had more influence on perceived curvature than the other textures. Of the remaining textures, the parallel-lines texture was the more heavily weighted for all subjects; particularly for subjects W.C. and C.C. In the case of M.F. the effect is much weaker; however, it should be noted that this subject assigned low weights to all the textures used. The bandpass texture, which did not contain straight line segments, was assigned the lowest weighting by all subjects.

The above results suggest that 2D line curvature was the primary source of texture curvature information utilised by subjects in these experiments. This was demonstrated by the observation that the parallel-lines texture was more effective than textures containing less 2D line curvature information. To address the possibility that texture compression may be the relevant cue, subjects were tested with a bandpass texture. This texture contains no straight lines, but does contain texture compression information, and has uniform, easily segmented, isotropic texture elements. The results plotted in figure 4.8 clearly demonstrate that this texture was the least effective of those tested, suggesting that texture compression was not being used by subjects in the curvature discrimination task. This adds more weight to the argument that 2D line curvature is the relevant cue.

4.3.5 DISCUSSION.

The aim of experiments five through seven was to test the hypothesis that the principal texture property being used by subjects in the curvature discrimination tasks was 2D line
curvature. The results of experiment five showed that the weights assigned to a checkerboard texture and a grid texture, in which the 2D lines were made explicit, were comparable. Experiment six further investigated the role of 2D line curvature by comparing the grid texture with the conjunctive-T and conjunctive-X textures, textures in which 2D contour curvature is reduced. It was reasoned that, if 2D line curvature is the primary source of texture curvature information for these textures, the grid texture should be assigned a higher weight than the other two textures. The results of experiment six support this hypothesis. However, the difference between the textures was small and the results, therefore, cannot be taken as conclusive. Furthermore, the results of experiment six did not rule out the possibility that subjects were making use of another potential source of texture curvature information - texture compression. Experiment seven dealt with these issues in two ways. Firstly, to overcome the problem of a weak texture influence on perceived curvature and, consequently, small differences in the effects of the different textures, the difference between the shading and texture curvature was increased. Subjects were then tested with a number of different textures. The results were similar to those in experiment five, in that the more 2D line curvature present in a texture, the more weight was assigned to that cue. Secondly, to test the possibility that subjects were utilizing texture compression and not, as proposed, 2D line curvature a new texture was used. The projected image of this bandpass texture was rich in other texture cues, but contained no 2D line curvature. The fact that this texture was the least effective of all the textures tested suggests that texture compression was not being utilized, thus strengthening the argument for 2D contour curvature.
CHAPTER FIVE

VARYING LIGHT SOURCE POSITION: THE EFFECT ON SHADING AND TEXTURE WEIGHTS, AND PERCEIVED CURVATURE

5.1 INTRODUCTION.

The ambiguous nature of shading as a source of 3-dimensional form information is well documented, with reports on the phenomenon appearing as early as the fourth century B.C. (Plato, 375 B.C.). The well known phenomenon of the ambiguity of protuberances and indentations defined only by shading is a typical example, and has attracted the attention of researchers in the past two decades (Benson & Yonas, 1973; Berbaum, et al., 1983; Kleffner & Ramachandran, 1992; Ramachandran, 1988), and is demonstrated in Figure 5.1. When presented with an array of computer-generated, spherical discs such as in Figure 5.1, in which the discs are defined solely by shading, subjects typically perceive the array as comprising mostly concave objects interspersed with four convex objects. However, when the array is rotated 180°, observers' perception of the stimulus reverses, with the objects which previously appeared concave now appearing convex, and those which previously appeared convex now appearing concave. The objects in Figure 5.1 are usually perceived as being illuminated by a light source positioned somewhere above the display. However, the "concave" objects are, in fact, convex objects illuminated by a light source positioned below the display. The fact that these objects are perceived as concave
Figure 5.1. An example of the ambiguous nature of shading as a curvature cue. The above image contains an array of thirty-six convex spherical patches containing just shading information. The patches are identical in all but one respect - the position of the illuminant for each patch. Thus four of the spherical patches are illuminated by a point light source positioned above each patch, and the remaining patches are illuminated by a point light source positioned below each patch. When presented with an image such as this observers typically report seeing an array of concavities interspersed with four convexities; such an interpretation is in accordance with an assumption of overhead illumination. The effect is most compelling when viewed at a distance, for example at arms’ length.
lit from above is taken as evidence that the visual system processes shaded images in accordance with an assumption of a single, overhead light source.

Our changing perception of surface curvature sign as a function of changing the light source position, as demonstrated in Figure 5.1, is a compelling example of the ambiguous nature of shading in the absence of other cues. The strength of this phenomenon leads naturally to the question of whether the weights assigned to the cues in the previous experiments are influenced by light source position. The first half of this chapter attempts to answer this question by estimating the weights assigned to the texture and shading cues for a wide range of light source positions. The results of this series of experiments suggest that both cues remain remarkably constant in their weightings across the range of light source positions tested. However, this was not found for all subjects tested. In the case of one subject the light source tilt had a clear effect on the shading cue weight. While it is not immediately apparent why this subject's results differed so much from the others, investigations establish that it is not a consequence of the subject in question being stereo-blind.

The second half of this chapter investigates the effect that varying light source position has on perceived curvature when shading information is disambiguated. The mapping of the checkerboard texture onto the spherical patches provides perspective information which disambiguates the surface curvature sign depicted by the shading cue. However, although perceived curvature sign is no longer influenced by light source position, it is not known if the degree of curvature is perceived veridically following this disambiguation. The experimental results reported here demonstrate that manipulating the
Figure 5.2. Light source slant and tilt as defined in experiment eight. With the Cartesian co-ordinate system centred on the stimulus being viewed, tilt is defined as the angle between the positive y axis and the projection of the light source vector $\mathbf{L}$ on the x-y plane, and slant is defined as the angle between the light source vector and the positive z axis.
light source position has a measurable effect on subjects' perception of the degree of surface curvature. The results also show that the effect is reduced when surfaces are given specular reflection properties, with specular highlights appearing to have a "correcting", rather than a simple additive effect, on perceived curvature. Furthermore, the effect of light source position is shown to be partly dependent on the weight of the texture cue.

5.2 THE EFFECT OF LIGHT SOURCE POSITION ON THE SHADING AND TEXTURE WEIGHTS.

The following section describes two main experiments. In experiments eight and nine perturbation analysis was carried out across a range of light source tilts and slants, respectively. Figure 5.2 provides a graphical definition of light source slant and tilt. Light source slant describes the angle that the light source vector makes with the z-axis; light source tilt describes the angle between the projection of the light source vector and the positive y-axis.

5.2.1 METHODOLOGY.

In each experiment perturbation analysis was used to estimate the weights of both the shading and texture cues across a range of light source slants and tilts. The anchor cue of the inconsistent-cues stimulus was fixed at 0.7cm\(^{-1}\) (r=1.4cm) and the perturbed cue varied between curvature values of 0.33 - 0.9cm\(^{-1}\). Subjects' perceived curvature of the inconsistent-cues stimulus was measured for this range of cue combinations, and as a function of light source position.
Figure 5.3. The five light source tilts used in experiment eight. From top to bottom, 0°, 45°, 90°, 135°, and 180°.
5.2.2 EXPERIMENT EIGHT: VARYING LIGHT SOURCE TILT.

In this experiment the weights of the texture and shading cues were estimated as a function of the light source tilt. Five light source tilts were tested: these were 0°, 45°, 90°, 135° and 180° (see Figure 5.3). Light source tilt was randomly chosen from trial to trial, while light source slant remained fixed at 45°. The random sequence of light source positions was identical for both patches, thus ensuring that both patches were always illuminated under identical lighting conditions. The curvature values chosen for the perturbed cue were 0.33, 0.45, 0.6, 0.75, and 0.9 cm\(^{-1}\). Two psychometric functions were obtained for each light source tilt and for each cue combination; thus each subject provided fifty psychometric functions.

5.2.2.1 Results. Figure 5.4(a-f) plots subjects' perceived curvature as a function of the curvature value of the perturbed cue. Data from the five light source tilt conditions are plotted in each of the graphs. Figure 5.4(a-c) plots subjects' perceived curvature as a function of the perturbed texture curvature cue, with the shading cue remaining fixed at 0.7 cm\(^{-1}\). Figure 5.4(d-f) plots subjects' perceived curvature as a function of the perturbed shading cue, with the texture cue anchored at 0.7 cm\(^{-1}\).

The data from the five tilt conditions plotted in Figure 5.4(a-c) are very similar. This similarity in the data suggests that rotating the light source around the line of sight had no effect on the weight assigned to the texture cue. A similar result regarding the shading weight is shown in the data for two subjects, M.F. and C.F. (Figure 5.4d & 5.4e). However, Figure 5.4f shows a clear effect of light source tilt on the shading cue weight for a third subject, W.C. The data in this figure clearly demonstrate that the shading cue
Figure 5.4(a-c). Perceived curvature of inconsistent-cue stimuli as a function of texture curvature and as a function of light source tilt. Shading curvature was anchored at 0.7 cm⁻¹ and texture curvature was perturbed between 0.33 cm⁻¹ and 0.9 cm⁻¹. Changing the light source tilt clearly has no effect on perceived curvature, and, consequently, has no effect on the texture weight.
Figure 5.4(d-f). Perceived curvature of inconsistent-cue stimuli as a function of shading curvature and as a function of light source tilt. Texture curvature was anchored at 0.7 cm\(^{-1}\) and shading curvature was perturbed between 0.33 cm\(^{-1}\) and 0.9 cm\(^{-1}\). While changing light source tilt had no effect on the weight assigned to shading by two subjects (M.F. & C.F.), there is a strong effect for subject W.C. As the light source is rotated beyond 90° tilt perceived curvature tends toward texture curvature, suggesting that the shading cue weight is reduced beyond this point. This is confirmed by regression analysis, which demonstrates that the 0 deg data has a significantly lower slope than the 135 deg data (df=16, t=-3.49, p < 0.05) and the 180 deg data (df=16, t=-6.91, p<0.05).
weight decreased for this subject as the light source was rotated beyond 90° tilt. This reduction in the weight of the shading cue is reflected in the relatively shallower slopes of the data from the 135° and 180° conditions. Because of this difference between the subjects’ data, part of the experiment was repeated for a larger group of naive subjects. Ten subjects were tested for the two extreme light tilt positions (0° and 180°) and for the two extreme curvature values in the perturbation range. Thus subjects’ curvature perception was tested for inconsistent-cue stimuli in which the texture cue was anchored at 0.7cm° and the shading cue was set to either 0.33cm° or 0.9cm°, and which were illuminated by a light source positioned either above or below the stimuli. Subjects provided eight psychometric functions each, two functions for each light source position and each cue combination.

Figure 5.5(a) plots the results. Because performance was similar for all subjects, the data in this figure have been averaged across subjects. Repeated $t$-test analysis was used to test for significant differences between light source positions. For the 0.9 condition (shading curvature = 0.9cm°) no significant difference was found ($t=0.012; s=0.012; df=9; t=1.93; p=0.085$). However, in the case of the 0.3 condition, $t$-test analysis found a significant difference between the data obtained from the two light source conditions ($t=-0.031; s=0.039; df=9; t=-2.45; p=0.037$). Although there is a statistically significant result for this condition, figure 5.5 clearly demonstrates that the effect is, in fact, very small. It is by no means similar in magnitude to the effect found for subject W.C. A possible explanation for W.C.’s seemingly atypical results relates to the observation that this subject lacks stereoscopic vision. It may be that this absence of stereoscopic ability has implications for the way in which other, monocular, depth cues are processed. Of
Figure 5.5. Subjects' perceived curvature of an inconsistent-cues stimulus as a function of the shading cue curvature and light source tilt. Texture curvature was anchored at 0.7 cm\(^{-1}\) and shading curvature was set to either 0.33 cm\(^{-1}\) or 0.9 cm\(^{-1}\). 5a: the average responses of 10 subjects with normal stereoscopic vision; 5b: the average responses of 7 subjects who are stereo-blind. Although both groups showed a significant difference in perceived curvature for the two light source conditions when shading curvature was set to 0.3 cm\(^{-1}\), the magnitude of the effect is much smaller than for subject W.C. (see Figure 5.4f). Using independent \(t\)-test analysis, no significant difference was found between the two groups of subjects for the above condition. This suggests that the magnitude of the effect observed in subject W.C. cannot be explained in terms of that subject being stereo-blind.
course this explanation would immediately be rejected if it were found that any of the other subjects tested in the above experiment also lacked stereoscopic vision.

Subjects C.F. and M.F. from experiment eight, and the larger group of naive subjects⁶, were screened for defects of binocular vision (T.N.O, 1972). Using the T.N.O test for stereoscopic vision, subjects were presented with a plate containing four green/red anaglyphs. Subjects were told that a "pacman" was hidden within each anaglyph. They were given a pair of red/green filter spectacles to view the anaglyphs, and were asked to indicate which direction each pacman was facing. Two anaglyphs were presented at a disparity of 8 min of arc, and the other two were presented at a disparity of 4 min of arc. The anaglyphs were used as a pass-fail criterion, as recommended (T.N.O, 1972). Thus a subject was considered to have normal stereoscopic vision only if he/she could successfully fuse each of the four images used. Otherwise, for the purpose of this screening, the subject was considered to be stereo-blind.

All subjects passed the test for stereoscopic vision. Because none of the subjects were stereo-blind, the proposed explanation for W.C.'s results could not be rejected. On the other hand, the results of the stereoscopic screening do not lend support to it either. The obvious way to test the validity of this explanation is to repeat experiment eight, or part of it, with stereo-blind subjects.

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⁶ Of the ten subjects from this group, nine were screened using this technique. The tenth subject was not available for testing, although he did report having normal stereoscopic vision.
5.2.2.2 TESTING STEREO-BLIND SUBJECTS.

The T.N.O. stereoscopic test was used to identify a group of seven stereo-blind subjects. Here stereo-blindness is defined by the inability to fuse any of the anaglyphs in the T.N.O. repertoire. Subjects' curvature perception was tested for inconsistent-cue stimuli in which the texture cue was anchored at 0.7 cm\(^{-1}\) and the shading cue was set to either 0.9 cm\(^{-1}\) or 0.33 cm\(^{-1}\). The stimuli were either lit from above (0° tilt) or from below (180° tilt). This group of subjects produced results that, on first sight, appeared similar to those obtained from the group of ten subjects with normal stereo vision (see Figure 5.5(b)). Repeated t-test analysis found no difference between subject performance for the two light source positions in the 0.9 condition (\(t=0.016; \alpha=0.034; df=6; \phi=1.29; P=0.25\)). A significant effect of light source position was found, however, for the 0.3 condition (\(t=0.052; \alpha=0.014; df=6; \phi=3.73; P=0.005\)).

If the difference in the magnitude of the effect between subject W.C. and the other subjects can be explained in terms of subject W.C. being stereo-blind, then one would expect that the magnitude of the effect should differ significantly between the stereo-blind group and the group with normal stereo vision. That is, when presented with an inconsistent-cue stimulus lit from below, in the 0.3 condition, the perceived curvature reported by the stereo-blind subjects ought to be significantly higher than that of the subjects with normal stereo vision. However, using a one-tailed independent \(t\)-test, no significant difference was found between these two groups (\(t=0.46; \alpha=0.45; \phi=0.05; \sigma=0.08; df=15; \phi=-0.33; P=0.37\)). Thus it cannot be concluded that the increased effect of light source position on perceived curvature for subject W.C. is due to this subject being stereo blind. While it is not clear why this subject's data were so different from
the others, it may be that he was attending to a different aspect of the stimuli than the other subjects.

5.2.3 EXPERIMENT NINE: VARYING LIGHT SOURCE SLANT.

Having found no relationship between light source tilt and the weights assigned to the texture and shading cues in the previous experiment, this experiment investigated whether manipulating the light source slant would affect the cues' weights. Subjects' perceived curvature for a range of inconsistent-cue stimuli was tested for three light source slants: 25°, 45° and 65°, with light source tilt remaining fixed at 0°. The experimental procedure differed from experiment eight in one important aspect. In experiment eight the light source position was always identical for both spherical patches. In contrast, the light source position remained constant at 45° slant, 0° tilt for the consistent-cues stimulus throughout experiment nine, with the light source position of only the inconsistent-cues stimulus varying. This adjustment to the experimental procedure has the advantage that, as well as providing information about the cues' weights, it is possible to judge whether subjects' perceived curvature is veridical. This is because the perceived curvature of the cue combination surface is no longer constrained to lie on the diagonal $c_p = c_s = c_t$, where $c_p$ is perceived curvature, $c_s$ is shading curvature, and $c_t$ is texture curvature. By anchoring the consistent-cues stimulus' light source at one point while varying the light source position of the inconsistent-cues stimulus, any effect of light source position on veridical curvature perception should become apparent. This change in the paradigm clearly depends on the assumption that the removal of the above constraint will have an additive effect on performance and, therefore, will not influence either cue's weight.
Subjects were tested with the same range of cue combinations as in experiment eight (0.33 - 0.9cm\(^{-1}\)). However, one of the inconsistent-cue combinations - 0.7 and 0.75cm\(^{-1}\) - was replaced with an "inconsistent-cue" combination in which both the texture and shading cues had a curvature of 0.7cm\(^{-1}\). Thus, if curvature perception is veridical for each light source slant, subjects should match this inconsistent-cues combination with a consistent-cues stimulus of the same curvature - 0.7cm\(^{-1}\).

5.2.3.1 Results. Figure 5.6(a-d) plots the results for two subjects, M.F. and W.C. Figure 5.6(a, b) plots subjects' perceived curvature as a function of the texture curvature cue, with the shading cue remaining fixed at 0.7cm\(^{-1}\). Figure 5.6(c,d) plots subjects' perceived curvature as a function of the shading cue, with the texture cue anchored at 0.7cm\(^{-1}\). We can see from these figures that the plotted data from the three slant conditions generally run parallel to each other. This suggests that the neither the shading weight nor the texture weight was affected by varying the light source slant.

Although varying the light source slant had no demonstrable effect on the texture and shading weights, it is clear from the graphs of figure 5.6 that this manipulation influenced perceived curvature. If curvature perception is veridical across the range of light source slants tested then, when the texture and shading curvatures of the inconsistent-cues stimulus are identical, subjects should match it with a consistent-cues stimulus of identical curvature. We can see from figure 5.6 that, when the light source position was identical for both stimuli (45° slant, 0° tilt), subjects curvature perception is veridical; when presented with an inconsistent-cues stimulus in which both cues had a curvature of
Figure 5.6(a-b). Subjects' perceived curvature of inconsistent-cues stimuli as a function of texture curvature and light source slant. Stimulus patches were modelled with a point light source positioned at one of three slant positions: 25°, 45° and 65°. Shading curvature was anchored at 0.7 cm⁻¹ and the texture curvature was perturbed around this value. The plotted data from the three light source slant conditions generally run parallel, suggesting that the texture weight was unaffected by varying light source slant. However, these data also show that the degree of curvature perception was affected by this manipulation. For example, when both texture and shading had a curvature value of 0.7 cm⁻¹, and the standard stimulus was illuminated by a light source positioned at a 25° slant, both subjects under-estimated the standard patch's curvature.
Figure 5.6(c-d). Subjects’ perceived curvature of inconsistent-cues stimuli as a function of shading curvature and light source slant. Texture curvature was anchored at 0.7 cm⁻¹ and shading curvature was perturbed around this value. As in Figure 5.6(a-b), the data from the three light source slant conditions run parallel, suggesting that the shading weight was unaffected by varying light source slant. Again, the perceived degree of surface curvature is influenced by light source position.
0.7cm⁻¹, subjects were unable to differentiate it from a consistent-cues patch of the same curvature. However, this was not the case for the other light slant conditions. When the same stimulus was illuminated by a light source positioned at a slant of 25°, curvature was substantially under-estimated by both subjects. Furthermore, when the light source was positioned at a 65° slant, curvature was over-estimated by one subject (Figures 5.6a & 5.6c). This apparent influence of light source position on curvature perception is reported in more detail in the following series of experiments.

5.3 EXPERIMENT TEN: THE EFFECT OF LIGHT SOURCE POSITION ON PERCEIVED CURVATURE.

The bi-stable nature of objects defined by just shading information was discussed in the introduction to this chapter, and is demonstrated in Figure 5.1. With the inclusion of other sources of 3-dimensional information, however, such as outlines (Ramachandran, 1988) or texture, this ambiguity regarding a surface’s curvature sign is often removed. This disambiguation is demonstrated in Figure 5.7. In this figure the spherical patches have identical curvature values and illuminated by the same light sources as those in Figure 5.1. However, because a texture has been mapped onto the surfaces, the resulting perspective information available disambiguates the perceived curvature sign of the patches.

Although the sign of surface curvature may be disambiguated by adding texture information to shaded images, the results of experiment nine suggest that our perception of a surface’s degree of curvature may be dependent on the position of the light source.
Figure 5.7. An example of another cue (texture) being used to disambiguate curvature depicted by the shading cue. The spherical patches are identical to those in Figure 5.1, with the exception that a checkerboard texture has been mapped onto each patch. The perspective information in the texture results in the patches all appearing convex.
Figure 5.8. Pairs of spherical standard and test stimuli depicting the five light source tilt conditions used for the test patches in experiment ten. All the patches in the image have identical curvature. Note that, as the light source tilt is increased, the standard patch appears less and less curved.
In this experiment subjects’ perceived curvature was measured for the same range of light source tilts and slants tested in experiments eight and nine. The standard stimulus comprised shading and texture cues, and had a 0.7 cm$^{-1}$ curvature. The light source for the test patch was fixed at 45° slant, 0° tilt. The tilt of the light source illuminating the standard patch was fixed at 0° in the slant condition and the light source slant set at one of three values - 25°, 45° and 65°. Light source slant was fixed at $45^\circ$ in the tilt condition and light source tilt was set at one of five values - 0°, 45°, 90°, 135°, and 180° (see Figure 5.8). As in experiments eight and nine, trials were interleaved so that the light source tilts chosen were randomly presented in the tilt condition, and the light source slants were randomly presented in the slant condition.

5.3.1 Results. Looking at Figure 5.9(a, b) it is clear that subjects’ perception of surface curvature was markedly affected by the position of the light source. From Figure 5.9a we can see that subjects’ curvature perception was veridical for the 0° and 45° tilt conditions. However, as the light source was rotated around the line of sight, the apparent curvature of the standard patch decreased, with the effect being greatest at 180°. Figure 5.9b shows a similar effect of light source slant. When the light source position was identical for both stimuli (slant = 45°), both subjects’ curvature perception was veridical. However, reducing the light source slant to 25° resulted in subjects underestimating surface curvature. When the light source slant was increased to 65°, surface curvature was over-estimated by subject M.F., but was accurately matched by subject W.C.

The stimuli in this (and earlier) experiments were modelled as having surfaces with Lambertian reflectance properties. Experiment eleven investigates whether adding a
Figure 5.9. Subjects' perception of a consistent-cues patch with a curvature of 0.7 cm\(^{-1}\), as a function of (a) the light source tilt, and (b) the light source slant. As light source tilt is increased beyond 45° the patch’s curvature is increasingly under-estimated by both subjects. Similarly, when light source tilt changed from 45° to 25° subjects under-estimate the curvature of the standard patch.
specular component to the Phong shading model alters the above effect in any way. Previous research (Bulthoff, 1991; Bulthoff & Mallot, 1990; Todd & Mingolla, 1983) suggests that this additional source of information may reduce this effect of light source position on perceived curvature.

5.4 EXPERIMENT ELEVEN: ADDING SPECULAR HIGHLIGHTS.

Todd and Mingolla (1983) investigated subjects’ perceived curvature of computer-generated cylindrical surfaces, defined by just shading and texture. Subjects were tested with both dull and shiny surfaces. Although curvature was underestimated for both types of surfaces, it was found that subjects’ perception of curvature was enhanced when specular highlights were present in the image. Similarly, Bulthoff et al (Bulthoff, 1991; Bulthoff & Mallot, 1990) report that the addition of a highlight to ellipsoids defined by shading, stereo and texture reduces the perceived elongation of a given ellipsoid (that is, it appears more spherical). Bulthoff and Mallot’s data also suggest that this subsequent change in perceived shape was additive. These results suggest that the effect of light source position on perceived curvature, reported in experiment ten, may be reduced if a specular component is added to the Phong shading model.

5.4.1 PROCEDURE.

Instead of having an ideal Lambertian reflectance function, as in experiment ten, a specular component was added to the standard patch. The specular component had a
Figure 5.10. Pairs of standard and test stimuli depicting the five light source tilt conditions used in experiment eleven, and the two reflectance functions modelled. The test patch was modelled as having a Lambertian reflectance function, and the standard patch was modelled as having a specular component.
specular-reflection exponent of 80, and a specular-reflection coefficient of 0.5. This one difference aside the experimental procedure was identical to experiment ten, with subjects being tested with the same range of light source tilts and slants (see Figure 5.10). Note that the test stimulus' surface has a Lambertian reflectance function, thus preventing subjects basing their judgments on comparisons of the position and sizes of the specularity on each stimulus.

5.4.2 Results. The plotted data of Figure 5.11(a-d) demonstrate a clear reduction in the influence of light source position on perceived curvature when specular highlights are included. Note that, for both subjects, the 'specular surface' data are not parallel to the 'matte surface' data. In Figures 5.11a - 5.11c the separate data plots clearly converge as the light source rotates towards the 0° tilt, 45° slant position. These results suggest that, rather than having a simple additive effect on perceived curvature, the addition of specular highlights results in a correcting of perceived curvature. This conclusion is further supported by the data of Figure 5.11d. This shows that, in the 'matte surface' condition, subject M.F. under-estimated curvature when the light source was at 25° slant and over-estimated curvature when the light source was at 65° slant. However, with the addition of a specular highlight, perceived curvature is closer to veridical for both light source slants.

Thus the addition of a specular highlight clearly reduces the perceived curvature effect reported in experiment ten. The next question addressed by this series of experiments is to what extent is the strength of this effect determined by the relative weights of the shading and texture cues.
Figure 5.11(a-b). Perceived curvature of a surface patch, which has a curvature of 0.7 cm⁻¹, as a function of light source tilt. The filled circles plot the data generated by both subjects when the standard patch had a Lambertian reflectance function, and the filled triangles plot the data for a patch with a specular component added to the reflectance function. The matte-surface data comes from experiment ten. We can see from these plots that the addition of a specularity to the image has a substantial correcting effect on perceived curvature, thus reducing the effect of light source position on subjects’ perception of surface curvature. Regression analysis confirms that there is a significant interaction between the 'matte' and 'specularity' data in the case of subject M.F. (df=16, t=4.77, p<0.05), but not for subject W.C. (df=16, t=0.99, p>0.05).
Figure 5.11(c-d). A further example of the presence of a specularity reducing the effect of light source position on perceived curvature. Here perceived curvature is measured as a function of light source slant for the two types of surface reflectance functions. Adding a specular highlight clearly reduces this effect of light source position for both subjects.
5.5 EXPERIMENT TWELVE: THE RELATIONSHIP BETWEEN TEXTURE WEIGHT AND PERCEIVED CURVATURE.

When texture is mapped onto shaded images, as in figure 5.7, the perceived surface curvature sign is no longer determined by the light source position (although it should be noted that this is dependent on viewing distance). However, the results of experiment ten demonstrate that, even following this disambiguation, light source position still has an effect on our perceived degree of curvature. This experiment investigates whether this effect of light source position is influenced by the texture cue weight. If this were the case, then one would expect that replacing the checkerboard texture with a texture of a lower weighting should augment the effect. To test this hypothesis subjects were tested with stimuli in which the checkerboard texture was replaced with a random-block texture. The results of experiment seven suggest that the random-block texture was given less weight than the checkerboard texture. However, this result was based on testing subjects on just one texture curvature value. To form a more accurate comparison of the two textures’ weights, perturbation analysis was performed on a range of curvature values for both textures.

5.5.1 EXPERIMENT 12a: COMPARING TEXTURE WEIGHTS.

Subjects’ perceived curvature was estimated for the same cue combinations as in experiment eight. Thus shading curvature was anchored at 0.7cm\(^1\) and the texture curvature was varied between 0.33 - 0.9cm\(^1\). The data for both subjects tested are plotted in Figure 5.12(a, b). The slope of the "random-block" data is shallower than that of the "checkerboard" data for both subjects, suggesting that the former texture was assigned a lower weight than the latter texture.
Figure 5.12. Estimating the weight assigned to two textures: a random block texture and a checkerboard texture. Perceived curvature of an inconsistent-cues texture was measured as a function of texture curvature. Shading curvature was anchored at 0.7 cm$^{-1}$ and texture curvature was perturbed about this value. Thus the more perceived curvature is removed from 0.7 (dashed line) for a given cue-combination, the more heavily weighted the texture cue. We can see from these data that the checkerboard texture was assigned a higher weight than the random block texture. This is confirmed by regression analysis, which shows that the slope of the checkerboard data is significantly higher than the slope of the random-block data (W.C.: df=16, t=-7.77, p<0.05; M.F.: df=16, t=-2.27, p<0.05).
Having established that the random-block texture is a less effective cue to curvature than the checkerboard texture, it is now possible to test the proposal that the texture weight is a contributory factor to the effect of light source position on perceived curvature.

5.5.2 EXPERIMENT 12b: LIGHT SOURCE POSITION AND PERCEIVED CURVATURE REVISITED.

This experiment was identical to the light-tilt condition of experiment ten, in which subjects' perceived curvature of a 0.7cm⁻¹ curved stimulus was measured as the light source was rotated around the line of sight, except that, for this experiment, the checkerboard texture was replaced with random-block texture. The results of this texture manipulation are plotted in Figure 5.13(a, b). This figure shows the results of the present experiment superimposed on the data from experiment ten. One can see from these plots that light source position had a stronger effect on perceived curvature when the less weighted, random-block texture was used. It is evident from these results that the strength of the effect reported in experiment ten is, in part, determined by the weight assigned to the texture cue; the lower the texture weight, the greater the effect.

When a specular highlight was included in the standard patch’s surface a similar result to experiment eleven was obtained. These results, plotted in Figure 5.14(a, b), demonstrate that the presence of a specular highlight results in a marked reduction of the effect. Again, as in experiment eleven, the addition of the specular highlight appears to lead to a correcting of perceived curvature, instead of a simple additive enhancement of perceived surface curvature. However, this is not supported by regression analysis, which demonstrates that there is not a significant interaction between the two conditions for either subject (see legend, Figure 5.14).
Figure 5.13. The effect of light source tilt on perceived curvature of a stimulus patch as a function of the texture type used, a random block texture (filled triangles) and a checkerboard texture (filled circles). 0.7 on the ordinate marks veridical curvature perception. The data demonstrate that the effect of light source position on perceived curvature is enhanced when the checkerboard texture is replaced with the less-weighted random block texture.
Figure 5.14. The effect of light source tilt on subjects' perceived curvature of a spherical patch with a random block texture mapped onto it. The filled circles plot the results when the surface patch has a Lambertian reflectance function, and the filled triangles plot the results for a specular surface. The 0.7 point on the ordinate marks veridical perception. Once again, the presence of a specularity reduces the effect of light source position on perceived curvature. Regression analysis shows that the slopes of the two sets of data are not significantly different (W.C.: df=16, t=1.82, p>0.05; M.F.: df=16, t=0.67, p>0.05). This suggests that, although the presence of a specularity reduces the effect of light source position on perceived curvature, it does not seem to have a correcting effect when surfaces are mapped with a random-block texture.
5.6 DISCUSSION.

The experiments reported in this chapter fall into two categories; those investigating the effect that changing light source position may have on the weights assigned to shading and texture cues to curvature, and those investigating the effect of light source position on perceived surface curvature.

Because of the ambiguity in our perception of surfaces defined solely by shading, as demonstrated by Figure 5.1, the goal of the first series of experiments was to establish whether the weights assigned to the shading and texture cues were influenced by light source position. In these experiments perturbation analysis was used to estimate the weight assigned to both cues for a number of different light source slants and tilts. For most subjects this manipulation of light source position had no apparent effect on the cues' weights, suggesting that the shading and texture weights remain constant across a wide range of lighting conditions. However, for one subject, W.C., there was a clear effect of light source tilt on the weight assigned to shading; as the light source was rotated beyond 90°, the influence of the shading cue on perceived curvature appeared to weaken for this subject. In an attempt to resolve this apparent inconsistent result, the two extreme light source conditions were repeated for a group of 10 naive subjects. The results showed that, although there was an effect of light source position on perceived curvature, its magnitude was very small. In further investigations subjects were screened for stereoscopic visual ability. The results showed that all subjects, with the exception of W.C., had normal binocular vision.

To investigate whether the apparently aberrant results of subject W.C. were a consequence
of this subject being stereo-blind, part of experiment eight was repeated for a group of seven stereo-blind subjects. As in the case of the group of ten subjects tested earlier, the stereo-blind subjects showed a small effect of light source position on perceived curvature. However, the effect did not differ significantly between these two groups; thus ruling out stereo-blindness as being the cause of W.C's results.

The second part of this chapter addressed the issue of the effect that varying light source position has on perceived curvature. Although our perception of surface curvature in an image containing just shading information can be bi-stable, the addition of other sources of information, such as texture, can disambiguate a surface's curvature sign. The latter half of this chapter sought to explore whether, following this disambiguation, light source position has an effect on the perceived degree of surface curvature.

The results of experiment ten demonstrated a clear effect of light source position on subjects' perception of surface curvature. It was found that subjects underestimated surface curvature when the light source was rotated beyond 90° around the line of sight. Similarly, surface curvature was underestimated when the light source slant was lowered to 25°. This effect of light source position on perceived surface curvature appears to be dependent on a number of different factors, including the number of 3D-shape cues available in the image and the relative weights assigned to the cues.

It seems intuitive that subjects' accuracy at curvature discrimination should increase with the number of cues available in the image. This was investigated in experiment eleven, in which a specular highlight was added to the Phong shading model of the standard
patch. Earlier research (Bulthoff, 1991; Bulthoff & Mallot, 1990; Todd & Mingolla, 1983) had already shown that the addition of specular highlights to stimuli defined by shading and texture cues results in enhanced curvature perception. It was also suggested that this enhanced curvature perception is a straightforward additive effect. Thus the results of these earlier experiments would suggest that including a specular highlight in the standard stimulus should reduce the effect of light source position reported in experiment ten. The results of experiment eleven show that the influence of light source position on perceived surface curvature is reduced when a specular highlight is included in the standard stimulus. However, rather than reducing the influence of the light source position by having a simple additive effect on perceived curvature, the presence of a specular highlight appeared to have a correcting effect on subjects' curvature perception.

Experiment twelve investigated the relationship between the weight assigned to the texture cue and the strength of the light source effect on perceived curvature reported in the previous two experiments. If the strength of the light source's influence on perceived curvature is determined, in part, by the weight of the texture cue, then, one would expect the effect to be enhanced as the texture weight is reduced. In this experiment the checkerboard texture was replaced with a random-block texture, which was shown to be a less effective curvature cue and, therefore, given less weighting by subjects. As predicted, it was found that the strength of the light source's influence on perceived curvature was noticeably increased when the random-block texture was mapped onto the stimuli surfaces. Again, when the standard surface had a specular highlight added to it, the effect was reduced for both subjects tested. The data were also similar to the results obtained in experiment eleven, suggesting that, rather than leading to a simple additive
enhancement of perceived curvature, the inclusion of a specular highlight results in a correcting of subjects’ perceived curvature.

Several conclusions can be drawn from the results of experiments eight through twelve. Firstly, the weights assigned to shading and texture cues are, for most subjects, unaffected by varying the light source position. Secondly, although mapping texture onto shaded images disambiguates our perception of surface curvature sign, our perception of a surface’s degree of curvature is, in part, dependent on the light source position. Thirdly, this effect of light source position on perceived curvature is reduced when a specular highlight is added to the surface image. Furthermore, rather than simply having an additive effect on perceived curvature, the inclusion of specular highlights appears to make curvature perception closer to veridical. Finally, the effect of light source position on perceived curvature was found to be partly dependent on the weight of the texture cue; the lower the weighting of the texture cue, the greater the effect.

An interesting outcome of the experiments described in this chapter is the observation that, although manipulating the light source position affects perceived curvature, it has no effect on the weights assigned to the shading and texture cues. The fact that perceived curvature is influenced by this manipulation suggests that either or both of the cues present may become somehow less reliable under this manipulation. Models that assume a positive correlation between a cue’s reliability and the weight assigned to it, such as Landy et al’s modified weak fusion model, would predict a change in the cues’ weights under the above conditions. However, the modified weak fusion model allows for one situation in which the above results would be expected. Because the rule of combination
applied to cues by this model is a weighted average, and because the cues’ weights are constrained to add to one, the weights would remain the same if the reliability of both cues was affected equally by some manipulation. Thus to explain the finding that manipulating the light source position affects perceived curvature, yet has no effect on the weights of the texture and shading cues, one would have to argue that changing the light source position had identical effects on the reliability of both the shading and texture cues.
CHAPTER SIX

INVESTIGATING 3D CURVATURE CONTRAST

6.1 INTRODUCTION.

The results of experiment ten in chapter five clearly demonstrate that, for surfaces defined by shading and texture cues, subjects' perceived curvature is influenced by the position of the illuminant. Thus when presented with two spherical surface patches of identical curvature, with one of the surfaces illuminated by a light source from above and the other illuminated from below, the former surface appears more curved than the latter. This chapter describes how a similar effect may be obtained by manipulating the background against which a pair of identically curved patches are set. This manipulation results in a previously unreported illusion, here referred to as 3D curvature contrast. In this effect two surface patches, defined by shading and texture cues and of identical curvature, can be made to appear dissimilar in their curvature by superimposing one patch on a more curved background surface and the other on a less curved background surface.

Figure 6.1 demonstrates the illusion. The figure depicts a pair of spheres partially occluded by circular apertures. The sphere on the left is larger, and therefore less curved, than the sphere on the right. Superimposed on each of the spheres is a spherical surface patch whose curvature is equal to the mean curvature of the background spheres.
Figure 6.1. A demonstration of 3D curvature contrast. The image is composed of two background spheres viewed through two circular apertures of identical diameter. Superimposed on each of the two spheres is a spherical surface patch whose curvature is equal to the mean curvature of the background spheres. The left and right background spheres have curvatures of 0.29 and 0.67 cm\(^{-1}\) (or radii of 3.5 and 1.5cm), respectively. Although the central surface patches are identical, the left patch clearly appears the more curved of the two.
Although the central surface patches are identical in their geometry, the one on the left appears more curved than the surface patch on the right. The effect is very compelling. It is possible that the illusion could be explained solely in terms of contrast-induced changes in brightness, caused by local interaction between the test patches and their contrasting curved surrounds. Examining Figure 6.1, one notices that the luminance gradients of the central patches is higher than the luminance gradient of the left background sphere and lower than that of the right background sphere. Consequently, the luminance gradient of the left surface patch appears higher than that of the right surface patch with the bottom half of the left patch looking darker than the bottom half of the right patch. These contrast-induced changes in brightness may be interpreted as changes in curvature by higher order mechanisms.

Experiments thirteen through sixteen were designed to measure the strength of the 3D curvature contrast effect and to investigate whether the effect could be explained simply in terms of brightness contrast induction. The results of experiment thirteen, which investigated the strength of the effect, show the phenomenon is easily quantifiable. The possibility that the effect could be explained in terms of brightness contrast was investigated in experiment fourteen. In this experiment an attempt was made to control for possible brightness contrast induced curvature effects by measuring the effect when the light source was positioned directly behind the viewpoint. The persistence of the effect following this manipulation is taken as evidence against the idea that brightness contrast is the sole underlying cause of the effect. In experiment fifteen evidence for the effect was tested for with stimuli containing either texture or shading on its own. The results suggest that the 3D curvature contrast effect persists when either cue is used in
isolation, although it was substantially reduced in the texture-only condition. Just as the results of experiment fifteen provide further evidence against brightness contrast effects being the sole cause of 3D curvature contrast, so, too, do the results of experiment sixteen. In this experiment each background sphere was replaced with a pattern of curved patches the same size as the test patch; like the background spheres they replaced, the only difference between the two arrays was their curvature. This manipulation served to reverse the local brightness-induced interactions described above. Despite this manipulation there remained a clearly measurable 3D curvature contrast effect.

The following section provides a detailed account of the above experiments. This is followed with a discussion of the experimental results and the relevance of 3D curvature contrast to the on-going debate of whether shape perception is a local or global process.

6.2 EXPERIMENT THIRTEEN: QUANTIFYING 3D CURVATURE CONTRAST.

The goal of this experiment was to attempt to quantify the strength of the effect. Subjects were presented with stimuli similar to figure 6.1. The background spheres were bounded by apertures with radii of 51 pixels (1.46cm); the apertures bounding the central patches had radii of 30 pixels (0.86cm). The mean curvature of the background spheres remained fixed at 0.48cm⁻¹. The curvature of the background spheres differed by either 0, 0.12, 0.24, or 0.38cm⁻¹; thus the radii of the left and right background spheres varied from 2.1cm to 3.5cm and from 1.5cm to 2.1cm, respectively. Two psychometric functions were obtained from subjects for each of these four "curvature-difference" conditions. The
magnitude of the curvature difference between the test patches was varied from trial to trial. On each trial the curvatures of both patches were set with the constraint that the mean curvature of the two patches was equal to the mean curvature of the background spheres. As in earlier experiments, subjects were given a curvature discrimination task, in which they had to indicate which patch appeared more curved.

6.2.1 Results. The results for two subjects are plotted in Figure 6.2, which plots the curvature difference of the two patches at the PSE (point of subjective equality on the psychometric function) as a function of the difference in curvature of the background spheres. The slope of each subject’s data plot may be considered as a measure of the strength of the illusion - the steeper the slope, the stronger the illusion. Looking at Figure 6.2 it is clear that the more the background spheres differ in their curvature the greater the curvature difference must be between the central patches in order for them to appear equally curved.

Having shown that the effect is measurable, the following experiments investigated the contribution of contrast-induced changes in brightness to the illusion (see discussion above).
Figure 6.2. A plot of the strength of the illusion as a function of the difference in curvature between the two background spheres. The PSEs were calculated as the 50% point on each psychometric function. The curvature difference between the patches at the PSE is defined as double the PSE. Each data point is based on the average PSE of two runs. The slope of the functions may be thought of as a measure of the strength of the illusion. The slopes for subjects W.C. and M.F are 0.583 and 0.43, respectively.
6.3 EXPERIMENT FOURTEEN: CHANGING THE LIGHT SOURCE POSITION.

In the previous experiment each of the surfaces was lit by a single light source positioned at 0° tilt, 45° slant to the surface. As pointed out earlier, it is possible that the illusion is caused solely by brightness contrast effects simulating curvature differences between the central patches. The present experiment sought to investigate this hypothesis. The light source for each surface was positioned at 0° tilt, 0° slant; thus each surface was illuminated face-on, with the light source vector perpendicular to the centre of the surface (see Figure 6.3). Looking at Figure 6.3 we can see that, although brightness contrast is still present in the display, it no longer appears to mimic the effects of changing curvature.

Having manipulated the light source position as described, the strength of the effect was measured for the same range of background curvature differences tested in experiment thirteen.

6.3.1 Results. The data for two subjects are plotted in Figure 6.4. We can see that, for both subjects, illuminating the surfaces in the display from the viewpoint does not abolish the illusion. For one subject, W.C., the illusion is unaffected by this manipulation. For M.F., however, the strength of the illusion is somewhat reduced. The persistence of the effect is evidence against the idea that brightness contrast is the sole underlying cause of 3D curvature contrast. However, the fact that the effect is weakened suggests that brightness contrast does play a part.
Figure 6.3. An example pair of stimuli used in experiment fourteen. Both the central and background spherical patches are illuminated by a light source positioned perpendicular to the centre of each surface, in an attempt to remove brightness induced effects. The left central patch is embedded in a less curved background sphere (0.29 cm⁻¹) and the right central patch is embedded in a more curved background sphere (0.67 cm⁻¹). Both central patches have the same curvature. Even following the above manipulation of the light source the 3D curvature contrast illusion persists.
Figure 6.4. The strength of 3D curvature contrast when stimuli are lit by a light source positioned perpendicular to the centre of each central patch. Although weakened, the effect clearly persists. The slopes for subjects W.C. and M.F are 0.517 and 0.231, respectively.
6.4 EXPERIMENT FIFTEEN: 3D CURVATURE CONTRAST AND SINGLE CUES.

This experiment investigated whether curvature contrast continues for surfaces defined by shading or texture alone. If, as seems likely, brightness contrast is an important contributing factor, the effect should persist when the surfaces contain just shading information. What is not known is whether the effect would persist when texture is the only available curvature cue. If there is a measurable effect under the latter condition, this would be a further indication that factors other than brightness contrast contribute to the effect.

The curvature differences chosen for the background spheres were identical to those used in the previous two experiments. Surfaces were illuminated by a light source position identical to that used in experiment thirteen (0° tilt, 45° slant). For the condition in which shading was the only curvature cue present, texture was removed by setting the texture contrast to zero. In the 'texture-only' condition shading was removed as a source of curvature information by setting the direct surface illumination parameter of the Phong model to zero, and illuminating the surfaces with just an ambient light source.

When the curvature of the central patch in the shading-only condition was identical to that of the background sphere on which the patch was superimposed, the central patch could not be visually segmented from the background sphere. Subsequently, subjects could not tell when a pair of test patches had appeared. To overcome this problem of identifying when the patches were presented, each stimulus pair presentation was accompanied by an audible signal. Furthermore, to overcome the segmentation problem, the boundary
Figure 6.5. The strength of the 3D curvature contrast effect when just (a) shading or (b) texture was the only curvature cue employed in rendering the stimuli. The shading cue can be removed by setting the intensity of the modelled point light source to zero, and by increasing the ambient light intensity in the illumination model. Texture cues can be removed by setting the texture contrast to zero. The results show that, although reduced in the texture-only condition, the effect persists when either cue is used in isolation. The slopes of the lines fit to the 'shading' data are 0.596 and 0.436 for subjects W.C. and M.F., respectively. The lines fit to the 'texture' data have slopes of 0.394 and 0.249 for subjects W.C. and M.F, respectively.
between the surface patch and background sphere was marked by a dark circle superimposed upon it. These "aids" were also implemented in the texture-only condition.

6.4.1 Results. Figure 6.5 (a-b) plots the results from both the texture-only and shading-only conditions. Figure 6.5a shows that there was still a strong curvature contrast effect when shading was the only curvature cue present. In the case of subject W.C., the strength of the effect was almost identical to that reported for experiment thirteen (see figure 6.2). In the case of subject M.F. the effect appears to be stronger than in experiment thirteen. The results from the texture-only condition are plotted in figure 6.5b. The results demonstrate that, although somewhat reduced, 3D curvature contrast persisted when stimuli were composed of just texture as a cue to curvature. Once again, the results suggest that brightness contrast is not the sole contributor to 3D curvature contrast. In experiment sixteen the brightness-contrast hypothesis is tested further by reversing local brightness contrast.

6.5 EXPERIMENT SIXTEEN: REVERSING LOCAL CONTRAST-INDUCED INTERACTIONS.

This experiment investigates whether the effect persists following the manipulation of the local brightness contrast effects observed in Figure 6.1. As noted earlier, the higher luminance gradient of the right-hand background sphere in Figure 6.1 contrasts sharply with the lower luminance gradient of the embedded central patch. Consequently, the lower part of the central patch appears brighter and, therefore, less curved than it actually is. The opposite relationship between the background sphere and patch on the left results
in the left central patch appearing more curved than it actually is. If, through some 
manipulation, this contrast-induced change in brightness was reversed for the stimuli on 
the right of Figure 6.1, one might expect that the illusion would be abolished - or even 
reversed.

Figure 6.6 shows such a manipulation. In this figure each background sphere has been 
replaced with a group of fifteen spherical patches identical in size to the test patch which 
they surround. The "surround" patches on the left of Figure 6.6 are less curved than the 
test patches, while the surround patches on the right are more curved than the test patches. 
Following this manipulation, the contrast in luminance gradients of the right test patch and 
its adjacent surround patches is now reversed. The top part of the test patch is now 
adjacent to the darker area of the surround patch, while the bottom part is now adjacent 
to the brighter area of the surround patch. A similar brightness relationship can be 
oberved for the test and surround patches on the left of Figure 6.6, although the contrast 
is not as strong. If local contrast-induced interactions are solely responsible for the 
ocurrence of 3D curvature contrast, then one would expect the effect to either be 
removed or, alternatively, reversed following this manipulation. Furthermore, because the 
test and surround patches no longer overlap, but are spatially separated, any local 
interactions should be eliminated.

Subjects were tested using the above paradigm. The apertures bounding the test and 
surround patches had radii of 30 pixels (0.86cm). The mean curvature of the surround 
patches remained fixed at 0.81cm\(^{-1}\). The curvature of the two groups of surround patches 
differed by either 0, 0.3, or 0.61cm\(^{-1}\); thus the radii of the left and right surround spheres
Figure 6.6. An example of the stimuli used in experiment sixteen. The background spheres used in the previous experiments were replaced with two arrays of spherical patches that were either more or less curved than the patches being compared. Subjects were asked to make curvature discrimination judgements between the second and seventh patch in the third row from the top. In the above example the array of surrounding patches on the left have a curvature of 0.5 cm\(^{-1}\), the surrounding patches on the right have a curvature of 1.1 cm\(^{-1}\), and the two patches being discriminated by subjects have a curvature of 0.81 cm\(^{-1}\). Note that the local brightness contrast has been reversed, yet the spherical patch on the left appears more curved than that on the right.
varied from 1.24cm to 2cm and from 0.9cm to 1.24cm, respectively. As in the earlier experiments, the curvatures of the two test patches were set with the constraint that their mean curvature was equal to the mean curvature of the surround patches. The patches were presented against a random grey-level noise background. Subjects were instructed to make curvature discrimination judgments between the second and seventh patch in the third row of the array. The surround patches remained on the monitor throughout the experiment; the test patches were replaced by a random grey-level noise pattern between test stimuli presentations, thus making explicit to subjects the spatial location of the patches being compared. Four psychometric functions were obtained from each subject for each of the three curvature-difference conditions above.

6.5.1 Results. The results of experiment sixteen are shown in Figure 6.7. It is apparent from these results that, despite manipulating the local luminance contrasts in this way, varying the curvature of the surround patches has a measurable effect on subjects' perceived curvature of the test patches. Note that the effect is in the same direction as the previous experiments. That is, when both test patches were of equal curvature, as in Figure 6.6, the left test patch appeared more curved than the right test patch.

The results obtained from experiment sixteen are compelling evidence that 3D curvature contrast cannot be explained simply in terms of local contrast-induced changes in brightness. However, it is possible that the persistence of the effect under the above manipulation may be explained in terms of either texture or spatial interactions in apparent contrast (Cannon & Fullenkamp, 1991; Cannon & Fullenkamp, 1993; Cannon & Fullenkamp, 1994; Chubb, Sperling & Solomon, 1989; Solomon, Chubb & Sperling,
Figure 6.7. The strength of 3D curvature contrast when each background sphere is replaced with an array of background spherical patches. Although substantially weakened, there is still a measurable effect; thus providing further evidence that brightness contrast is not the only factor underlying the illusion.

The slopes for subjects W.C. and M.F are 0.13 and 0.106, respectively.
1990), In contrast-matching experiments in which grating patches were surrounded by an annulus containing a grating of a different contrast, Cannon and Fullenkamp (1991, 1993) reported that the apparent contrast of a central disc was suppressed regardless of whether the contrast of the surround was higher or lower than that of the central disc. Solomon et al (Solomon, et al., 1990) reported similar findings. When investigating this suppression phenomenon with larger numbers of subjects, however, Cannon and Fullenkamp (1993) reported individual differences; the majority of subjects showed suppression, although a small number did show enhancement effects. In a more recent study Cannon and Fullenkamp (1994) tested for suppression of apparent contrast of a test gabor patch which was flanked by two peripheral gabor patches with twice the contrast than that of the test patch. This study demonstrated a mainly inhibitory effect of flanking stimuli on the apparent contrast of the test gabor patches being flanked. Cannon and Fullenkamp do not report testing whether reducing the contrast of the flanking patches to below that of the test patch results in suppression or enhancement of the test patch’s apparent contrast. However, assuming that the mechanisms responsible for the suppression in this study are the same as in their earlier studies, it would be anticipated that the effect of such a manipulation would be mainly inhibitory.

The work of Cannon and Fullenkamp, and Solomon et al, suggests that 3D curvature contrast may still be reducible to a simple brightness contrast explanation. It could be argued that apparent curvature is suppressed for both test patches in Figure 6.1. The perceived curvature difference between the two test patches would then be a consequence of differential suppression of the two patches’ apparent curvatures; that is, there is a stronger inhibitory effect when the patch is surrounded by a more curved surface than.
when it is surrounded by a less curved surface. A similar argument could be used to explain the persistence of 3D curvature contrast under the conditions of experiment sixteen.

If it were found that the curvature of a spherical patch is underestimated by subjects, regardless of whether the patch is surrounded by less or more curved background patches, this could be explained in terms of differential suppression and would support the argument for a brightness contrast induced effect. Furthermore, if it were found that the apparent curvature of a spherical patch was suppressed when surrounded by more curved spherical patches, but enhanced when surrounded by less curved spherical patches (or vice-versa), this, too, could be explained on the basis of the brightness contrast effects reported by Cannon and Fullenkamp. These authors found individual differences between subjects, reporting that, under some circumstances, a number of subjects exhibited enhanced apparent contrast effects. Regardless of whether individual subjects demonstrate differential suppressed apparent curvature effects, or both suppressed and enhanced apparent curvature effects, when presented with arrays of spherical patches as described above, it is clear that they should demonstrate similar effects in the contrast domain if brightness contrast underlies the effects.

Experiments seventeen and eighteen explore the possibility that the persistence of 3D curvature contrast under the conditions of experiment sixteen can be explained in terms of the brightness contrast effects reported by Cannon and Fullenkamp. Experiment seventeen adopts a paradigm similar to that used by Cannon and Fullenkamp (1994), and assesses subjects’ perceived contrast of a gabor patch when surrounded by gabor patches.
of either half or twice the contrast of the test patch. Experiment eighteen investigates whether the subjects tested in experiment seventeen display the same pattern of results in the curvature domain, by replacing the gabor patches with, the now familiar, spherical surface patches.

6.6 EXPERIMENT SEVENTEEN: PERCEIVED CONTRAST OF A TARGET STIMULUS IN THE PRESENCE OF PERIPHERAL FLANKING STIMULI.

In this experiment an adaptive method of constants was used to determine how the apparent contrast of a small, vertically oriented gabor patch was affected by embedding the patch in an array of higher or lower contrast gabor patches. The contrast of the standard gabor patch remained fixed at 0.5, and the contrast of the surrounding patches was fixed at one of two contrasts. In the high-contrast condition, the contrast of the surrounding patches was fixed at 0.99; in the low-contrast condition, the surrounding patches were given a fixed contrast of 0.25. A test gabor patch was displaced from the array, along the central horizontal axis. Thus subjects were presented with an array of 25 gabor patches, with the standard patch placed in the centre of the array and the test patch displaced to the right of this array (see Figure 6.8). Subjects were given a discrimination task in which they had to decide, with the press of a button, whether the test gabor patch had a higher contrast than the standard. Subjects generated eight psychometric functions each, four for each of the two contrast conditions described above.
Figure 6.8. An example set of gabor patches used in experiment seventeen. The standard patch is located in the centre of the array of gabor patches, and the test patch is located to the right of this array. The contrast of the surrounding array of gabor patches is 0.99. The contrast of the standard and test patches is 0.5.
Figure 6.9. The results of experiment seventeen, in which subjects' perceived contrast of a central gabor patch was measured as a function of the contrast of surrounding gabor patches. The central gabor patch contrast remained fixed at 0.5 throughout the experiment. Both subjects show suppressed apparent contrast effects in the high contrast condition, in which the contrast of the surrounding gabor patches was twice that of the central gabor patch. The results from the low-background-contrast condition, in which the contrast of the surrounding gabor patches was half that of the central gabor patch, shows subject variability. While subject W.C. showed no effect, subject M.F. showed an enhanced contrast effect.
6.6.1 Results. The results are shown in Figure 6.9 (a-b), in which the apparent contrast of a 0.5 contrast gabor patch is plotted as a function of the contrast of the surrounding gabor patches. In the high contrast condition, in which the contrast of the surrounding gabor patches was twice that of the central gabor patch, both subjects underestimated the contrast of the central gabor patch. Thus suppressed apparent contrast was found for the high contrast condition. In the low contrast condition, in which the contrast of the surrounding gabors was half that of the central gabor, subjects showed individual differences. W.C’s data (Figure 6.9a) suggest that the low contrast condition had little or no effect on perceived contrast; subject M.F, on the other hand, showed a small enhanced contrast effect (Figure 6.9b).

If brightness contrast is responsible for the persistence of 3D curvature contrast in experiment sixteen, then subjects’ data from experiment seventeen should be a good predictor of the direction of individual subjects’ perceived apparent curvature when the gabor patches of experiment seventeen are replaced with spherical surface patches. Thus when a test spherical patch is surrounded by spherical patches of a higher curvature, both subjects’ data should demonstrate suppressed apparent curvature. When the surrounding patches are of a higher curvature than the test patch, the data from experiment seventeen suggest that subject M.F’s data should demonstrate enhanced apparent curvature, whilst subject W.C’s data suggest that perceived curvature should be veridical. These predictions, based on the brightness contrast hypothesis, are tested in experiment eighteen by replacing the gabor patches of experiment seventeen with spherical surface patches.
6.7 EXPERIMENT EIGHTEEN: PERCEIVED CURVATURE OF A TARGET STIMULUS IN THE PRESENCE OF FLANKING STIMULI.

The paradigm of experiment eighteen was identical to experiment seventeen, with the exception that the spherical surface patches were substituted for the gabor patches used in the latter experiment. Thus subjects were presented with an array of 25 spherical patches, with the standard patch placed in the centre of the array and a test patch displaced to the right of the array. The curvature of the standard patch remained fixed at 0.81cm⁻¹ (radius = 1.4cm) throughout the experiment. The curvature of the surrounding spherical patches was set to either 0.5cm⁻¹ (radius = 2cm) in the low curvature condition or 1.1cm⁻¹ (radius = 0.9cm) in the high curvature condition. The radius of the occluding aperture for each spherical patch was identical to that used in experiment sixteen (0.86cm). Subjects were given a Binary Choice curvature discrimination task, with each subject generating four psychometric functions for each curvature condition.

6.7.1 Results. Looking at Figure 6.10 (a-b) we can see that one subject, M.F., showed neither suppressed nor enhanced apparent curvature effects in either of the conditions; the second subject, W.C., showed a suppressed apparent curvature effect for the high curvature condition, but no effect for the low curvature condition.

The data obtained from one subject, W.C., show a similar trend to the same subject's data when tested with the gabor patches. Subject M.F., on the other hand showed no effect in the curvature domain, but had shown both suppression and enhancement effects in the contrast domain. It cannot be inferred from M.F.'s data, however, that 3D curvature contrast is not underpinned by brightness contrast effects. The fact that there was neither
Figure 6.10. The results of experiment eighteen, in which perceived curvature of a central spherical patch was measured as a function of surrounding patches’ curvature. The central patch curvature was fixed at 0.81 cm⁻¹. Veridical curvature perception is indicated by the dashed line. Both subjects show neither suppression nor enhancement effects in the low-background-curvature condition, in which the surrounding patches had a curvature of 0.5 cm⁻¹. In the high-background-curvature condition, in which the surrounding patches’ curvature was 1.1 cm⁻¹, M.F. shows neither suppression nor enhancement; subject W.C., on the other hand shows a suppressed apparent curvature effect.
suppression nor enhancement effects for this subject merely tells us that there was no 3D curvature contrast effect. This hardly seems surprising considering the weakness of the effect recorded earlier in experiment sixteen; the effect would be expected to be further weakened in this experiment given that only one of the spherical patches was surrounded by other patches of a different curvature.

Thus the above results are inconclusive in determining whether the presence of 3D curvature in experiment sixteen was underpinned by brightness contrast effects alone. The difficulty in obtaining conclusive results for experiment eighteen was compounded by the observation that curvature contrast was weakened for one subject and absent for the other.

6.8 DISCUSSION.

The experiments in this chapter have investigated a previously unreported visual illusion, referred to here as 3D curvature contrast, in which the apparent curvature of a spherical patch can be changed by simply embedding the patch in a background sphere of a different curvature. Although similar contrast effects in the depth domain have been reported (Anstis, 1975; Graham & Rogers, 1982) this is the first time that such an effect has been investigated in the 3D-curvature domain. The results of experiment thirteen show 3D curvature contrast to be a strong effect and easily quantifiable. Experiments fourteen through sixteen investigated whether this illusion is reducible to brightness contrast effects, or whether some other factor(s) also contribute to the effect.
In an attempt to reduce/remove the possible curvature-inducing effects of brightness contrast, stimuli were lit face-on in experiment fourteen. Despite this manipulation the effect persisted. The results of experiment fifteen demonstrate that the effect persists when stimuli contain only the shading or the texture cue. The strength of the effect was undiminished when stimuli contained just shading information, suggesting that brightness contrast plays an important role. When stimuli contained just texture information, however, there was still a measurable effect, suggesting that brightness contrast is not the only factor underlying 3D curvature contrast.

The results of experiment sixteen provided further evidence that 3D curvature contrast may not be explained simply in terms of brightness contrast. In this experiment local contrast-induced interactions were reversed by replacing each background sphere with an array of spherical surface patches of the same size as the test patch; like the background spheres they replaced, the two arrays differed in their curvature. Again, there was a measurable curvature contrast effect under these conditions, although it was considerably reduced, suggesting that, as well as brightness contrast, other factors underpin curvature contrast. However, recent experimental findings on spatial interactions in apparent contrast suggest that the results of experiment sixteen may be explicable in terms of simultaneous contrast effects (Heeger & Robison, 1994). Experiments seventeen and eighteen investigated this possibility. Using a modified version of Cannon and Fullenkamp’s (1994) apparent contrast paradigm, subjects’ responses in a contrast discrimination task were used as predictors of their performance in a curvature discrimination task following substitution of the gabor patches with spherical surface patches. However, because curvature contrast was absent for one subject and weakened
for another under the manipulations of experiment eighteen, it was not possible to draw any firm conclusions from the results.

The above experiments have demonstrated that brightness contrast is likely to be the most important factor underlying 3D curvature contrast. However, the results also suggest that there are other factors contributing to the effect. The fact that the effect persisted when no brightness contrast effects were present in the image, for example when texture was the only cue available, suggests that 3D curvature contrast may not be explained simply in terms of brightness contrast effects. Furthermore, although brightness contrast probably plays an important role in the effect, subjects believed they were making shape discrimination judgements, not contrast discrimination judgements. Thus the low-level effects of context on perceived brightness were influencing the recovery of shape from shading.

The experimental results reported in this chapter demonstrate that the perceived curvature of a surface is influenced by the curvature of surrounding surfaces. While it is not clear why the visual system should be influenced in this way, the occurrence of 3D curvature contrast does have some bearing on the on-going debate of whether shape from shading and/or texture is a local or global operation. At present there are two main schools of thought regarding human visual shape processing. Those who believe that local operations are employed in shape processing argue that perceived shape is accomplished by registering point-by-point some geometrical property of the object's surface. For example, some authors have argued that local representations take the form of a point-by-point orientation and depth map (Barrow & Tenenbaum, 1978; Maloney &
Landy, 1989; Marr, 1982; Young, et al., 1993), while others have suggested that it takes the form of a local curvature map (Johnston & Passmore, 1994a) or a local shape map (Johnston & Passmore, 1994a; Koenderink, 1990). The second school of thought on the subject argues that the visual system applies global operations to shape processing (Mingolla & Todd, 1986; Ramachandran, 1988). If the visual system used only local operations (for example, by registering point-by-point the surface orientation) in constructing a perception of shape, one would predict that the curvature of surrounding surfaces should have no effect on the perceived curvature of a surface patch. The results from the experiments described in this chapter, however, clearly demonstrate that the perceived curvature of a surface is influenced by the curvature of a background surface or surrounding surfaces. This would suggest that the visual processing of shape from shading and texture is not a purely local operation, but that global processes are also involved.

3D curvature contrast is further investigated in chapter seven. Context is thought to influence the weight assigned to a given cue (Dosher, et al., 1986; Johnston, et al., 1993). Chapter seven describes research which makes use of the 3D curvature contrast paradigm to investigate contextual effects on the weights assigned to shading and texture cue.
CHAPTER SEVEN

INVESTIGATING THE EFFECT OF 3D CURVATURE CONTRAST ON CUE WEIGHTS

7.1 INTRODUCTION.

The experiments described in chapter six provide a clear demonstration of the influence that background/surrounding surfaces have on the perceived curvature of an embedded surface patch. The results of these experiments showed that subjects underestimated the curvature of a surface set against a more curved background surface, and over-estimated surface curvature when the surface was embedded in a less curved background surface. The experiments in this chapter aim to investigate the effect, if any, of introducing a curved background surface on the weights assigned to the shading and texture cues defining the central patch. In these curvature contrast experiments curvature contrast sign refers to the sign of the difference between the curvature of a central patch and the curvature of the background surface. Using this definition positive curvature contrast describes a stimulus in which the central patch is more curved than the background, and negative curvature contrast describes a stimulus in which the central patch is less curved than the background.

The experiments described in this chapter are motivated by one of the tenets of the Modified Weak Fusion model (Johnston, et al., 1994; Landy, et al., 1990; Maloney & Landy, 1989; Young, et al., 1993), which states that the weight assigned to a cue depends, in part, upon "...the viewing conditions ... and the physical characteristics of the scene".
There is already some empirical support for this concept, with several studies reporting contextual or spatial configuration effects on cue weights (Dosher, et al., 1986; Johnston, et al., 1993; Ono, et al., 1988; Rogers & Collett, 1989).

Ono et al (Ono, et al., 1988) report that, when conflicting motion parallax and dynamic occlusion cues are used to simulate a spherical surface, the magnitude of the depth separation of the two cues determined which cue dominated perceived depth order. Motion parallax dominated when the depth separations were small, and dynamic occlusion dominated when the depth separations were large. Johnston, Cumming and Parker (1993) found that the spatial configuration of a scene affected the weight assigned to two cues, stereo and texture. In their experiments subjects were given a global three-dimensional shape judgement task (the apparently circular cylinder or ACC task) first described by Johnston (1991), in which they had to decide whether horizontally oriented elliptical cylinders were more or less extended in depth than a cylinder of circular cross section. The shape-judgement task was also extended to 'roof' shaped stimuli. Using perturbation analysis, Johnston et al estimated the texture cue weight across two viewing distances. They found that the texture cue’s weight, although substantially lower than that of the stereo cue’s, was influenced by viewing distance. Thus the weight assigned to texture was greater when stimuli were viewed from a 200cm distance than when they were viewed from a 50cm distance, supporting the idea that a cue’s weight is also partly dependent on viewing conditions.

Buckley and Frisby (1993) describe a vertical/horizontal cue integration anisotropy in stereograms of three-dimensional ridges. In their experiments subjects were presented
with vertical and horizontal ridges containing three depth cues - stereo, texture and outline cues. The texture and outline depth cues remained fixed while subjects’ depth perception of the ridges was measured as a function of the stereo cue depth. While stereo strongly dominated the texture/outline cues in stereograms of horizontal ridges, the reverse was true for stereograms of shallow vertical ridges.

Dosher et al (Dosher, et al., 1986) found that the relative weights assigned to two cues, stereo rotation disparity (SRD) and proximity luminance covariance (PLC), were partly determined by whether a rotating Necker cube viewed by subjects was preceded by a still preview of the same Necker cube. When the rotating necker cube was preceded with a still preview, perceived direction of rotation was controlled by stereo rotation disparity; however, in the absence of a still preview, the PLC cue determined in which direction the necker cube appeared to be rotating. Thus more weighting was given to stereo rotation disparity in the former context, and more weighting was given to PLC in the latter viewing condition.

Rogers and Collett (1989) report that the weights of two discrepant depth cues, motion parallax and binocular disparity, depended on the depth portrayed by each cue. In their experiments these authors presented subjects with a horizontally corrugated test surface translating to and fro along a path orthogonal to the observer’s line of sight. Rogers and Collett found that motion parallax was most heavily weighted when the stereo cue specified zero disparity; although the reduction in perceived corrugation amplitude

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7Note that this effect of still preview on the relative weights for both cues was not found for all subjects, and that there was substantial differences across subjects with respect to the degree of importance given to the two cues.
suggested that, even under these circumstances, motion parallax was not given more weighting than the stereo cue. As the stereo disparity gradient was increased, so the weight of the motion parallax cue decreased, until, for steep disparity gradients, motion parallax had little or no effect on observers’ perceived amplitude of a corrugated surface. Thus manipulating the stereo-defined surface geometry resulted in a dynamic re-weighting of the two cues. Results reported by Curran and Johnston (Curran & Johnston, 1993; Curran & Johnston, 1994) also demonstrate a dynamic re-weighting of cues as a function of manipulating surface geometry, with texture weight increasing and shading weight decreasing with increasing surface curvature (see experiment two, chapter three).

Thus there is some evidence to suggest that cue weighting is, to some extent, context-dependent. The concept of context-dependent cue weighting is further investigated in this chapter. In experiment nineteen the context in which stimuli were presented was changed, by changing the curvature of a background surface, and the effect that this manipulation had on shading and texture weights was assessed. Any effect that this manipulation has on the weights of the shading and texture cues can be measured using perturbation analysis. Thus by anchoring one cue at a given curvature and perturbing the curvature of the second cue, the weight of the perturbed cue can be estimated for each background condition. If there is no effect on the cues’ weights, then the results from the perturbation analysis paradigm for both conditions (when the background sphere is more curved and when it is less curved than the standard patch) will run parallel. If, on the other hand, changing the sign of the curvature contrast effect from, say, positive to negative (which changes the appearance of the standard patch from more curved to less curved than it actually is) does result in a change in the weight of a given
cue, then there should be some, as yet unspecified, interaction between the results obtained from both conditions.

7.2 EXPERIMENT NINETEEN: CURVATURE CONTRAST - EFFECTS ON SHADING AND TEXTURE WEIGHTS.

In this experiment subjects were presented with pairs of standard and test spherical patches, with the standard patch embedded in a background surface and the test patch spatially separated from the other two surfaces (see Figure 7.1). The test surface and the background surface (in which the standard patch was embedded) both contained consistent cues throughout the experiment; the standard patch, on the other hand, contained mixed curvature cue values for most presentations. Thus the curvature of one cue in the standard patch was anchored at a given value while the second cue’s curvature was perturbed around that point. Subjects’ perceived curvature of the standard patch was measured as a function of the perturbed cue’s curvature. Perturbation analysis was used to estimate the weights of both cues under both curvature contrast conditions. Thus, in the ‘texture weight’ condition shading curvature was anchored at 0.48cm\(^{-1}\) (radius = 2.08cm) while texture curvature was perturbed about this value, and in the ‘shading weight’ condition texture curvature was anchored while shading curvature was perturbed. The occluding apertures of the standard and test patches were identical in size (radius = 1cm), and the occluding aperture of the background sphere had a radius of 1.46cm. In the low-curvature background condition, in which the background sphere was less curved than the standard patch, the curvature of the background sphere was fixed at 0.29cm\(^{-1}\) (radius = 3.5cm). In the high-curvature background sphere, in which the background sphere was more curved than the standard patch, background surface curvature remained fixed at 0.66cm\(^{-1}\) (radius
Figure 7.1. An example stimulus used in experiment nineteen. The inconsistent-cues patch comprises a shading cue with a curvature of 0.6 cm⁻¹, and a texture cue with a curvature of 0.48 cm⁻¹. The consistent-cues patch has a curvature of 0.48 cm⁻¹. The standard (inconsistent-cues) patch is embedded in a background sphere with a curvature of 0.29 cm⁻¹.
The radii of the occluding apertures for the standard and background surfaces were always smaller than the radii of the spheres from which the surfaces were derived. Subjects were given a Binary Choice curvature discrimination task, in which they had to decide which of the two patches - the mixed-cues standard patch or the consistent-cues test patch - was the more curved. Perceived curvature was measured for the following curvature values of the perturbed cue - 0.36cm$^{-1}$ (r=2.76cm), 0.44cm$^{-1}$ (r=2.28cm), 0.48cm$^{-1}$ (r=2.08cm), 0.51cm$^{-1}$ (r=1.95cm), and 0.6cm$^{-1}$ (r=1.66cm). Subjects generated two psychometric functions for each mixed-cue stimulus in both curvature context conditions; thus each subject provided forty psychometric functions in total.

7.2.1 Results. The results for two subjects are plotted in Figure 7.2(a-d). Figure 7.2(a-b) plots both subjects’ data from the shading weight condition, in which the texture cue was anchored at 0.48cm$^{-1}$ and perceived curvature was measured as a function of the shading cue’s curvature. The results of the texture weight condition, in which shading and texture were the anchor and perturbed cues, respectively, are shown in Figure 7.2(c-d). In each plot the data from the low-curvature background experiment are represented by the filled circles, while the filled triangles plot the data taken from the high-curvature background condition.

The data in Figure 7.2 reveal that, under the conditions of 3D curvature contrast, the shading cue was consistently given more weight than the texture cue. The slopes of the plots from the shading weight condition (Figures 7.2a & 7.2b) are steeper than those from the texture weight condition (Figures 7.2c & 7.2d) for both subjects. The results of this experiment also demonstrate that the weight of either cue was unaffected by changing the
Figure 7.2(a-b). Perceived curvature of an inconsistent-cues stimulus as a function of the shading cue’s curvature and as a function of the background sphere’s curvature. The data plots from the two background conditions run parallel for both subjects, particularly in the case of subject W.C., suggesting that the weight assigned to shading is unaffected by the sign of curvature contrast.
Figure 7.2(c-d). The results from the texture weight condition of experiment nineteen, in which the weight of the texture cue was estimated as a function of the sign of curvature contrast. As in Figure 7.2(a-b) the results suggest that varying the sign of curvature contrast has no effect on the weights assigned to the texture cue for either subject.
sign of curvature contrast. The slopes of the data plots are similar for both background curvatures in each figure. Figure 7.2a, for example, shows that increasing or decreasing the curvature value of the shading cue resulted in an increment or decrement in perceived curvature, and that this change in perceived curvature was the same regardless of the sign of curvature contrast. This pattern of results was found for both subjects, and for both cues. Thus, with the aid of perturbation analysis, it has been demonstrated that the weight assigned to either the shading or texture cue was unaffected by changing the context of the embedded patch in the manner considered here.

As pointed out above, within the framework of perturbation analysis, the weight assigned to a cue is defined as the ratio between the change in the subject’s estimate of overall curvature and the change in the curvature of the cue. Thus if the curvature of one cue is fixed and the curvature of the other cue perturbed, the weight of the perturbed cue can be estimated from the slope of the line fit to the observer’s perceived curvature as a function of the perturbed cue’s curvature. If the regression line has a slope of 1, this indicates that changing one cue has an identical effect on perceived curvature as simultaneously changing both the shading and texture cues together. In the perturbation analysis paradigm we assume that the perceived curvature of a consistent-cues patch is veridical. If the weight of a given cue is less than 1, then the slope of the line fit to an observer’s perceived curvature as a function of the perturbed cue’s curvature will be shallower than if both cues had been perturbed together. The lower the weight of the cue, the greater the difference will be between the slopes of the lines fit to the data in these two situations. Thus, within the framework of perturbation analysis, a cue’s weight may also be interpreted as being inversely proportional to the difference between the slopes of the data.
in the inconsistent-cue and consistent-cue conditions.

The above interpretation of a cue's weight, which is a generalisation of the common interpretation, highlights a potential problem in analyzing the data from experiment nineteen. The experiments in chapter six have demonstrated that the curvature of a consistent-cues patch is not perceived veridically in the context of curvature contrast, and that the sign of the error in perceived curvature is dependent on the sign of curvature contrast. It is also known from the experiments in chapter six that perceived curvature becomes closer to veridical as the curvature of the central patch nears that of the surround. At the limit, when the central patch curvature is identical to the background curvature, perceived curvature is veridical. The non-veridical curvature perception of the central patch tells us that an observer's perceived curvature of the central patch will be fit by a line whose slope must be different to 1 in both curvature contrast contexts (see Figure 7.3). Thus the slopes of the functions in experiment nineteen cannot be taken as an indication of the cues' weights. To correctly determine a cue's weight in this case we have to calculate the difference between the slopes of the line fitted to perceived curvature as a function of the value of the perturbed cue and the slope of the line fitted to perceived curvature as a function of the curvature of a consistent-cues patch. Experiment twenty addresses this question by measuring subjects' perceived curvature of a consistent-cues patch as a function of the patch's curvature for two background curvatures.
Figure 7.3. The perceived curvature of a central patch in both curvature contrast contexts. The broken line plots veridical curvature perception and, thus, has a slope of 1. The upper solid line plots perceived curvature of a central patch which is more curved than the background surface. The lower solid line plots perceived curvature of a central patch which is less curved than the background. As the difference in curvature between the central patch and surround decreases in both curvature contrast contexts, perceived curvature becomes closer to veridical. Thus the two solid lines are constrained to converge on the broken line and, therefore, cannot have a slope of 1.
7.3 EXPERIMENT TWENTY: CHANGES IN PERCEIVED CURVATURE AS A FUNCTION OF SURFACE CURVATURE AND BACKGROUND CURVATURE.

In this experiment subjects' perceived curvature of a consistent-cues, central patch was measured for a range of surface curvatures, and as a function of the sign of the curvature contrast.

7.3.1 METHODOLOGY.

Subjects performed a binary choice, curvature discrimination task in which they had to decide which of a consistent-cues test patch appeared more curved than the standard. For each presentation the standard patch was embedded in a background spherical surface which was either more curved or less curved than the standard patch. A test patch, which was spatially separated from the other surfaces, was presented simultaneously. As in experiment nineteen, the occluding apertures of the standard and test patches were identical in size (radius = 1cm), and the occluding aperture of the background sphere had a radius of 1.46cm. The curvature of the background was fixed at 0.66cm⁻¹ (radius = 1.5cm) and 0.29cm⁻¹ (radius = 3.5cm) in the high-background and low-background conditions, respectively. The curvature of the embedded standard patch was set to the same values for both background conditions; these were 0.36cm⁻¹, 0.44cm⁻¹, 0.51cm⁻¹, and 0.6cm⁻¹.

Subjects generated two psychometric functions for each of the four standard patch curvatures in both background curvature conditions. Thus a total of eight psychometric functions per subject were generated.
Figure 7.4. Perceived curvature of a central spherical patch as a function of that patch’s curvature. The filled circles show the data from the low-curvature background condition, in which the standard patches used in the experiment were embedded in a less curved background sphere (0.29 cm⁻¹). The filled triangles plot the data from the high-curvature background condition, in which the background sphere was more curved (0.66 cm⁻¹) than the standard patches used. The central line (no symbols attached) marks veridical curvature. Note that the data from each condition converge on this line as the difference between the patch and background curvature tends to zero. We can see that the slopes of the data plots from both conditions are similar, thus demonstrating that increasing the curvature of a standard patch results in a similar increment in perceived curvature regardless of the sign of curvature contrast.
7.3.2 Results. Figure 7.4(a-b) plots the results for two subjects. In this figure subjects' perceived curvature of a standard patch is plotted along the ordinate as a function of the curvature of the standard patch. The filled circles plot the data obtained from the low-curvature background condition, in which the standard patch curvature is over-estimated, and the filled triangles plot the data from the high-curvature background condition, in which the standard patch curvature is under-estimated. The data show that as the difference between the patch and background curvatures decreases perceived curvature becomes nearer to veridical. This can be demonstrated by superimposing a line marking veridical curvature perception on Figure 7.4(a-b). Notice that the data from each background curvature condition converge on this line as the difference between the patch and background curvature tends to zero. This is particularly clear in the case of subject W.C.

The data from Figure 7.4 show that increasing the curvature of the standard patch resulted in a similar increment in perceived curvature regardless of the sign of curvature contrast. This is particularly well demonstrated by the data obtained from subject W.C. (Figure 7.4a). The slopes of the curves were calculated by linear regression. It is clear that the slopes of the regression lines fitted to the two sets of data are almost identical (the slope m for the plots from the low- and high-curvature background conditions is 1.2 and 1.3, respectively). Although not identical, the slopes of the regression lines fit to M.F.'s two sets of data are similar (m = .98 and 1.2 for low- and high-curvature background plots, respectively).

Thus the results of experiment twenty show that changes in subjects' perceived surface
curvature of a spherical patch as a function of changing the patch’s curvature are similar for both the high and low curvature-background conditions. We can see that for high and low curvature backgrounds the presence of the surrounding surface does not have a differential effect on the slope of the consistent cues stimulus patch. It is safe to conclude, therefore, that the parallel lines in the data for inconsistent cues in the perturbation experiment, experiment nineteen, reflect an equivalence in the weights given to shading and texture in the positive and negative curvature contrast conditions. Changing the context in this way does not appear to change the weights.

Although the context manipulation described in experiment nineteen had no effect on the cues’ weights, there may be other manipulations of 3D curvature contrast that result in a re-weighting of the shading and texture cues. This is investigated in experiment twenty-one.

7.4 EXPERIMENT TWENTY-ONE: REMOVING INDIVIDUAL CUES FROM THE SURROUND.

Until now, in the 3D curvature contrast paradigm, the same curvature cues have been used to depict the standard patch and surround. This experiment investigates the effect on cue weights of making the standard and surround surfaces ‘inconsistent’ with respect to the combination of cues used to depict them. More specifically, it looks at the effect of removing either shading or texture from the surround, while keeping both cues in the standard patch. The experiment was similar to the low-curvature background condition of experiment nineteen, in which the shading and texture weights were estimated for a standard patch set against a less curved background sphere. In this case, however, the
background sphere contained only one curvature cue - either texture or shading.

As in experiment nineteen, one of the cues in the standard patch was anchored at 0.48cm\(^{-1}\) while the other cue was perturbed across the same curvature range (0.36cm\(^{-1}\) - 0.6cm\(^{-1}\)). The background sphere curvature was fixed at 0.29cm\(^{-1}\). The task was a binary choice curvature discrimination task.

7.4.1 Results. Figure 7.5(a-d) plots the results for two subjects. Figure 7.5(a-b) plots the data from both background conditions (shading-only & texture-only) when texture was the anchor cue and shading was the perturbed cue. The data plotted in Figure 7.5(c-d) were obtained from the two background conditions in which shading was anchored and the texture cue curvature was perturbed. Superimposed onto the data in each of these figures are the data from experiment nineteen in which both texture and shading were present in the background. Thus in each figure there are three curves, with the slope of each curve reflecting the weight of the cue in question in the context of three backgrounds. The filled circles plot the data from experiment nineteen; the filled triangles plot the data from the shading-only background condition of experiment twenty-one; and the filled squares plot the data from the texture-only background condition of the latter experiment. The slopes of the curves were calculated by linear regression.

Comparing the slopes of the three data plots in Figure 7.5a reveals that the shading cue weight was almost identical in the shading-only and shading+texture conditions for subject W.C. This is reflected in the almost identical slopes of regression lines fit to these two sets of data (1.0 and 0.99). The data from the texture-only condition, on the other hand,
Figure 7.5(a-b). Estimating the weight assigned to shading as a function of the cues present in the background. Perceived curvature of an inconsistent-cues patch is plotted as a function of the shading curvature for three background sphere conditions. The background sphere, in which the standard patch was embedded, contained either shading and texture cues (filled circles), shading only (filled triangles), or texture only (filled squares). In the case of subject W.C., the data from the three conditions suggest that the weight assigned to shading was reduced in the texture-only condition. For subject M.F., on the other hand, the data suggests that the shading weight is significantly increased in the shading-only condition. Note that for both subjects the curvature contrast effect disappears when texture is removed from the background (filled triangles); when shading and texture have a curvature of 0.48 cm⁻¹, perceived curvature is veridical for this background condition (the intersection of the two dashed lines marks veridical curvature perception).
Figure 7.5(c-d). Estimating the weight assigned to texture as a function of the cues present in the background. Perceived curvature of an inconsistent-cues patch is plotted as a function of the texture curvature for the three background sphere conditions. The weight assigned to the texture weight is substantially reduced for both subjects when only one cue is present in the background. Again, as in Figure 7.5(a-b) the curvature contrast effect disappears for both subjects when texture is removed from the background (filled triangles).
suggest that the shading weight may be significantly lower when compared with the shading+texture condition. A regression line fit to the data from the former condition has a slope of 0.81. If it were demonstrated that regression lines fit to these two sets of data were significantly different from parallel, this would indicate a significant difference in the shading weight across these two conditions. Regression analysis was carried out for the two conditions simultaneously, making an allowance for the possibility of both differing intercepts and slopes. Analysis indicated that the interaction term was significant ($t_{16} = -2.89; p < 0.01$). Thus it appears that the shading weight was reduced for subject W.C. when texture was the only cue available in background surface. In the case of subject MF, the slopes of the data plots from the texture-only and shading-only conditions suggest that the shading weight was similar across these two conditions, although it was somewhat higher than in the shading+texture condition. Regression analysis was carried out to determine if there was a significant interaction between either of the single cue conditions and the shading+texture condition. No significant interaction was found between the data sets from the texture-only and shading+texture conditions ($t_{16} = 2.1; p >0.05$) and, hence, it is reasonable to assume that the shading weight remained unchanged across these two conditions. A significant interaction was found, however, between the two data sets from the shading-only and shading+texture conditions ($t_{16} = 3.78; p<0.01$). Thus M.F.'s data show the opposite pattern to the data obtained from subject W.C.; the shading weight was not affected in the texture-only condition, but was significantly reduced in the shading-only condition.

Whereas manipulating the cue content of the background has a mixed effect on the shading cue weight for both subjects, the same manipulation seems to have a more
clear-cut effect on the texture cue weight. This is demonstrated in Figure 7.5(c-d). When shading and texture are both present in the background, perceived curvature changes as the texture curvature of the standard patch is perturbed about the shading curvature. But, when either shading or texture is removed from the background, the effect that perturbing the texture cue has on perceived curvature is noticeably reduced. This difference is made explicit by comparing the slopes of regression lines fit to the three data plots for each subject. Thus for subject WC, the data from the condition in which shading and texture are both present in the background fall on a line with a slope of 0.37; the data from the condition in which shading was the only cue present in the surround fall on a line with a slope of 0.12. The slopes of these two lines differ by a factor of three, suggesting that the texture weight is substantially reduced when the shading is the only cue present in the surround. This is confirmed by regression analysis, which found a significant interaction between the two sets of data (t_{16} = -3.79; p <0.01). Similarly, the data from the texture-only condition fall on a line with a slope of 0.12, suggesting that the texture cue weight is reduced by a similar amount under both contextual manipulations of experiment twenty-one. Again regression analysis shows a significant interaction between the two sets of data obtained from the texture-only condition and the shading+texture condition (t_{16} = -5.23; p<0.001). Analysis of M.F.'s data shows that the texture weight was significantly reduced in the shading-only condition (t_{16} = -2.37; p<0.05), but was not affected when texture was the only background cue (t_{16} = -1.69; p=0.11).

When comparing the data of the texture-only and shading-only conditions in Figure 7.5(a-d) it is apparent that the 3D curvature contrast effect disappears when texture is removed from the background, leaving shading as the only cue. On the other hand, when
Figure 7.6a. A pair of spherical patches of identical curvature (0.48cm\(^{-1}\)) and comprising both shading and texture curvature cues. The spherical patch on the right is embedded in a less curved background sphere (0.29cm\(^{-1}\)) comprising just the texture cue. Although shading information is not present in the background sphere, the embedded spherical patch appears more curved than the spherical patch on the left, demonstrating that 3D curvature contrast persists when shading information is removed from the surround. This is in contrast to Figure 7.6b (overleaf), which demonstrates that the effect disappears when the background sphere comprises just the shading curvature cue.
Figure 7.6b. A pair of spherical patches of identical curvature (0.48cm^{-1}) and comprising both shading and texture curvature cues. The spherical patch on the right is embedded in a less curved background sphere (0.29cm^{-1}) comprising just the shading cue. In contrast to Figure 7.6a neither of the two smaller spherical patches appears convincingly more curved than the other, demonstrating that 3D curvature contrast is removed under these conditions.
shading is removed from the background surface, leaving texture as the only available cue, the effect is found to persist. This is demonstrated by the stimuli in Figure 7.6(a-b). Both figures depict two identically curved spherical patches, which have a curvature of 0.48cm⁻¹, with the patch on the right embedded in a spherical patch of curvature 0.29cm⁻¹. The background sphere in Figure 7.6a comprises just the texture cue. The embedded patch on the right appears more curved than the spherical patch on the left, demonstrating that 3D curvature contrast persists when shading information is removed from the surround. By contrast, in Figure 7.6b, in which shading is present in the surround and texture has been removed, the two smaller patches do not appear obviously different in their curvature. The absence of 3D curvature contrast in the shading-only condition is reflected in the reduction in perceived curvature across the range of curvatures tested. Furthermore, when the shading and texture cues in the standard patch have equal curvature (C_s = C_t = 0.48cm⁻¹), perceived curvature is veridical; thus confirming that the illusion is indeed absent under this manipulation. On the other hand, the data suggest that the standard patch curvature continues to be overestimated for the texture-only condition and, therefore, that 3D curvature contrast persists under this manipulation.

7.5 DISCUSSION.

The experiments in this chapter address two issues. The first, and main, issue to be addressed was whether the weights assigned to shading and texture could be changed by varying the context in which a standard patch was viewed. Experiment nineteen investigated the issue of context-dependent weighting by manipulating the context in which a standard patch was presented. The results of this experiment failed to
demonstrate any effect of changing the curvature contrast on the weights assigned to shading or texture. However, because curvature perception of a consistent-cues patch is no longer veridical under the context of curvature contrast, it was pointed out that it may not be appropriate under the conditions of experiment nineteen to consider a cue’s weight as being reflected in the ratio between the change in subjects’ perceived overall curvature and the change in the curvature of the cue in question.

To control for this possibility experiment twenty investigated whether changing the curvature of a consistent-cues, standard patch had the same effect on the perceived curvature, regardless of the sign of the curvature contrast. The results of this experiment demonstrated that changes in perceived curvature were similar for low and high curvature surrounds. These results lend support to the earlier conclusions drawn from experiment nineteen; that is, the texture and shading cue weights are unaffected by varying the curvature of the background surface.

Having found no evidence from the results of experiments nineteen and twenty that manipulating the background context of a surface patch affects the texture and shading weights, experiment twenty-one investigated further the effects of the background context by excluding one of the two cues. The weights for both the shading and texture cues in the central patch were then estimated for the two background conditions. While the shading weight was affected differently for both subjects across the two background conditions, the effect on the texture weight was more consistent across subjects, with the background manipulations generally resulting in a reduction in the texture weight. Thus the results of experiment twenty-one support the notion that the assignment of a cue’s
weight may be partly context-dependent.

An interesting finding of experiment twenty-one was the disappearance of the curvature contrast illusion when texture information was removed from the background surface, leaving only shading. However, the effect persisted when texture was the only cue available in the background surface. This is further evidence in favour of the conclusion that brightness contrast is not the only factor underlying 3D curvature contrast. The texture cue also appears to have a role to play.
CHAPTER EIGHT

DISCUSSION

The experimental results reported in this thesis are relevant to several issues relating to 3D cue integration and 3D shape processing by the human visual system. These issues include the following:

• What is the locus of cue integration for shading and texture?
• Is the integration of shading and texture by the visual system a linear operation?
• What factors affect the weights assigned to texture and shading cues?
• What texture properties are important for surface curvature perception?
• Is shape from shading and/or texture a global or local process?
• How does light source position affect perceived surface curvature?

8.1 THE LOCUS OF INTEGRATION FOR SHADING AND TEXTURE.

There is, as yet, no general consensus among vision researchers regarding the form of representation in which 3D information is held prior to integration. Until recently two popular proposals were a range map and orientation map (Maloney & Landy, 1989; Marr, 1982; Mingolla & Todd, 1986; Pentland, 1984; Young, et al., 1993). However, there is
evidence that neither of these are likely candidates for a primary representation of objects containing just monocular cues (He & Nakayama, 1994; Johnston & Passmore, 1994a; Koenderink, et al., 1994; Todd & Reichel, 1989), with some researchers suggesting that other, 'higher-order' geometric representations, such as curvature, may be primary (Johnston & Passmore, 1994a; Koenderink, et al., 1994; Rogers & Cagenello, 1989; Rogers, 1986; Stevens, 1992; Stevens, et al., 1991).

Given that shading and texture cues do not provide information about absolute distance, it is unlikely that a range map is the primary representation for surfaces containing just these cues. This is confirmed by the results of experiment one suggesting that the locus of integration was more likely to have been a curvature map. This conclusion is given further support by the results of experiment two, in which subjects' curvature judgements of inconsistent-cues stimuli were fitted to identical surface models in both the curvature and depth domains. All three models tested gave a better fit to the curvature data than to the transformed depth data.

8.2 THE NON-LINEAR INTEGRATION OF SHADING AND TEXTURE CUES.

The increasing availability of computer graphics systems over the past decade has been accompanied by a growing literature on the integration of cues to three-dimensional form. The results of subsequent research have suggested a number of different cue integration strategies that may be employed by the human visual system, such as vetoing (Bulthoff & Mallot, 1990; Bulthoff & Mallot, 1988; Stevens & Brookes, 1988), disambiguation (Braunstein, et al., 1982; Ramachandran, 1988), cooperation (Buckley, et al., 1989;
Bulthoff, 1991; Bulthoff & Mallot, 1990; Tittle & Braunstein, 1990), and accumulation (Bruno & Cutting, 1988; Dosher, et al., 1986; Johnston, et al., 1993; Landy, et al., 1990; Rogers & Collett, 1989; Young, et al., 1993). One of the simplest methods of accumulation is a weighted linear combination rule. A growing body of evidence over the past few years suggests that the visual system may employ such a strategy in the integration of a number of different cue combinations.

The main thrust of experiment two was to test whether the integration of shading and texture cues is best described by a weighted linear combination rule, or whether their integration is better described by some other combination rule. This was investigated with the use of perturbation analysis. Perturbation analysis allows one to estimate the relative weights of individual cues by varying one of a number of cues and measuring its influence on the combined percept. It has recently been applied to the problem of estimating cue weights. Landy et al (Landy, et al., 1990) demonstrate that, with the use of the perturbation analysis paradigm, a cue's weight is equivalent to the ratio between the change in an observer's estimate of overall depth and the change in the cue being perturbed. Thus by measuring the slope of a line fit to the data generated by the above technique, Landy et al were able to estimate the weight assigned to motion and texture depth cues. This idea was generalized in experiment two to deal with more complex data surfaces, which were generated by testing subjects on a wide range of cue combinations. It is clear that if we define a cue's weight in terms of the partial derivatives of the perceived curvature data surface, any data surface can be treated as being locally planar, and that, in these terms, we may think of the cue combination rule as being linear. However, by testing subjects on a wide range of cue combinations, and investigating the
shape of the surface generated by subjects' responses, we can discover whether a cue's weight remains constant or whether it varies across the range of cue combinations. If the change in the combined percept is proportional to the change in the level of the cue for all increments in the cue then the combined percept may be modelled as a planar function of the values of the component cues. Under this global criterion the results of experiment two show that the linear model does not generalize to the integration of shading and texture cues. An alternative, non-linear model is proposed.

The value of the proposed model is its role in highlighting the way in which the shading and texture weights change as a function of the values of the component cues. Another advantage of the model is that, rather than having weights scale the absolute values of cues to derive a value of perceived curvature, as in the Maloney and Landy model (Maloney & Landy, 1989), the weights scale increments in cues to derive a value for a change in perceived curvature. Thus the weights describe how changes in shading or texture determine the change in perceived curvature. Further support for the model is found in the results of experiment three. In this experiment a wider range of cue curvatures was tested than in experiment two, and, as in experiment two, the one parameter non-linear model was found to account for more of the variance in the data than the linear model.

Thus, although there is evidence of linear integration for a number of different cue combinations, the results described in chapter three suggest that this is not the case for texture and shading cues. Although the integration of these two cues may be considered to be locally linear, the data suggest that their integration is not globally linear.
Furthermore, the evidence suggests that, in these experiments, the locus of integration for the two cues was more likely to be a curvature map than a range map.

8.3 WHAT FACTORS AFFECT CUE WEIGHTS?

It has been proposed that the weights assigned to cues are influenced by a number of factors, and that manipulating these factors results in a change in the relevant cue's weight. These include cue availability (Young, et al., 1993), cue reliability (Cumming, et al., 1993; Young, et al., 1993), and the context within which a stimulus is viewed, such as the viewing conditions or the physical characteristics of the scene (Dosher, et al., 1986; Johnston, et al., 1993; Maloney & Landy, 1989; Rogers & Collett, 1989). Experiments three and four investigated the influence of cue availability and cue reliability on the weight assigned to a checkerboard texture. The influence of cue availability was investigated by estimating the texture cue weight as a function of the size of the aperture bounding the inconsistent-cues stimulus. The influence of cue reliability was investigated by estimating the texture cue weight for a number of supra-threshold texture contrast levels. The paradigm used for these experiments was a modified version of that used by Young et al (Young, et al., 1993). In their study the reliability of texture and motion cues was manipulated for the cues in the inconsistent-cues stimulus, and perceived depth of the combined cues was measured by comparing this stimulus with consistent-cues stimulus in which cue reliability had not been manipulated. The problem with this paradigm is that an observed change in the weights of the cues could be attributed to one of two factors - reducing cue reliability, or the fact that the perceived depth of the inconsistent-cues
stimulus is no longer constrained to pass through the diagonal $d_p = d_m = d_i$, where $d_p$ is perceived depth, $d_m$ is the inconsistent motion depth, and $d_i$ is the inconsistent texture depth.

This problem was avoided in experiments three and four by applying identical cue availability/reliability manipulations to both the consistent- and inconsistent-cues stimuli. This ensures that subjects’ perceived curvature continues to be constrained to pass through the diagonal $d_p = d_m = d_i$. Any subsequent change in the texture cue’s weight could then be attributed to the manipulation of that cue’s availability or reliability. The experimental results demonstrated that these manipulations do have an effect on the weight assigned to the texture cue. As the aperture bounding the stimuli was increased in size, thus increasing the availability of the texture cue, the influence of the texture cue on subjects’ perceived curvature of inconsistent-cues stimuli grew, suggesting that the weight of the texture cue increased as the aperture size was enlarged. Experiment four investigated the effect on the texture cue weight of varying texture contrast across a supra-threshold range. The results showed that, for texture contrasts below 0.24, the weight assigned to texture rises rapidly and starts to level out as texture contrast is increased beyond 0.24. Thus the change in texture weight with changing texture contrast is not a linear one, with the results suggesting that the texture cue reliability is relatively unaffected by changes in contrast above some critical point. These experimental results support the assertion that the weight assigned to a cue depends, in part, on the cue’s availability and reliability.

Given that shading is an intrinsically ambiguous cue to curvature sign (ie the same surface may appear convex or concave) one may have anticipated that manipulating the light
source position would have an effect on the shading weight. However, changing the light source position, by either rotating it around the line of sight or varying the slant angle with the surface, generally has no effect on the weight assigned to shading when combined with a texture cue. Similarly, the texture cue weight was unaffected by this manipulation. This consistent weighting of the shading cue regardless of the light source position may partly explain the findings of experiment ten, in which it was demonstrated that the curvature of a stimulus containing texture and shading cues is increasingly under-estimated as the light source position is moved further away from above the object.

If, as is suggested (Benson & Yonas, 1973; Kleffner & Ramachandran, 1992; Ramachandran, 1988), the visual system processes shaded images in accordance with an assumed illuminant position, and the shading cue weight remains constant as the light source rotates around the line of sight, then the shading cue should drag perceived curvature in the direction consistent with the assumed light source position. The perspective information present in the texture cue has a stabilising effect on the perceived curvature sign, but the fact that the shading weight is unaffected by changing the light source position may explain why surface curvature is under-estimated.

The suggestion that the observed effect of light source position on perceived curvature may be explained in terms of an assumed overhead light source and constant weight of the shading cue is indirectly supported by the results of experiment 12b which showed that replacing the checkerboard texture with a texture which was given less weight resulted in surface curvature being even more under-estimated. With the texture weight reduced, the shading cue is likely to have even more influence over perceived curvature, resulting in the reported enhancement of the effect of light source position on perceived
Other contextual effects on texture and shading weights were investigated using the 3D curvature contrast paradigm. Shading and texture weights were estimated as a function of curvature contrast sign in experiment nineteen. The results from this experiment suggest that the weight of either cue was similar for both curvature contrast conditions. Although this manipulation of background context had no effect on the cues' weights, a different manipulation in experiment twenty-one did alter the cues' weights. In this experiment cue weights were estimated when stimuli were set against a less curved background surface containing just one curvature cue - shading or texture - or containing both cues. While the shading weight was affected differently for both subjects across the two background conditions, the effect on the texture weight was more consistent across subjects, with the background manipulations generally resulting in a reduction in the texture weight. These results support the notion that a cue's weight is partly dependent on the background context.

8.4 TEXTURE PROPERTIES USED IN CURVATURE PERCEPTION.

There is evidence to suggest that image texture compression is the most likely texture gradient to be used in extracting information about surface curvature (Blake, et al., 1993; Cumming, et al., 1993; Cutting & Millard, 1984; Todd & Akerstrom, 1987). Experiments five to seven attempted to identify, with the use of perturbation analysis, which property of the checkerboard image texture was being used by subjects making curvature
discrimination decisions. It seems reasonable to assume that the more effective a cue is in providing information about a given geometric property, the more weight that cue should be given in a task requiring the discrimination of two stimuli on the basis of the geometric property in question. Thus by estimating the weights of a number of textures that differ in the gradients and other properties they contain, one can identify which texture property is the more salient for the task at hand. The data from experiments five to seven suggest that, for the checkerboard texture, image texture compression was not the primary source of curvature information. Rather, 2D line curvature appears to have been the primary source of texture curvature information used by subjects. This is particularly clear from the results of experiment seven, which demonstrated that a number of image textures rich in 2D line curvature information were given more weight than an image texture containing image texel compression but no 2D line curvature information. Furthermore, the weights for the former textures were correlated with the amount of 2D line curvature present in the texture - the more 2D line curvature, the greater the texture weight. The fact that the texture with 2D line curvature was given more weight suggests that this was the more likely texture property being used to extract curvature estimates. It is worth noting that the stimuli used in these experiments were substantially smaller than the stimuli used in those experiments in which image texture compression was an effective cue. This suggests that the usefulness of compression gradients may be related to the visible spatial extent of the surface being presented, and that below some critical level this cue is redundant.
8.5 SHAPE FROM SHADING AND TEXTURE: A LOCAL OR GLOBAL PROCESS?

The 3D curvature contrast illusion, described in chapter six, is relevant to the debate regarding the processing of shape from shading and texture. Some theorists argue for purely local processes in shape perception. For example Marr (1982) proposed that the visual system constructs a 2.5D sketch from point-by-point depth and orientation maps. This concept has been taken up by a number of vision researchers and has also been instrumental in choosing the appropriate metric for subjects participating in experiments on shape perception (Bulthoff & Mallot, 1990; Todd, et al., 1986). Others have argued on the basis of a growing body of evidence that local shape representations are in the form of a local curvature map (Johnston & Passmore, 1994a) or a local shape map (Johnston & Passmore, 1994b; Koenderink, 1990). In juxtaposition to these local process approaches are those who argue that shape perception is a global operation (Mingolla & Todd, 1986; Ramachandran, 1988).

The phenomenon of 3D curvature contrast, in which the perceived curvature of a central surface patch can be radically influenced by the curvature of a surrounding patch, is compelling evidence that shape perception cannot be just a purely local operation. Rather, it suggests that some global operations are at work. If the illusion only occurred for those stimuli in which the central patch was embedded in a background surface, the case for purely local shape processing could be defended by arguing that the effect is brought about by local interactions at the occluding boundary where the two surfaces meet. However, the fact that the effect persists even when the central patch is surrounded by surfaces that are spatially separated from it provides a strong counter-argument in favour
of the visual system using global, as well as local, processes to derive a perception of three-dimensional shape from 2D images.

8.6 LIGHT SOURCE POSITION AND ITS INFLUENCE ON CURVATURE PERCEPTION.

It is well documented that the perceived curvature sign of a shaded, convex, disc-like object illuminated from below is ambiguous when the light source position is not explicitly known by the observer. The same object can be perceived as being either concave lit from above or convex lit from below. This effect is particularly compelling when a number of convex spherical objects lit from above are interspersed with a number of identical objects lit from below, as in Figure 5.1. In accordance with an assumption of overhead illumination the latter group of objects appear concave. This bi-stability in our perceived curvature sign of shaded images may be removed by adding other sources of information, such as occluding contours (Ramachandran, 1988) or texture. However, what has not been investigated previously is whether light source position still has an effect on perceived degree of curvature following such disambiguation.

The results of experiment ten demonstrate a clear effect of light source position on the perceived curvature degree of surfaces containing texture and shading cues. In this experiment varying light source slant or tilt was accompanied with a change in perceived curvature, with a spherical patch lit from below appearing substantially less curved than one with identical curvature but lit from above. Furthermore, the strength of this effect of light source position on subjects’ perceived degree of curvature was influenced by the weight of the texture cue. As the texture cue weight was reduced, this was accompanied by a complementary increase in the influence of the light source position. Thus the
Curvature of a given spherical patch, comprising texture and shading cues and lit from below, was increasingly under-estimated as the weight of the texture cue was reduced. Although the addition of other sources of information, such as texture, may disambiguate the perceived curvature sign of a shaded object, these results clearly demonstrate that the position of the light source still has an influence on perceived surface curvature.

The addition of a specular component to the shading information (experiment eleven) led to a marked reduction in the above effect of light source position. Furthermore, the results of this experimental work suggest that the presence of specular highlights has a 'correcting' influence on perceived curvature. This contrasts with earlier work suggesting that adding specular highlights has a simple additive effect on perceived curvature (Bulthoff, 1991; Bulthoff & Mallot, 1990; Todd & Mingolla, 1983). When previously presented with a spherical matte surface containing shading and texture cues, and which was lit from below, subjects reported that the stimulus appeared convex. Bearing this in mind, it seems reasonable to assume that the presence of a specular highlight has the effect of aiding the observer to identify more accurately the direction from which the stimuli are illuminated. Making the light source position explicit in this way should, in turn, undermine any assumption of overhead illumination, thus rendering the shading information less ambiguous. This may explain why the effect of light source position on perceived curvature was reduced with the introduction of specular highlights in the image.
8.7 GENERAL CONCLUSIONS.

The application of perturbation analysis to the problem of cue integration is a relatively recent development. The main contributions of the work in this thesis have been, firstly, in extending the use of this paradigm to deal with more complex data surfaces generated by a more comprehensive range of curvature combinations, and, secondly, in recognising the usefulness of perturbation analysis in identifying those texture properties that are important to curvature perception. The successful application of perturbation analysis in dealing with the latter problem is encouraging, suggesting that it is a potentially useful tool with which to identify the important characteristics of cues to other geometric properties, such as slant and depth. Finally, the work in this thesis also describes a novel illusion, 3D curvature contrast, which promises to be a useful paradigm within which to further investigate 3D shape perception.
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