tion in magnitude judgments (McCleary, 1975; Griffin, 1985) and that map context created further problems (Gilmartin, 1981).

Based on the extensive testing Flannery did in 1956 and repeated in 1972, Robinson et al, (1984) and other authors of cartographic texts adopted the guideline of adjusting scaling on graduated circle maps to account for underestimation of differences. Others (e.g., Cox, 1976) have suggested that we might be better off simply providing more anchors (in the form of legend circles). The among-experiment and among-subject variations together with context effects have made many practitioners suspicious of the empirically derived guidelines for perceptual scaling, and today it is doubtful whether many cartographers actually use them.

In relation to gray tones for quantitative maps, there seems to be a bit more consensus. Kimerling (1985) was able to demonstrate a correspondence among what were apparently divergent results and showed that usable gray scales could be devised. The two most significant issues he considers are the interaction between area fill texture and perception of value and the interaction between judgment task and value perception. In terms of texture, Kimerling found that the finer the texture, the more curvilinear the relationship between perceived and actual gray tone. The implications of this finding are that a different set of gray tones is required for maximum discriminability if a map is produced on a laser printer (with dots spaced at about 60 lines per inch) versus on a film recorder (with dots at 100 or 120 lines per inch) (Figure 3.68). Judgment was also found to be dependent upon the visual task, with a different actual–perceived gray tone function for judgment of percent black versus a partitioning task or tasks leading to a set of maximally discriminable gray tones.[17]

PERCEIVING DEPTH FROM A TWO-DIMENSIONAL SCENE

Closely related to concepts of judging order and magnitude (as well as to the visual levels discussed above) is the simulation of depth in two-dimensional displays.[18] Vision is designed to deal with a three-dimensional world. Interpreting depth in a visual scene is a complex process that appears to be facilitated by a large number of interdependent cues. For good evolutionary reasons, vision does not require all depth cues to be present in order to interpret features of a scene as being at varied distance from the observer. This makes it possible to trick vision into interpreting a map or other display as three-dimensional by combining some of these cues in appropriate ways. How vision interprets depth cues is relevant to cartography because cartographers are often faced with the problem of simulating three-dimensional information on a two-dimensional display (when depicting terrain, but also for more abstract multivariate information).

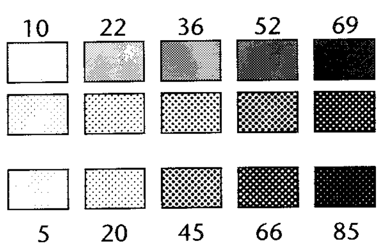

FIGURE 3.68. A gray scale designed for maximum between-category contrast with production on a 100 lines/inch image setter (top) compared to the same grays produced at 45 lines/inch resolution (typical of laser printers) (middle), and to grays adjusted in color value to achieve maximum contrast at the coarser resolution (bottom).

A Taxonomy of Depth Cues

Kraak (1988) provides a taxonomy of cues for depth perception and a review of the cartographic literature relevant to each. His taxonomy distinguishes between "physiological" and "psychological" depth cues. Some authors have called the latter "pictorial." Since this latter term puts emphasis on characteristics of the display rather than of the cognitive processing of that display, it is adopted here. The physiological depth cues have to do with the physical processes of vision as it reacts to the real three-dimensional environment. Pictorial cues, in contrast, are those related to the object's structure and the way that structure organizes visual input. In the context of computer graphics, Wanger et al., (1992) provide a list of depth cues similar to those cited by Kraak. Each of these sources includes pictorial cues (or subcategories of cues) omitted by the other and disagree on whether motion parallax should be considered a physiological or a pictorial cue (with Kraak opting for the former, and Wanger et al. for the latter). If we look to the art literature, we find additional depth cues not included in either the cartographic or the computer graphic taxonomies (along with some differences in terms for cues in common) (Metzger, 1992). A composite of these sources results in the following taxonomies of depth cues that may be relevant to maps:

Physiological

Accommodation: A change in thickness of the eye's lens as it focuses on an object.

Convergence: The difference in angle of gaze by the two eyes focused on the same object.

Retinal disparity: The difference in image (visual array) derived by each eye (which has a slightly different point of view).

Pictorial

Perspective: Kraak (1988) subdivides perspective into four components, and we will follow this subdivision here.

Oblique projection: Representation of a scene from a viewpoint that is not an elevation (profile) or plan view (overhead) suggests a three-dimensional solid, thus depth.

Linear perspective: Lines that are parallel in reality seem to converge with distance (e.g., a pair of railroad tracks).

Retinal image size: Objects appear smaller the farther away they are.

Texture gradient: Texture appears to decrease with distance.

Motion: Movement (actual or simulated) of the observer's point of observation produces changes in the relative retinal displacement of objects at different distances. Successive presentation of static images in which objects are displaced relative to one another can (particularly in the presence of other cues) also result in a sensation of depth.

Interposition: Using Gestalt principles of good continuation, vision will assume that whole objects juxtaposed with what appear to be part objects are really whole objects blocking our view of other whole objects farther away.

Shadow: A cue to obstruction or overlap, indicating that one object is blocking light from falling on another object.

Shading: Illumination gradient can indicate the shape and orientation of a surface.

Color:

Chromostereopsis (also called color stereoptic effect or, more commonly, advance-and-retreat): The differences in wavelength of colors are thought to result in apparent differences in distance (with reds appearing closer than blues at the same true distance).

Aerial perspective: With distance colors become less distinct (less saturated) and lighter (higher value), often with a bluish tint due to atmospheric scattering.

Detail: With distance detail becomes less visible and edges become blurred.

Reference frame: In order to judge relative size, vision must match retinal size to some frame of reference—apparent distance will therefore vary with what an object is compared to.

Not surprisingly, the bulk of cartographic attention to depth perception and how specific cues might prompt this perception is related to terrain mapping. Terrain is three-dimensional and cartographers have struggled with collapsing those three dimensions onto a two-dimensional page since the earliest maps were made. Although contour lines involve no depth cues, virtually all other methods of depicting relief rely on one or more of the cues listed above. Simulation of three dimensions on maps can be grouped into techniques that involve physiological cues, that rely on perspective, that use static nonperspective pictorial cues, and that include motion. For motion to cue depth, the user must assume a perspective view (but linear perspective is not essential). Since the possibility of motion as a depth cue requires a dynamic display, further discussion of these cues will be postponed until Chapter 8 in the context of geographic visualization environments (which, as they will be defined here, are dynamic).

Applying Depth Cues to Maps

Physiological Approaches

Computer technology has facilitated production of displays that make direct use of binocular parallax as the primary depth cue. Such displays consist of pairs of representations, usually perspective views, that depict the mapped area from slightly different points of view (simulating the different points of view resulting from the spacing of our eyes). Seeing depth in stereo pair maps usually requires that the observer's head does not change position while viewing, and/or that special glasses be worn. One technique, referred to as anaglyph plots, uses opponent colors of red and green to produce two overlapping views. When an observer wears glasses having one red and one green lens (if she has normal color vision) the two views will be separated with one seen by each eye. This technique was used for maps at least as early as 1970 in the Surface II package that could generate anaglyph fishnet maps.

Perspective Approaches

Included here are the four perspective cues of oblique projection, linear perspective, retinal size, and texture gradient. These cues are typically manipulated together on perspective view maps, with oblique projection common to all. Different representational techniques can put uneven emphasis on the remaining three perspective cues. The well-known fishnet plot (Figure 3.69), for example, emphasizes texture gradient. In contrast, layered contours (Figure 3.70) and block diagrams emphasize linear

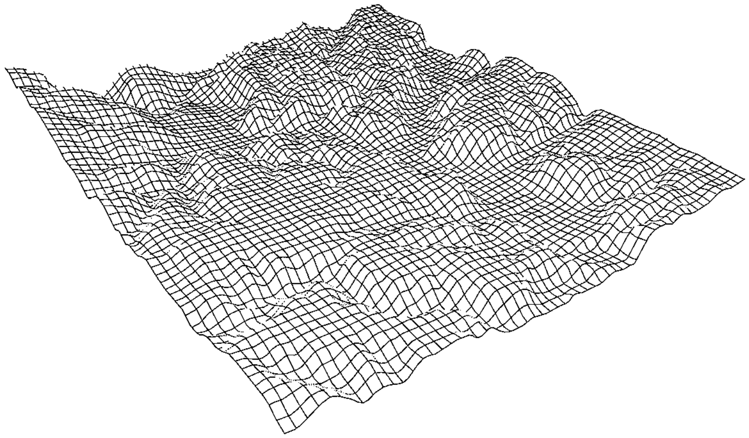

FIGURE 3.69. A typical fishnet plot depicting the terrain around Johnstown, Pennsylvania.

perspective and size disparity, and solid modeling (Figure 3.71) emphasizes linear perspective with shading and shadow as additional (nonperspective) depth cues. All of the methods mentioned make use of interposition as an additional cue (e.g., fishnet plots are rarely generated without hidden line removal). I have uncovered no empirical comparisons among the various styles of perspective map, but some attention has been given to perception of fishnet plots.

FIGURE 3.70. Layered contours applied to the same region as shown in Figure 3.69.

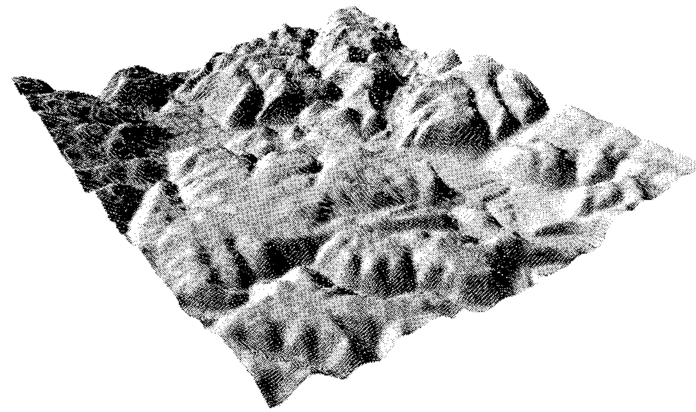

FIGURE 3.71. Solid rendering of the region from Figure 3.69.

That fishnet plots, with their strong texture gradient, do work was convincingly demonstrated by Rowles (1978). She found that subjects were able to judge relative height quite accurately, even when the point of view for the perspective was as high as 75° (nearly overhead) or as low as 15° (Figure 3.72). The view from 15°, however, results in considerable occlusion of map sections, something that probably helps to cue depth but can make the map much less useful (unless it can be dynamically oriented to allow hidden locations to be uncovered).

Nonperspective Approaches

Whether or not fishnet and other perspective view maps are effective, they all suffer from two problems. No matter what point of view is taken, there will be some hidden features and (if linear perspective is used) scale will change across the map. To avoid these issues, considerable attention has been given to use of nonperspective depth cues with the goal of an effective plan-view relief representation that suggests depth. Most cartographic attempts to create the illusion of depth without perspective use shading and/or color.

With shading, there is a long history of manual techniques using pencil, airbrush, and other tools. The procedures for what is termed "plastic relief"[19] borrow from principles of light and shadow in art and psychological principles of depth perception, but to be effective must also incorporate considerable knowledge of geomorphic structure of the terrain

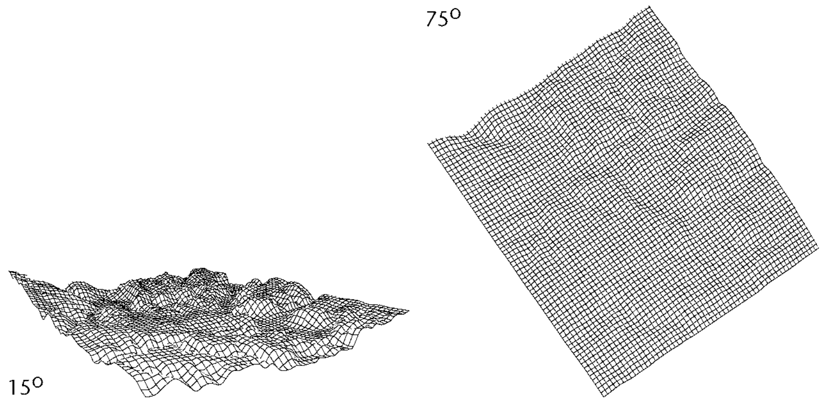

FIGURE 3.72. The Johnstown fishnet terrain map shown at elevations of 15° and 75°, viewpoints for which Rowles (1978) found no significant decrease in ability to estimate height. In Rowles's examples, however, relative relief was much greater.

being represented. Imhof (1965/1982) provides the most comprehensive account of these methods. One of the things that has been learned (primarily from long experience and years of marginal success at computerizing the process rather than from empirical research) is that perception is sensitive to what might be called the texture of shading as well as to its value. Humans can immediately recognize the difference between a perfect match of shading with slope–aspect values and shading that looks real. Not only do real surfaces not reflect light as perfectly as a virtual computer surface can, the real environment has complex interactions of direct with reflected light that our visual system has evolved to expect. For terrain shading to look real, it must incorporate at least some of the subtle variation from perfect reflectance that occurs in the real environment. Many theories have been proffered for the ideal reflectance model, but little empirical research has been done to determine their relative merits. In spite of the lack of empirical research, plastic shading has developed to the point in cartography that it has been successfully modeled with computer software (Figure 3.73). Perhaps the most impressive result thus far is Pike and Thelin's (1989) digital relief map of the United States, described by Lewis (1992) as a "cartographic masterpiece."

One issue that all disciplines interested in shading as a depth cue seem to agree upon is that the simulated light source needs to be from above the scene, and above-left is usually cited as best. This phenomena seems to be based upon a schema (or expectation) that light in the environment is from above. When applied to art (e.g., in the representation of a vase of flowers on a table or a figure in repose) this light-from-above rule is quite logical. On a map, the rule results in light from the north-

FIGURE 3.73. The Johnstown terrain map produced with computer-generated plastic shading (using ArcInfo).

west, a direction that is at odds with reality in the northern hemisphere. In spite of the physical impossibility of the scene, humans consistently treat terrain shading on maps in the same way that they treat shading on a painting. This reaction is so strong that a map produced with terrain illuminated from the south will appear inverted, with the hills looking like valleys and the valleys like hills.

In an effort to represent terrain aspect information clearly while also creating effective relief shading, Moellering and Kimerling (1990) developed a unique color-rendering process that has subsequently been labeled MKS-ASPECT™ (Moellering, 1993). They started with the assumption that aspect is a nominal (qualitative) phenomenon for which color hue differences provide a suitable representation.[20] They set out to devise a color-matching system that would allow observers to visually separate terrain regions with different aspects while also providing appropriate depth cues leading to interpretation as a three-dimensional surface. The system relies heavily on OPT (described above in the discussion of eye and brain). As noted above, OPT predicts four unique hues from which all others are derived. It also predicts that certain hue combinations are not possible: those across the diagonals of the square color space (red–green or blue–yellow). The four unique hues are considered to be the maximally discriminable hues (when at maximum saturation and medium lightness). One guideline that Moellering and Kimerling arrive at from OPT is that aspect should be grouped into four, eight, sixteen, and so on, classes using the four unique hues or these four plus their first order combinations, second order combinations, and the like. They argue that the resulting hues (for eight or more classes) should be seen as a circular progression of related colors.

Moellering and Kimerling (1990) had the primary goal of depicting aspect classes clearly. Initially they matched the four unique hues with cardinal directions. Although a discriminable map was obtained, the resulting representation prompted a number of inversions of features (e.g., ridges seen as valleys). Their technique (unlike true relief shading) does not take into account a light source or reflectance due to that light source. The impression of relief obtained is due entirely to slope aspect. Moellering and Kimerling were able to achieve a reasonable impression of depth by rotating the unique colors so that yellow (the highest value color) was aligned with the standard light source azimuth (315° or northwest), and the value of all other hues was adjusted to match the deviation of azimuth from northwest.[21] It is claimed that the MKS-ASPECT™ system eliminates one of the most severe problems with standard gray tone relief shading: that the visual interpretation of the scene will be highly dependent upon the exact angle of illumination for the hypothetical light source (Moellering, 1993). By not relying on color value alone, identification of ridge lines or valleys is not as dependent upon how their alignment matches with that of the illumination. No empirical test of Moellering's claims has yet been undertaken.

Recentely Brewer (1993) has developed an alternative color scheme for mapping slope and aspect in conjunction. This scheme uses a hue range to represent aspect, with yellow as the anchor hue aligned with northwest. Other hues were selected so that a value progression was achieved in each direction from yellow, and each of the eight distinct aspect categories would have a sufficient saturation range for three saturation steps (plus unsaturated gray) to be discernable. Slope categories were depicted with these saturation steps; the higher the saturation, the steeper the slope. Its main advantage over Moellering and Kimerling's MKS-ASPECT™ system is that Brewer's color scheme results in a much more effective depiction of the terrain form, while still providing easily interpreted aspect information and adding three categories of slope.

An alternative use of color hue as a depth cue in terrain representation is found in Eyton's (1990) application of color chromostereopsis. As noted in the introduction to Part I, the idea of chromostereopsis (or more commonly advance-and-retreat) can be traced cartographically at least to Karl Peucker in 1898. The theory seems to have found at least partial support in research spanning the intervening decades (e.g., Eyton cites German publications on the topic as early as 1868 as well as Luckiesh, 1918; Kishto, 1965; etc.). A variety of explanations for the processes involved have been offered (see discussion of judging order above). It is uncertain, however, whether any standard layer tinting used on maps actually produces the effect (because there seem to have been no empirical cartographic tests). One problem, identified by Eyton (1990), in applying chromostereopsis to most paper maps is that the halftone processes of four-color lithographic printing will interfere with the effect. This interference is due to the fact that color appearance on lithographically printed maps results from the combination of overprinted inks and visual combination of adjacent dots.

Eyton (1990) experimented with several methods of producing the chromostereopic effect. He achieved limited success when a set of spectrally ordered colors were used on a layer tint map in which contours were created by adjacency of different colors. When he added black contours, the result (viewed as a color transparency) was said to have a "quite apparent" effect. Only an informal evaluation is offered, however, with 21 of 23 students in a cartography class claiming to see the effect. A map with black contours at double the contour interval was found to produce a weaker effect, leading Eyton to conclude that contour interval controlled the degree of depth seen. To explain the impact of the black contours, Eyton (1990, p. 23) argues that "the contour lines helped to create a rounding of the terrain form. Without contour lines the colors floated in planes; with the contour lines the display took on the appearance of a plastic surface with smooth, rounded features." An even more dramatic effect is cited for a continuous tone version of the map (in place of layer tinting). On this map, contour intervals of 200, 100, and 50 feet were compared, with the 50-foot interval producing the most dramatic effect. Eyton suggests that an explanation for the impact of contour lines on the perception of depth might be found in the fact that contour spacing is a cue to steepness of slope. This contour-enhancing effect remains to be empirically evaluated.

According to Eyton, the main problems involved in successful printing of maps using the chromostereopic effect are that standard printing changes the relative brightness of various hues (and brightness or color value interacts with the effect) and printed colors (particularly when inks are overprint or dithered) lack spectral purity. A solution proposed is to use fluorescent inks at full saturation with no overprinting. Fluorescent inks give the appearance of reflecting more light than is incident on the page. Again, Eyton provides anecdotal evidence, indicating that few students saw a fluorescent ink map as having depth, but the same map with black contours appeared to be three-dimensional to almost all the students. A final variation on the maps was obtained by adding hill shading (in gray) to the fluorescent ink maps. The added cue seemed to aid the perception of depth, but again the effect was strongest when contours were included as well.

A final depth-cue technique for static plan view maps worth noting is the "Tanaka method." Tanaka (1932) made use of shadow rather than shading (or color) to produce a sensation of depth in contour maps. The basis of the technique is to treat contours as if they represent a three-dimensional "layer-cake" model of terrain (which in a perspective view would result in a layered contour depiction of the sort discussed in Crawford and Marks, 1973). Tanaka's technique simulated the appearance of a layered contour map by putting white and black contours on a gray background. Contours toward the light source are in white with those away from the light source in black (Figure 3.74). Width of contours "varies

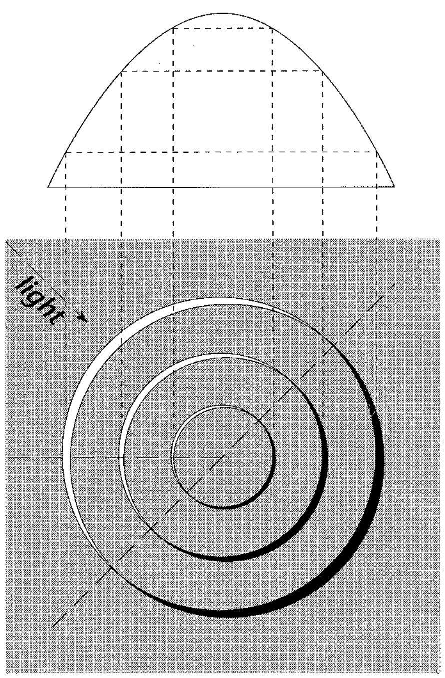

FIGURE 3.74. Representation of Tanaka's layer-cake method of terrain depiction. *After Japan Cartographers Association (1980, Fig. 4, p. 162).*

with the cosine of the angle θ between the horizontal direction of the incident ray and the normal to the contour at the point under consideration" (Japan Cartographers Association, 1980, pp. 162–163). Although the ability of Tanaka's method to provide a 3-D appearance is clear from examining a color version of a map using the Tanaka method (Japan Cartographers Association, 1980, f. 162), no empirical evaluation of the method exists nor any empirically derived guidelines on appropriate maximum widths for the variable contours.

SUMMARY

The goal of this chapter has been to provide an overview of a range of issues relevant to visual processing of maps. Perspectives from neurophysiology, psychology, cognitive science, human factors engineering, and cartography are woven together in an effort to build an understanding of how maps are seen that can serve as a framework for research on and guidelines for map symbolization and design. It is only by understanding what vision is for and its limits that we can hope to comprehend the complex process involved in "seeing" a map.

Vision has been treated as a complex information-processing system that generates a succession of "representations." At the lowest level are representations of the visual scene on the retina of the eye. These are processed by our neurological hardware through a series of stages leading toward an organization of input into a coherent description of the visual scene in a form that can be interrogated by higher level cognitive processes.

After briefly reviewing the neurophysiological hardware issues and the limits that they place on map displays, the bulk of the chapter emphasized perceptual organization and perceptual categorization and judgment—two areas that have received considerable attention in the cartographic literature of the past four decades. In terms of perceptual organization of map information, the topics of perceptual grouping, attention, visual search, and figure–ground are emphasized. Psychological, cartographic, and other research on these topics is considered in relation to Bertin's contentions about the fundamental graphic variables available for creating map symbols. Although a great deal of cartographic research of the 1960s and 1970s dealt with issues of magnitude estimation, it is now clear that other aspects of perception are more relevant to map design. In the section on perceptual categorization and judgment, the emphasis, therefore, was placed on what we know about discrimination of symbols and patterns and about the propensity of the visual system to distinguish differences in kind and differences in order, two topics that seem particularly relevant to design of interactive visualization tools. Finally,