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CHAPTER 36

THEORETICAL APPROACHES TO PERCEPTUAL ORGANIZATION

Simplicity and Likelihood Principles

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CONTENTS

1. INTRODUCTION

Our sensory receptors do not detect all aspects of the world around us. What information our receptors *do* manage to detect is integrated by the nervous system to yield perceptions of the world that are sufficiently accurate for us to identify visual objects, recognize speech sounds, and generally make our way around the world. The concept of perceptual organization is central to the key question of perception: how do we make the leap from the information detected by our sensory receptors, which some theories hold to be incomplete or at least ambiguous, to our perceptions of the world, which are typically accurate, unambiguous, and phenomenologically complete? Achieving this feat requires not just the *detection* of information from the environment but the *organization* of that information into veridical (accurate) and informative percepts.

The goals of this chapter are to describe the major theoretical approaches to perceptual organization and to present evidence relevant to these approaches. Two points should be made at the outset. First, the precise mechanisms that govern perceptual organization, and the rules by which these mechanisms operate, are not yet well understood. Second, and despite the former, the processes of perceptual organization are indispensable to understanding the pervasive fidelity (and the occasional infidelities) of human perception.

1.1. Basic Concepts

One example should demonstrate the problem. Consider the perception of an ellipse, as shown in Figure 36.1. When we view this pattern in isolation, it is usually perceived "veridically" as an ellipse drawn on paper. But when we view it in the context of a scene, as in Figure 36.1b, it is now perceived as a circle viewed at an angle. It should be clear that the elliptical pattern presented to the eye could represent either the ellipse of Figure 36.1a or a circle. In fact, the distal stimulus might even be a horizontally oriented ellipse (that is, an ellipse whose major axis is parallel to the horizontal) viewed from an extreme line of sight almost parallel to the plane of the ellipse. In any event, the decision our perceptual system makes may be based on information from the shape of the retinal projection of the stimulus, from its surrounding context, from memory about similar

Figure 36.1. The coupling of perceived shape and perceived slant. (a) An isolated ellipse; (b) the same elliptical shape in a scenic context rich with depth cues. For a variety of factors, including these depth cues and familiarity with the objects likely to occur in the scene, the elliptical shape is perceived in (b) as a round hoop oriented at an angle to the picture plane. ((b) From R. L. Gregory, *Eye and brain; The psychology of seeing* (2nd ed.). McGraw-Hill Book Co., 1972. Reprinted with permission.)

shapes seen in the past, from rules that are "wired" into our nervous systems, or from any combination of these.

Under rich, ecologically valid viewing conditions, where enough information arrives at the receptors to determine the precise identity and position of the stimulus, organizational processes are required to ensure that, for example, the various regions in the retinal mosaic are grouped together properly and the orientation of surfaces is specified accurately. But the need for organizing processes in perception is most critical when the information in the proximal stimulus (i.e., the information picked up by our receptor organs) does not sufficiently specify the distal stimulus (the object we wish to perceive). When this situation arises, the perceptual system may resort to heuristics to obtain an interpretation (or "hypothesis") regarding the distal stimulus, and no correct solution is guaranteed. Thus we must settle for what is at best an educated bet. For this reason, theories of perceptual organization must account for *errors* of perception that arise with imperfect stimulus information as well as for the cases when perception turns out to be veridical.

If conditions for perception are poor (e.g., if the viewing conditions are impoverished), no unique solution may be found; two or more equally good solutions may exist. This state of affairs is demonstrated with the Necker cube shown in Figure 36.2a. The Necker cube can be perceived with at least three different organizations: (1) as a two-dimensional design drawn on paper; (2) as a wire cube seen from above, Figure 36.2b; or (3) as a wire cube viewed from below, Figure 36.2c. Most observers (those who are aware of the alternative organizations of the stimulus; see Girgus, Rock, & Egatz, 1977) report that the Necker cube undergoes spontaneous reversals in its perceived organization, mostly between the two three-dimensional interpretations shown in Figures 36.2b and c. Such percepts that alternate between two or more distinct organizations are called *multistable* (Attneave, 1971). Theories of perceptual organization must account for some stimuli being multistable (and others not), certain organizations being preferred over others, and for the various parameters of multistability, such as the rate of perceived alternation, the role of attention, the role of familiarity with the alternative organizations, and the like.

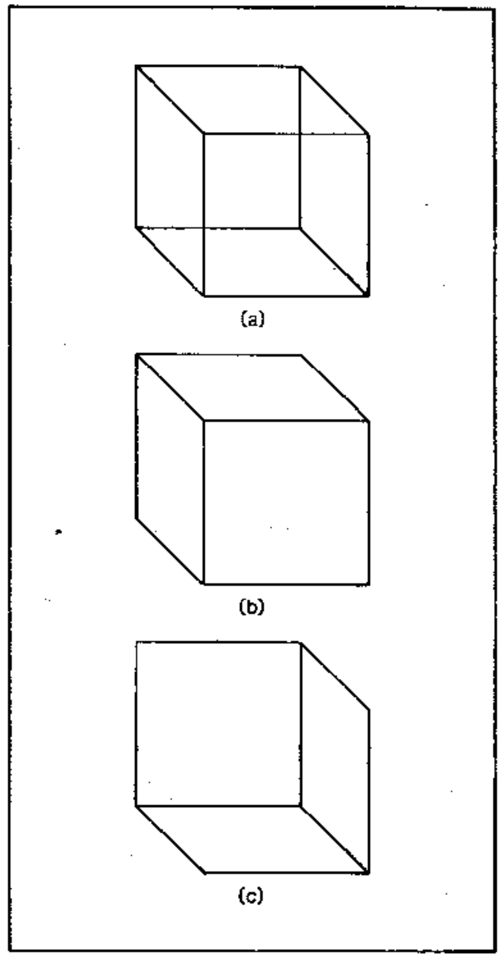


Figure 36.2. Three views of a cube. (a) The well-known Necker cube, a perspective drawing of a wire (or outline) cube. It is usually perceived in either of the two orientations shown unambiguously in (b) and (c) with solid cubes. The orientation of the Necker cube in (a) tends to change spontaneously for the observer, a phenomenon known as multistability.

The manner in which the parts of an object form a perceptual whole is another stock question facing theories of perceptual organization. Complex stimulus configurations, such as faces, are defined by the parts from which they are composed (eyes, noses, mouths, etc.) as well as by the arrangement of those parts. Similarly, simpler stimuli such as letters may be described by the arrangement of their component line segments or strokes. The organization of parts into global shapes is often assumed to be accomplished by *grouping* together subsets of parts into higher-order parts or features. Grouping can occur at several levels of hierarchy, with groups of lower-order features themselves being grouped into intermediate-level features, which are in turn grouped into higher-order features. Figure 36.3 shows some classic examples believed to illustrate what the rules of perceptual grouping might be; the putative rules themselves are discussed later in this chapter.

Theories of perceptual organization must also explain how *figure-ground segregation* is achieved in perception. The multistable stimulus shown in Figure 36.4 may be perceived as a white triangle on top of a black square that lies, in turn, on top of a white rectangle. Alternatively, it can be viewed as a black square, with a triangular hole cut out of its center, lying on top of a white rectangle. In the first case, the white triangular region is seen as a *figure* lying atop a black square, which serves as the *ground*; in the second case, the black square is seen as the figure, and both the white rectangle and the white triangular region are seen as part of the same continuous ground underlying the figure. Inspection of Figure 36.4 will show that yet other figure-ground organizations are possible.

1.2. Four Major Phenomena of Perceptual Organization

This chapter discusses theoretical approaches to perceptual organization and therefore should maintain a broad perspective on general principles. However, the only way to communicate these principles effectively is through a description of particular phenomena. At least two perils are unavoidable in this approach. The first is that the particular phenomenon we present to illustrate a general principle might prove to be a poor choice, even though the principle itself remains valid. Some of the phenomena we present are not understood thoroughly enough for anyone to proclaim them definitive illustrations of general principles. Second, it is possible that there are *no general principles* governing perceptual organization, in which case we would be left with a morass of independent phenomena, each requiring its own ad hoc explanation. If this were true, there would be

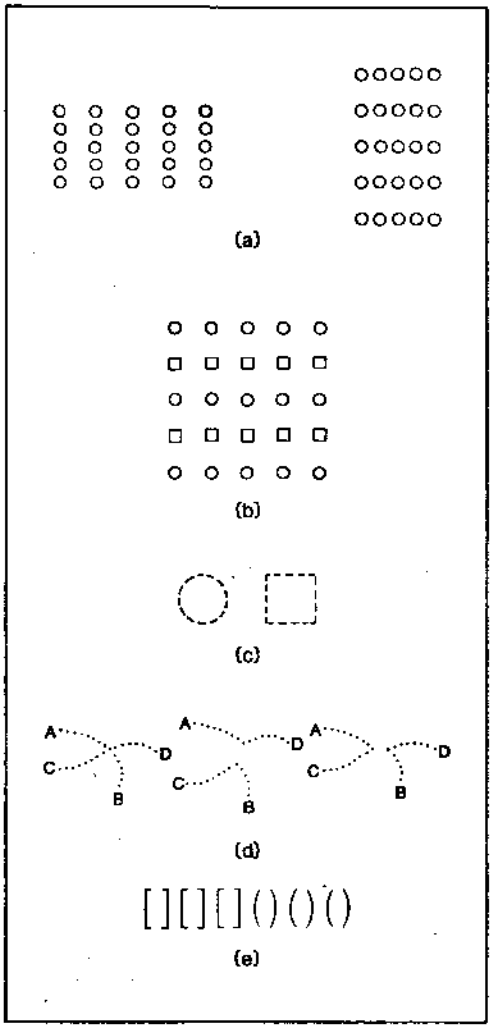


Figure 36.3. Illustration of five Gestalt principles of grouping. (a) Proximity: the dots tend to group into rows if the horizontal interdot spacing is less than the vertical. Otherwise they group into columns. (b) Similarity: the items tend to group into rows of identical shapes rather than into columns of alternating shapes. (c) Closure: when elements are arranged so they define a closed region, they will group together to form perceptually unified shapes. (d) Good continuation: elements will group so as to minimize abrupt changes in a contour's direction. Here, dots group into smoothly curving lines. At the point of intersection, the two lines of dots group such that the dots A and B belong to one line, and C and D belong to the other. The alternative groupings suggested to the right are not usually perceived. (e) Symmetry: elements will group in such as way as to maximize the symmetry of the resulting organization. We tend to organize the discrete elements into three pairs of square brackets and three pairs of parentheses. As the text indicates, there are many other laws of grouping. These laws are not inviolate, and their explanations are not entirely clear.

little need for any theoretical approach to perceptual organization as a whole; rather, an explanation for (or a mechanism capable of reproducing) each phenomenon would be sufficient. Given that this chapter is intended to discuss theoretical issues, we concentrate on evaluating correspondingly broad claims, in particular the *prägnanz* and *likelihood* principles.

The examples we have given are not an exhaustive compendium of the phenomena to be explained by theories of perceptual organization, but they do capture the breadth of the problem. We group the perceptual phenomena to be explained into four major classes.

1.2.1. The Problem of Perceptual Coupling. The shape of an image as projected onto the retina is a function of two variables: the shape of the distal object (or surface), and the orientation of the object with respect to the eye. This fact of optics creates a chicken-and-egg dilemma for perception: how can the true shape of the object be determined until its orientation is known, and how can its orientation be determined until its shape is known? It is easy to demonstrate that shape and orientation are coupled in perception. (For reviews of perceptual coupling see Epstein, 1982; Hochberg, 1981a, 1981b.) If the shape in Figure 36.1a is perceived as a circle, its perceived orientation will be different than if it is seen as an ellipse. Similarly, size and distance are coupled perceptually. Consider the ball next to the set of faces in Figure 36.5. If it is perceived to be the size of a ping-pong ball, it will be seen as nearer to the observer (and so closer in depth to one of the larger faces) than if it is perceived to be the size of a basketball. The perceived lightness of a surface and its perceived illumination are coupled as well. Given a patch of fixed luminance, the more strongly it appears to be illuminated, the darker its surface color will appear.

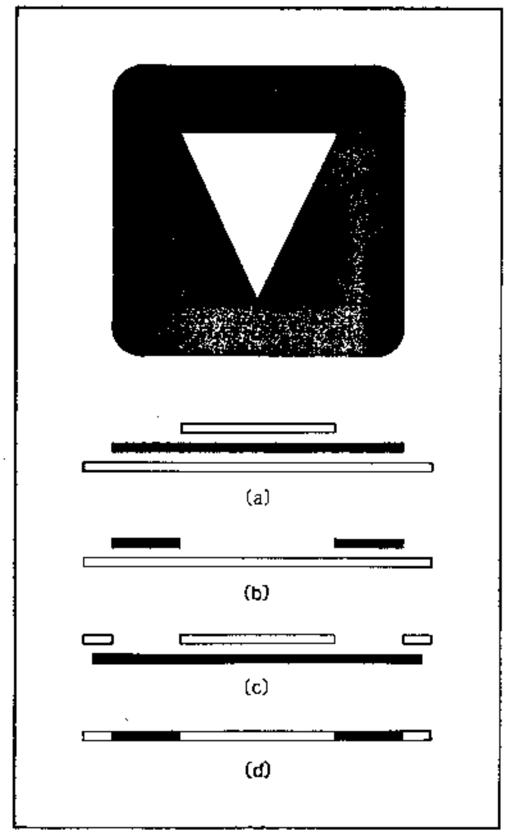


Figure 36.4. A multistable figure-ground demonstration. The pattern at the top can be perceived in several different depthful organizations, as indicated in the side views shown below. In interpretation (a), a white triangle is seen as lying on top of a black square, which in turn lies on top of the white page. In (b) the center white triangle is perceived as a hole cut through the black square; the white background of the page shows through the hole. In (c) the background is black; placed on this background are a white triangle and a large, surrounding white region with a square hole cut through. Finally, (d) shows an inlayed or mosaic interpretation, in which all regions lie in the same depth plane. All four of these interpretations are reasonable and correct. The fact that the interpretation in (a) is the one most observers prefer must be explained by the laws of figure-ground organization. (From G. A. Miller, *Psychology: The science of mental life*. Harper & Row, 1962.)

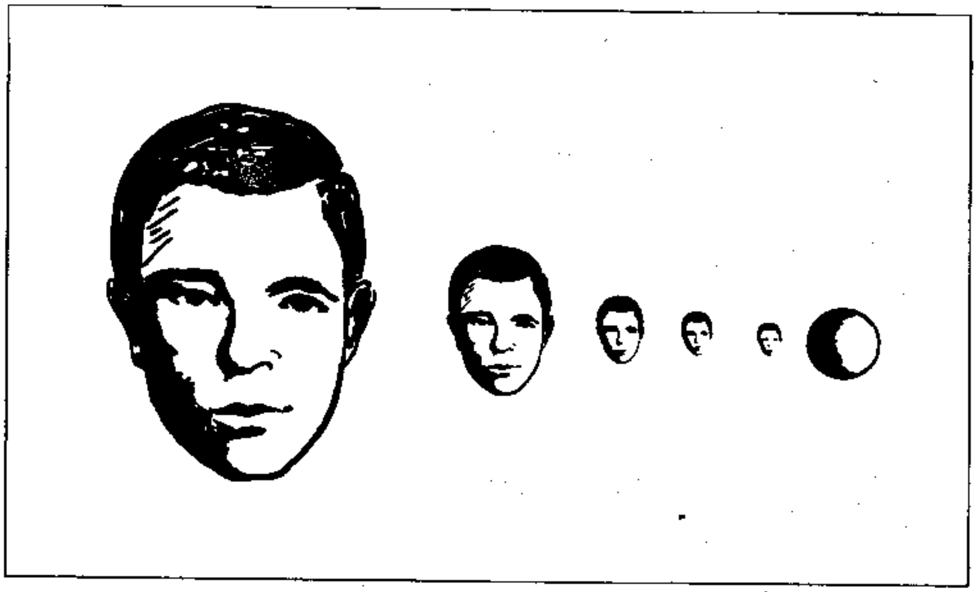


Figure 36.5. The coupling of perceived size and perceived distance. The size variations in the five faces shown make them appear to recede into depth, partly because the size of human faces is well known to observers. The ball on the right lacks any familiar size cue; it could be as small as a marble or as large as the moon. Depending on the size the observer assigns to the ball, its apparent position in depth changes. For example, if it is seen as a ping-pong ball, it will appear at about the same distance as the nearest face; if seen as the moon, it will appear behind the furthest face. (From G. A. Miller, *Psychology: The science of mental life*. Harper & Row, 1962.)

How the perceptual system achieves these couplings is the first of the four classes of problems. (See Rock, Chapter 33, Section 1.1, for arguments why coupling should be considered a problem for theories of perception in general and not of perceptual organization in particular.)

1.2.2. The Problems of Grouping and of Part-Whole Relationships. One of the enduring contributions of the Gestalt psychologists was found in their demonstrations of how the perception of a whole stimulus is different from the mere sum of its perceived parts: the organization of those parts makes further contributions to perception that can override the role of the parts considered separately. Two factors contribute to this organization (see Rock, Chapter 33): the grouping of parts into wholes, and the emergent features that arise from these wholes. (Cf. Koffka's, 1935/1963, pp. 132, 168, distinction between unit formation and shape and Metelli's, 1982, p. 223, distinction between an aggregation and a Gestalt.) The human face may be the quintessential whole, or Gestalt. It has been noted how a face may possess beauty although none of its features may be attractive; similarly, a face composed of attractive features is not guaranteed to be attractive. To take another example, consider a stimulus first investigated by Duncker (1929/1950). If a light is mounted on the rim of an otherwise unseen wheel, and the wheel is rolled across the floor, the light will be perceived (veridically) as following a cycloidal path. But if a second light is added at the hub of the wheel, the cycloidal path vanishes; the light on the rim is now perceived (again veridically) as revolving in a circular path about the hub light, as the whole wheel rolls across the floor. Thus the appearance of the whole (the constellation of lights) is quite different from the sum of the parts (the component lights) seen in isolation.

1.2.3. The Problem of Figure-Ground Organization. It is rare outside the laboratory for an isolated object to stand against a plain, unpatterned background. More frequently the eye regards a complex scene that is better described as a multitude of surfaces seen at different distances against varied backgrounds, with some surfaces occluding our view of others, casting shadows on others, and so forth (Gibson, 1979). Perceptually isolating a single object in a cluttered field is no minor accomplishment; merely deciding where one object stops and the next begins is a thorny problem in computational vision (see Barrow & Tenenbaum, Chapter 38), despite the apparent ease with which the human perceptual apparatus achieves rapid and (usually) veridical solutions. Identification of words in a speech stream poses a similar problem: in a speech spectrogram, it is not obvious to the eye where the boundaries separating the words lie. Figure 36.6 reproduces a well-known demonstration in which the visual system has difficulty determining which regions of the field are figure and which are ground. This demonstration illustrates the visual system's use of rules for deciding figure-ground assignments, rules that in this case lead to difficulty in perceiving a "hidden" but familiar stimulus (the word THE).

1.2.4. The Problem of Multistability. Multistable stimuli have played an important role in theories of perceptual organization. This is mainly because the flip-flop status of the perceived stimulus lays bare the operation of processes that are attempting to converge on a single, stable organization. Multistability implies that the rules of perceptual organization do not always impose a rigid, permanent organization on the stimulus. Instead, fluctuations in attentional processes, in the weights assigned to the various rules, or perhaps even in the neural substrates of perception can lead to changes in the perception of the stimulus. Multistable phenomena also remind us that we always perceive a single, internally consistent organization of the stimulus that does not involve compromises between the competing possibilities. Thus when we perceive the Necker cube of Figure 36.2a we experience at any instant a single, coherent

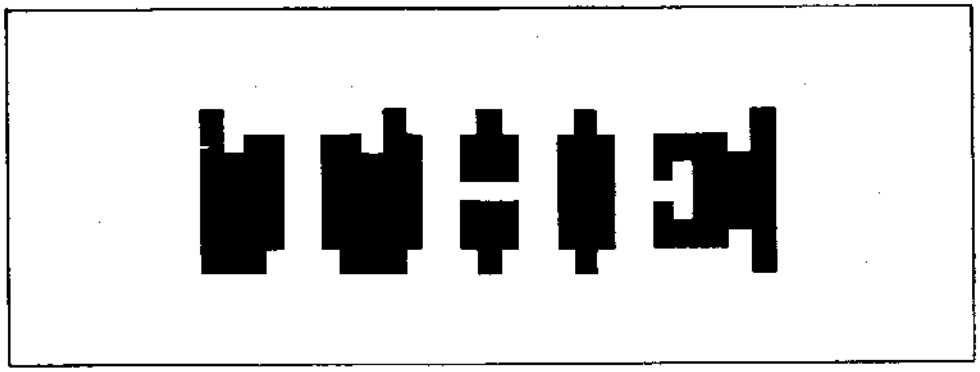


Figure 36.6. The robustness of figure-ground organizational rules. Naive observers perceive this pattern as six black rectilinear figures. If this figure-ground organization is reversed so the white spaces between the black regions are seen as figure, a common word will appear. The text describes a number of rules for figure-ground organization that make the hidden word difficult to perceive. (Adapted from G. Miller, 1962.)

organization of the stimulus rather than a jumble of organizational compromises in which one part of the pattern is seen in one three-dimensional orientation, another part is seen in an incompatible orientation, and a third part is seen as flat. This suggests that the overall organizational process is constrained to fit the stimulus into a unitary and internally consistent configuration. This idea is discussed further later.

1.3. The Central Questions Surrounding Perceptual Organization

The preceding section described four major phenomena of perceptual organization, but it presented no definition of the concept. Let us offer the following: perceptual organization is the process by which particular *relationships* among potentially separate stimulus elements (including parts, features, and dimensions) are perceived (i.e., selected from alternative relationships) and in turn guide the interpretation of those elements. These relationships can occur in space, time, frequency, and so forth (see Kubovy, 1981). Perceptual organization does *not* concern itself with the psychophysics of specific attributes such as loudness, except in cases where the perception of relationships or the effects of context arise. In sum, perceptual organization is concerned with how we process sensory information *in context.*

The principles of perceptual organization are more restrictive than the principles of perception itself. For example, there may exist stimulus properties that, although unquestionably perceptible, nonetheless play no role in perceptual organization. For example, there is little doubt that symmetry is a property of visual patterns that is often salient to the perceiver. However, it is a separate matter whether our perception is organized so as to maximize the degree of symmetry in our interpretation of the proximal stimulus. For example, in attempting to determine the orientation of an object in three-dimensional space, do we take into account the degree of symmetry associated with each potential orientation?

1.4. Distinguishing These Questions from Other Related Questions

The major focus of this chapter is on evaluating the two primary organizational principles that have some degree of plausibility. These are the principles of simplicity and likelihood. These principles suggest, respectively, that perception is organized to achieve the *simplest* or most economical interpretation of the stimulus, and that perception is organized to achieve the interpretation *most likely* to match the source of distal stimulation.

It is important to keep the distinction between these two organizational principles separate from several other distinctions. These others include the distinctions between nativism and empiricism, between "hardware" and "software," and finally between unconscious inference and direct perception.

The nativism-empiricism debate is among the most venerable and treacherous in psychology. In the words of Boring (1942), "No simple exposition of this great and largely fruitless controversy can, however, be adequate to its complexities" (p. 233). It is neither possible nor appropriate to take on that question in this chapter. However, there is an unavoidable link between the simplicity-likelihood issue and the nativism-empiricism issue. The link occurs because the principle of likelihood seems inexorably tied to an empiricist position, for what is likely in the environment must be learned. As we argue later, the internalization of these likelihoods (or ecological probabilities) could be learned ontogenetically or could be the result of phylogenetic adaptations on an evolutionary time scale. The simplicity principle is linked with a nativistic position, perhaps because the Gestaltists instantiated this principle with a model based on innate brain functions. However, organizing percepts on the basis of simplicity or economy could just as easily be a strategy learned during the organism's development. With practice, after all, humans learn to find parsimonious and elegant solutions to many sorts of problems, both intellectual and physical. The same could apply to the problem of organizing sensory data.

Our aim is to disassociate the issues of perceptual organization from the nativism-empiricism issue. These are two separate (albeit interrelated) issues. Ultimately we must determine whether the rules of perceptual organization are innate, are acquired, or (most likely) arise from some combination of these two. Where our rules come from, however, is a question for another time and place.

The second separate-but-related distinction concerns "hardware" versus "software," or (in roughly equivalent terms) whether our organizational tendencies in perception are imposed through fixed neurophysiological mechanisms or result from more flexible (and possibly voluntary) procedures. Not surprisingly, this question can become confused with the nativism-empiricism question if one assumes that neurophysiological mechanisms (hardware devices) are necessarily innately endowed and not acquired. However, there is no reason to suppose that brain mechanisms could not evolve during the lifespan of the organism. Again, we do not tackle this thorny problem in this forum; it is difficult enough to establish any broad principles of perceptual organization without at the same time taking on the question of whether these principles can be reduced to physiological mechanisms.

Finally, the distinction between unconscious inference and direct perception must be kept separate from distinctions involving principles of perceptual organization. The former contrast, discussed at length later, concerns whether perceptual interpretations are essentially inferences drawn from ambiguous stimulus information supplemented with information from memory, or whether there is enough information in the stimulus array alone to specify accurately and directly how the stimulus array should be interpreted, without need for inferences based on information stored in the perceiver's memory. The principles along which perception is organized are separate from processes (or mechanisms) that employ these principles. One could imagine, for example, an unconscious inference system striving to maximize either *likelihood* or *simplicity*. There may be some link between the unconscious-inference-direct-perception contrast and the empiricism-nativism contrast, but that is not directly relevant to principles of organization.

2. THE STRUCTURALIST, GESTALT, AND HELMHOLTZEAN APPROACHES

There have been three major approaches to perceptual organization. The first, Structuralism, denied the existence of the problem. The second, put forth by the Gestalt psychologists in reaction against the Structuralist solution, proposed that perception is organized so as to simplify the representation of the stimulus. The third approach, linked most clearly with Hermann von Helmholtz, also acknowledged the existence of the problem but held that likelihood, rather than simplicity, was the crucial factor in structuring perceptions.

2.1. The Structuralist View

In the Structuralist view no global processes are needed to integrate the component parts of a stimulus. The perceived whole is nothing other than the sum of its perceived parts. By the structuralist account, perceptual organization is not implicated in perception, except to the extent that a linear concatenation of parts (or simple sensory elements) is considered an organization of those parts. The Structuralist view holds primarily that there exist innately endowed sensory organs that relay to the brain highly specific and irreducible sensory elements (specific nerve energies, or most simply, sensations). Sensations leave enduring traces, called memory images, that can be evoked on subsequent encounters with the stimulus. Any nonlinear effects would have to be attributed to interactions of these memory images, not to elementary sensations. The brain at birth is seen as a tabula rasa, and so no specific structures exist for combining these elements into percepts, or do any preconceived links exist between sensations. Percepts instead evolve gradually over time as associations (learned by way of contiguity) link various memory images.

The main experimental tool of the Structuralists was *analytic introspection*: a "highly trained" observer would examine a stimulus closely and report verbally the primary sensory elements that stimulus evoked. The purpose of the training was to eliminate any learned interpretation of the stimulus (all associative embellishments that the stimulus might trigger) and to focus on the "pure" sensory responses engendered by the stimulus. For example, an observer asked to describe his or her perception of a red book lying on a wooden table would be admonished not to use the words "book" or "table" in describing the stimulus; instead, the book should be reported in less meaning-laden terms, such as a "reddish parallelogram," adjacent to (not "lying on") a mottled brown surface whose texture contained wavy streaks running roughly parallel to each other (not adjacent to a "table") (Köhler, 1929/1947, chap. 3; Miller, 1962). The verbal protocol resulting from such sessions formed the data base for the structuralist's explanation of perception.

2.2. The Gestalt View

The first major analysis of perceptual organization was provided by the Gestalt psychologists (most notably Koffka, Köhler, & Wertheimer), who in the first half of this century launched a counter-offensive to the then-prevailing Structuralist view. (For a review of this history see Boring, 1942.) The Gestalt view differed from the Structuralist view in almost every important feature, including the structure and function of the brain and the role of learning versus innate functions in perception. The widely heralded slogan of the Gestalt psychologists was that "the whole is more than the sum of its parts." Their claim was actually that "the whole is different from the sum of its parts," because in their view, "summing is a meaningless procedure" (Koffka, 1935/1963, p. 176; see also Pomerantz & Kubovy, 1981). However, even that rephrasing is problematic if summing is regarded as meaningless. Probably the best statement of the Gestalt view is that elementary parts or sensations interact nonlinearly in perception, whereas in the Structuralist view sensations are superimposed upon one another within a fully linear perceptual system (Kaufman, 1972).

Nevertheless, the commonly cited claim that the whole is greater than the sum of its parts correctly conveys the key notion that it is the particular *arrangement*, patterning, or organization of the parts into perceptual wholes that determines the apperance and identity of a stimulus; the mere enumeration of parts plays little (or sometimes even no) role in the appearance or identity of the stimulus. The Gestalt psychologists in no way denied the existence of parts, although that claim, as well, is often attributed to them. According to Köhler (1929/1947, p. 98), "No statement could be more misleading . . . one of the main tasks of Gestalt psychology is that of indicating the genuine rather than any fictitious parts of wholes."

The Gestalt psychologists put little weight on the role of learning in perception; learning was seen as a consequence, not as a cause of organization (see Köhler, 1929/1947, pp. 81, 158; see also Metelli, 1982, p. 228). Instead they placed the burden of perceptual organization on the innate structure of the brain. (Here we restrict our definition of learning to ontogenetic changes within an organism; later we discuss the possibility of phylogenetic adaptations.) They argued that the brain is structured to deal directly with the holistic properties of the stimulus, such as the configuration, symmetry, and closure of a visual form. Although conceding that the component parts of a stimulus can be attended to, the Gestalt psychologists argued that dismantling a stimulus into its parts is not the norm in perception and that such analysis can be achieved only through deliberate acts of scrutiny. These acts were not elaborated upon, but presumably they require unusual viewing conditions or attentional strategies, such as viewing a whole stimulus from so close a vantage point that only its details (and not its global structure) may be perceived clearly.

The Gestalt psychologists made their model of the brain's operations more concrete by borrowing from then-current notions of field theory in physics the idea that the brain could act as a volume conductor of electric currents (Köhler, 1920/1950; for a complete account see Köhler & Wallach, 1944). The brain was held to contain fields of electric currents whose topological configuration was believed to be isomorphic with perceptual experience. Koffka (1935/1963, p. 98) asserted that "Things look as they do because of the field organization to which the proximal stimulus distribution gives rise." According to the principle of brain-experience (or psychoneural) isomorphism, "all experienced order in space is a true representation of a corresponding order in the underlying dynamical context of physiological processes" (Köhler, in Boring, 1942, p. 303). Just as local perturbations in a field could alter the distribution of electric currents over great distances, so could a change in a local part of a stimulus alter the appearance of the whole stimulus pattern. Another metaphor for brain functioning is the soap bubble (Koffka, 1935/1963): applying a force to a single point on a soap bubble's surface film may produce wide-ranging distortions in the shape of the bubble. Similarly, Köhler (1929/1947, p. 77) advanced an analogy to the manner in which droplets of oil distribute themselves in a medium such as water.

2.2.1. Prägnanz. The field model of the brain was held to account for the specific characteristics (and not just the existence) of global or holistic processes in perception. According to the Gestalt view, the brain organized its representations of stimuli to make them into *better* patterns, just as a soap bubble automatically configures itself into the simplest possible form (i.e., the one that minimizes variations in surface tension and the total surface area required to contain a fixed volume; see Almgren & Taylor, 1976, and Boys, 1912/1959). Köhler (1929/1947) vowed that "Dynamic self-distribution in this sense is the kind of function which Gestalt Psychology believes to be essential in neurological and psychological theory" (p. 78). The Gestalt notion of *pattern goodness* is elaborated later, but for now we are concerned with only the claim that stimuli were organized in the way that most *simplified* their global structure. This organization rule, known as the *principle of prägnanz* (or equivalently as the *minimum principle*), is clearly the heart of the Gestaltist's view of perception. The rule of prägnanz constitutes a claim (both supported and refuted later in this chapter) that of all the alternative organizations possible for a stimulus, the organization perceived will be the one that is the simplest (or that minimizes the complexity of the stimulus, as the term minimum principle would imply). The prägnanz principle, devised originally by Wertheimer, was summarized by Koffka (1935/1963) as follows: "Psychological organization will always be as 'good' as the prevailing conditions allow. In this definition the term 'good' is undefined. It embraces such properties as regularity, symmetry, simplicity and others . . ." (p. 110).

2.2.2. Differing Conceptions of Prägnanz. Like many other concepts devised by Gestalt psychology, prägnanz has been interpreted in three different ways not entirely compatible with one another: (1) stimuli will be organized into the simplest possible configuration, even if that involves distortion of the percept with respect to the stimulus; (2) stimuli will be represented by the simplest, most economical description compatible with the physical stimulus; (3) stimuli will be organized using the simplest possible organizational mechanism.

The third interpretation can easily be dismissed. Although soap bubbles (and the like) provide a simple method for solving otherwise formidable geometric problems, this metaphor was adopted by Gestalt psychology because of the simplicity of the configurations it produces, not because of how simple those configurations are to achieve. Of course, parsimony dictates that the simplest mechanism consistent with available evidence be favored in constructing models, but that is not the point of prägnanz. Architects, biologists, and mathematicians use soap bubbles to help solve spatial problems in part because of the elegance and economy of the solutions achieved and in part because of the ease with which the solution is obtained (Schechter, 1984). Soap bubbles were used for such purposes before it was known exactly *how* soap bubbles achieve optimal spatial solutions to problems and before it was proven that they *do* do so. The prägnanz principle is a testable hypothesis that perceptions are organized so as to minimize their complexity. Our first order of business is to test this hypothesis. If it turns out to be correct, then the soap bubble should be pursued further as a possible model for how the prägnanz principle is instantiated.

The first two interpretations require a deeper analysis. The main difference between them is whether the organizational process will allow regularity to be imposed upon percepts at the expense of veridicality. It is not clear how far the Gestalt psychologists were willing to go in allowing a percept to be distorted in the interests of good configuration. On the one hand, they attempted to show how figures are altered in perception and memory in the direction of good or closed form. On the other hand, the law of prägnanz stated that psychological organization will be as good *as the prevailing conditions allow*. Even Koffka conceded that an observer, given a long, close look at an irregular form, would be unlikely to perceive it as a regular form. He did claim, however, that minor irregularities would be discarded in perception (or at least in memories of perceptions) and that even a conspicuously irregular form would be perceived primarily as a regular one with its irregularities (such as dents and protuberances) being perceived only secondarily.

Koffka (1935/1963, p. 138) distinguished between two kinds of organizing forces in perception, the external and the internal. The external forces were presumed to be retinal in origin and acted to make the neural representation veridical to the distal stimulus. The internal (or autochthonous) forces were those acting within the dynamic field of the brain, often in opposition to the external forces. Following Wulf (1922), Koffka noted that the internal forces could produce three types of distortions (1935/1963, p. 499): normalizing (distorting the representation in the direction of a familiar figure); pointing (exaggerating features of the configuration that are attended to); and most important, autonomous changes, which distort percepts in the direction of greater symmetry and better configuration. Although the evidence supporting autonomous changes is quite thin (Zusne, 1970), it is clear that Koffka allowed for some distortion or nonveridicality in both memory and perception of form. It is not clear, however, how large these distortions could become (cf. Attneave, 1982; Restle, 1982).

There is more to prägnanz than distortion aimed at achieving simplicity, however. For example, many of the Gestalt laws of grouping, illustrated in Figure 36.3 and reviewed in detail later, describe our perception of "what goes with what" in the perceptual field without necessarily entailing a distortion of our perception of the stimulus. (Coren & Girgus, 1980, found that elements in a visual array that are perceptually grouped appear to be closer together than elements that are not grouped. Although this indicates that grouping can lead to nonveridicality, the observed effect was quite small.) In view of the marginal evidence supporting the Gestalt prediction of distortion, it might prove more profitable to focus on the second interpretation of prägnanz given, namely, that stimuli will be organized in the simplest fashion possible consistent with the distal stimulus.

When the proximal stimulus fails to specify the distal stimulus uniquely, two or more interpretations may be equally possible and so be equally likely to be veridical. By the second interpretation of prägnanz, the simpler interpretation(s) should dictate the organization perceived. As we demonstrate later, the experimental evidence for this second version of prägnanz is much more favorable than for the first. But this evidence can be explained as well by the Helmholtzean as by the Gestalt approach.

2.2.3. Gestalt Methodology. The methodological sophistication of the Gestalt psychologists was comparable to that of the Structuralists, although the former group (sanctimoniously, it would seem) deplored the methods of the latter (Köhler, 1929/1947, chap. 3; Koffka, 1935/1963, chap. 3; but see Metelli, 1982, for a defense of the Gestalt scientific method). The experimental approach of the original Gestaltists, which has been improved upon in recent years, was based almost entirely on the *method of demonstration*. In this method the observer was asked to view a stimulus and to describe its apparent organization. These stimulus patterns were designed so that, in principle, a number of different and distinct organizations were possible. An example is shown in Figure 36.7a. This pattern consists of a row of equally spaced, alternating parentheses. This row could, in principle, be perceived as (1) an undifferentiated row of discrete elements that may be denoted as {1, 2, 3, 4, 5, 6}; or (2) as a row of elements perceptually grouped into pairs as {1, 2} {3, 4} {5, 6}; or (3) as grouped into the sets {1} {2, 3} {4, 5} {6}; or (4) as grouped into two sets as {1, 2, 3} {4, 5, 6}; or (5) as organized into any other possible grouping. Typically, observers report seeing the organization described under the second of the foregoing organizations. To the extent that different observers agree on the organization they report perceiving, we have evidence for rules of perceptual organization, rules that are claimed to produce the simplest possible organization of the stimulus.

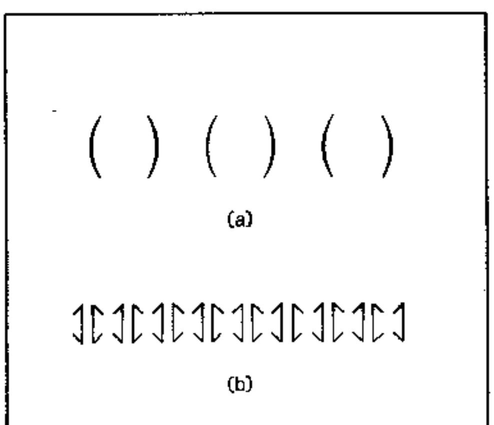


Figure 36.7. The phenomenological method applied to grouping. (a and b) The standard Gestalt demonstrational technique in which observers are asked only to view the displays and indicate how they appear to be organized. In both parts the preferred organization tends to produce pairs of adjacent elements that form closed figures. Part (b) is intended to show the factor of closure overcoming the effects of proximity and good continuation. [(b) Adapted from Koffka, 1935/1963.]

2.3. The Helmholtzean View

The third view of perceptual organization derives mainly from Helmholtz (1910/1962), although the ideas presented here come also from Hebb (1949), Hochberg (1978; 1981a), Brunswik (1956), and Gregory (1974). This view holds much in common with Structuralism; in fact, it can be thought of as an elaboration of Structuralism. The Helmholtzean view shares the Structuralist position that sensations are the starting point for perception and that sensations are combined with acquired associations (memory images) to complete the perceptual process. However, the Helmholtzean view is more flexible in that it allows the organization of sensations to extend beyond their mere concatenation. In fact Helmholtz (1910/1962) stated that "We are not in the habit of observing our sensations accurately, except as they are useful in enabling us to recognize external objects" (p. 6). Moreover, Helmholtz adds the *likelihood principle*, which states that sensory elements will be organized into the most probable object or event (distal stimulus) in the environment consistent with the sensory data (the proximal stimulus).

By the Helmholtzean view, the perceptual process acts as a problem solver assembling clues to form the most likely hypothesis that matches the facts to an acceptable goodness of fit. Although the reasoning processes involved in problem solving are often available to consciousness, perception (according to Helmholtz) proceeds by way of *unconscious inferences*. In fact, not only are the inferences of perception unavailable to consciousness, but also conscious knowledge per se does not affect perception. Our conscious knowledge that the Necker cube (a drawing on paper) is not changing has little effect on its multistable perception. Despite psychologists' concern over the *stimulus error* ("confusing our knowledge of the physical conditions of sensory experience with this experience as such"; Köhler, 1929/1947, p. 95), most organizational effects persist when the observer learns the characteristics of the true (distal) stimulus. The goal of perceptual theories is to determine what sensory evidence (clues) is available to perception and how this evidence is weighted or combined to determine what we perceive.

The Helmholtzean approach shares little with the Gestalt view save for the agreement that percepts can be organized in ways that go beyond the simple concatenation of parts. First, the Helmholtzean view places great emphasis on learning and little emphasis on the hard-wired organization of the brain (although the response characteristics of the receptors are important to this view because these determine the raw material on which perception operates). Second, Helmholtz believed that perception follows logical rules of inference not unlike those used in thought; the Gestaltists, by contrast, rejected this idea (Kanizsa & Gerbino, 1982). The third and most crucial point of contrast is Helmholtz's commitment to the likelihood principle as opposed to the Gestalt alignment with the minimum principle. Finally, the methodology underlying Helmholtzean investigations more easily allows for proper experiments (often in the psychophysical tradition) to demonstrate specific predictions, for example, regarding learning processes or the utilization of certain cues in perception; the Gestalt commitment to innate and sometimes mysterious brain processes made experimentally testable hypotheses somewhat harder to come by.

How would the Helmholtzean view accommodate the prägnanz principle, if sufficient evidence were available to support this concept? The most direct approach would be to claim that "simple" interpretations of the stimulus are in fact the most likely. This point of view was stated succinctly by Attneave (1982), who argued that "a possible distal source that contains certain regularities . . . is more probable than one that does not, or one that contains them to a lesser degree" (p. 21). That is, if, of the various possible interpretations of the proximal stimulus, one stands out as highly regular and symmetrical, then that interpretation is likely to be the veridical one. This view represents an educated guess not that the world is simple but rather that it is more likely that a detection of good configuration represents a "hit" than a "false alarm." (See Hoffman & Richards's, in press, notion of deception probability.) For how probable is it that a distal stimulus that is a poor configuration would arrive at the receptors as a proximal stimulus that could be interpreted as a good configuration? The optical transformation of a visual stimulus from distal to proximal entails distortion, but this distortion is much more likely to destroy symmetry than to create it.

2.4. The Gibsonean View

Before examining the evidence bearing on the Gestalt versus Helmholtzean approaches, it is important to acknowledge yet other views of perception that are not allied with either camp. Most prominent among these is the *direct perception* view of J. J. Gibson (1950, 1966, 1979). According to Gibson, perceptual organization is not a problem for theories of perception because our percepts are organized in a way that parallels the environment. In other words, the organization resides in the stimulus, and no special organizational processes (operating either by unconscious inference or by automatic, *autochthonous* brain forces) need be hypothesized to account for the structure of our percepts. Rather, our perceptual systems need only be tuned somehow (the precise mechanism was of no particular concern to Gibson) to pick up the structure ("affordances") of the environment from the stimulus array available at the receptors.

According to Gibson, it is only under abnormal, ecologically invalid conditions of perceiving that any contribution of the perceiver to organization manifests itself. The primary perceptual phenomena used to demonstrate such contributions (e.g., multistable stimuli) are mere laboratory contrivances that seldom occur under ecologically valid conditions. Ordinarily, information in the proximal stimulus *overdetermines* the distal stimulus; there is such a wealth of diagnostic information available to the receptors that no inferences or other mental processes are needed; normally, only one distal stimulus is commensurate with the sensory data.

One of Koffka's (1935/1963) answers to his own question, "Why do things look as they do?" was, "Because the proximal stimuli are what they are." In other words, the stimulus itself contains all the information needed to direct its organization in perception. This answer parallels the Gibsonean position that all the information necessary for veridical perception is available in the stimulus array that meets the receptor surfaces. Koffka explicitly rejected this answer on the grounds of multistable percepts, filling-in of the blind spot, and the like. Gibson's position is that the organization we perceive actually exists in the physical stimulus distribution. Köhler (1929/1947) dubbed this reasoning the "experience error," in which "certain characteristics of sensory experience are inadvertently attributed to the mosaic of stimuli" (p. 95).

Gibson has persuaded many psychologists that there is more information in the stimulus than they realized previously. In fact, some of the dilemmas of perceptual theory (e.g., which of the infinity of distal stimuli does the proximal stimulus actually indicate?) disappear under Gibson's analysis. For example, the distal shape that produces a given retinal shape can be determined from invariances picked up regarding texture gradients on the shape's surface, motion parallax produced by movements of the perceiver relative to the object, and so forth. When outline shapes drawn on paper are flashed tachistoscopically to observers, such invariances disappear, and the distal stimulus may no longer be overdetermined. Gibson (1979) conceded that under such impoverished viewing conditions, multistability may surface and cognitive factors may begin to affect perception. In sum, Gibson's most important and lasting contribution centers around his insight that there is rich information in the stimulus that may eliminate the need to resort to information from memory and to inferences to disambiguate and organize the stimulus. This emphasis on exploring useful diagnostic properties of the proximal stimulus is one major component of the computer vision approach discussed by Barrow and Tenenbaum in Chapter 38.

Granting Gibson his due, most perceptual psychologists still believe that the contribution of the observer to perceptual organization is a necessary topic of inquiry. Their reasons are many and varied, but they include at least the following five (see Gregory, 1974, pp. 273–274, Hochberg, 1978, pp. 130–131, for further reasons). First, although some of the information necessary for a veridical organization of the stimulus may reside in the stimulus itself, there is no evidence that *all* (or even most) of it is there, even under "ecologically valid" viewing conditions. The status of this claim must await more detailed investigations of the stimulus of the kind performed by Gibson himself, by Lee (1974), Shaw and Turvey (1981) and others. Second, even when the information in the stimulus is sufficient to specify the stimulus unambiguously, it must be shown that the necessary information is detectable by the observer. It is necessary but not sufficient to show only that the information is available in the proximal stimulus. Consider the case of texture information, an example drawn upon heavily by Gibson himself. As Julesz (1981) has shown, humans are not sensitive to certain "higher-order variables" of texture that are physically available and that could be used for figure-ground segregation and stimulus discrimination. Third, even if the necessary stimulus information exists and can be detected, that too does not guarantee that the information is in fact used by the observer. Granting the artificiality of laboratory viewing conditions, observers in ecologically valid situations may, in effect, impose on themselves degraded viewing conditions. That is, they may not have the time or the capacity to pick up all the detail in a rich perceptual field and so may sample the stimulus input sparingly and rely on (usually helpful) cognitive processes to organize their percepts. Extending the Helmholtzean analogy of perception as problem solving, it is well known that humans do not fully utilize all the information potentially available to them in making decisions but instead use partial information supplemented by heuristics to arrive at their decisions (Kahneman, Slovic, & Tversky, 1982). When people are performing under time pressure or are in a fatigued state, serious perceptual errors occur (e.g., errors in landing an airplane) that suggest a similar incomplete processing of the perceptual field.

Fourth, even under ecologically valid conditions, it can be shown that observers use inferences to organize their perceptions despite all the necessary information being available in the stimulus. An example is the Ames trapezoidal window, depicted in Figure 36.8. Although this "window" could be perceived directly as having a trapezoidal shape, observers apparently presume (following either the minimum or the likelihood principle) that it is rectangular. This error in turn leads to errors in the window's perceived direction of rotation. Most important, this error persists under normal, ecologically valid viewing conditions (binocular viewing, free movement of the observer relative to the stimulus, unlimited viewing time, etc.). Other illusions attributed to faulty perceptual organization are obtained under ecologically valid viewing conditions (e.g., the moon illusion; Kaufman & Rock, 1962; Restle, 1970a). Fifth, and finally, even granting that Gibson's position could successfully accommodate all of the foregoing, we must still explain how percepts are organized under impoverished viewing conditions. If our perceptions were unorganized (or amorphously organized) in these situations, we might justifiably conclude that our perceptual apparatus is not equipped to process ecologically invalid stimulation. Why, after all, should organisms have evolved to perceive under conditions that do not arise in the environment? But our percepts *are* demonstrably organized in these situations (as, for example, the Gestalt demonstrations show clearly), and so we must explain the underlying processes that achieve this organization. Such an explanation would shed light on how perception works not only under unimpoverished stimulation but also in impoverished cases that arise with information displays studied by human factors psychologists.

In sum, the point of the Gibsonean camp is well-taken: in some situations the stimulus itself may contain all the information needed for veridical perceptual organization. Nevertheless, it is both legitimate and necessary to understand the processes through which this information is picked up as well as the contribution of the observer in organizing percepts.

Therefore, the following sections focus on evaluating the relative merits of the Gestalt versus the Helmholtzean approaches to perceptual organization; they deal no further with the Gibsonean viewpoint or address such other approaches to perception as computer vision and artificial intelligence (see Barrow & Tenenbaum, Chapter 38). Our rationale is that a chapter on theoretical approaches to perceptual organization should focus on general principles by which organization proceeds; the Gestalt and Helmholtzean approaches provide the two broadest sets of principles. By denying that organization presents any theoretical problem, Gibson's position provides no principles of perceptual organization. Other approaches, such as computer vision, do address in great detail the processes required to organize a stimulus, but they do so mainly with large numbers of highly specific mechanisms difficult to describe in terms of general principles. That is, it is not clear if there is any unitary theoretical approach shared by those working in computer vision; in fact, computational theories could be constructed that embody virtually any approach to organization, including the Gestalt or the Helmholtzean approaches.

3. GESTALT VERSUS HELMHOLTZEAN APPROACHES: EVIDENCE

We have delineated three areas of contrast between the Gestalt and the Helmholtzean views, including the role of brain mechanisms that organize stimulation, the role of learning, and, most important, the prägnanz versus likelihood principles of perceptual organization.

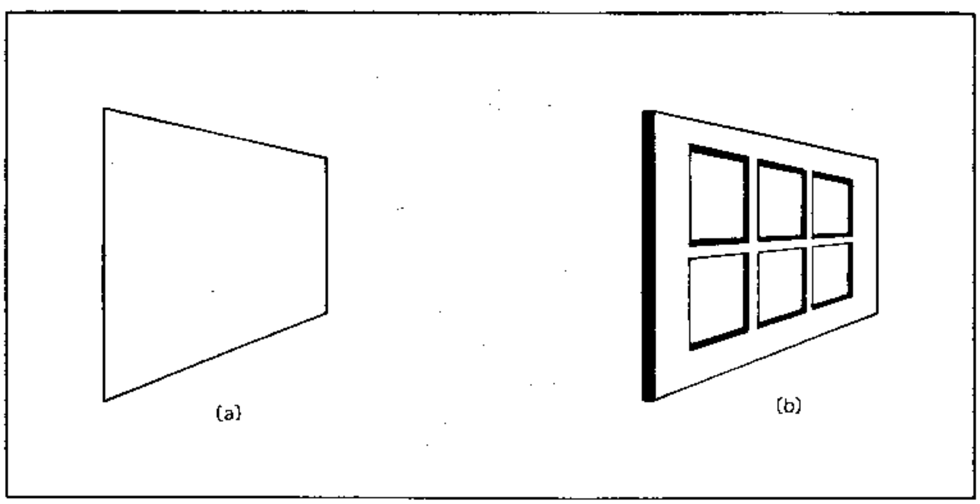


Figure 36.8. The Ames trapezoidal window. (a) The actual shape of the window as oriented perpendicular to the line of sight. (b) The window in the same orientation but with additional depth cues (of shading and linear perspective) that cause it to be perceived as a rectangular window viewed at a slant. The misperception of the window's orientation and shape leads to further misperceptions of its direction of motion when the window is rotated about its central, vertical axis. This figure illustrates the couplings that exist in perception between shape and slant and between size and distance. The figure also argues against the Gibsonean position of direct perception. (Adapted from Rock, 1975.)

3.1. Physiology

The only specific brain mechanisms proposed by the Gestaltists were readily falsified (Lashley, Chow, & Semmes, 1951; Sperry & Miner, 1955). It is now clear that although the brain is a volume conductor of electric currents, these currents are irrelevant to perception and so cannot be used as a plausible physiological mechanism for achieving prägnanz. But this specific disconfirmation cannot be taken as evidence against the general notion that the brain is somehow structured to organize stimuli automatically. The Gestaltists may merely have advocated the wrong mechanism, and so we must ensure that we do not needlessly dismiss the entire Gestaltist concept.

Neither can the Helmholtzeans claim to have won the battle about brain processes because they remained noncommittal and so avoided neurophysiological speculations that could have been falsified. Helmholtz believed that humans' perception of the color yellow was an unconscious inference from sensory data regarding the relative components of red and green in the stimulus (Hochberg, 1978, p. 106). Today, evidence exists for cells that respond directly to yellow. So what might have been a problem requiring a solution in "software" (i.e., learned methods of interpreting sensory data) turned out to have been solved in "hardware" (see Pomerantz & Kubovy, 1981; Runeson, 1977; Simon, 1978).

It could be argued that such cells represent the anatomical embodiment of a Helmholtzean unconscious inference mechanism, although we cannot say whether Helmholtz would have granted inferential capacities to single neurons. Certainly one cannot credit the Gestaltists with winning this particular battle, since the sensory mechanism that codes yellow does not in any way operate in a manner they could have anticipated. In sum, neither camp described the intrinsic organization of the brain with sufficient clarity to credit it with victory. As we discuss later, the question of which principle, prägnanz or likelihood, better describes how percepts are organized is separate from the question of whether that principle is instantiated in hardware or in software.

3.2. Learning

Regarding the role of learning in perceptual organization, the scorecard is equally indecisive. A vast and growing literature exists on the issue of learned versus innate mechanisms in perception, including the discriminative abilities of human infants, the neural effects of sensory deprivation in early development, and the response of adult observers to altered sensory input. The general conclusion from this literature (Movshon & Van Sluyters, 1981) is that although organisms are endowed innately with a powerful complement of perceptual capabilities and neuronal mechanisms, these structures require experience with stimulation to remain viable. Further, experience may alter the functions of these structures, so that their role in perception is not firmly dictated at birth. Such a finding undermines the often tacit assumption held by many (including Helmholtz, as cited in Hochberg, 1978, p. 68) that if a structure exists at birth, it must have a fixed and unmodifiable function that will be unaffected by learning.

However, disappointingly little is known about the role of learning in the *organization* of percepts, as opposed to its role in more basic perceptual processes. Many of the most critical phenomena of perceptual organization, such as the perceived fluctuations of multistable stimuli, are difficult or impossible to test with infants or with animal subjects. Newborns of many species perceive depth fairly well, and human infants seem to organize the visible spectrum into the same color categories that adults perceive (Bornstein, 1976). Certain of the categorical effects in speech perception appear to be present in humans at birth too (Eimas, Siqueland, Jusczyk, & Vigorito, 1971). It has been claimed (Bower, 1974) that infants have some capabilities for figural completion that parallel those of adults. Similarly, it has been argued (Hebb, 1949) that some rudimentary capacity for figure-ground segregation must be present from birth, for without the capability to distinguish an object from its background, the process of learning the distinctive features of objects could not begin. Infants respond to the optical expansion (looming) of an image as though the image were rushing toward them. Moreover, they seem able to determine whether the object is or is not approaching them on a collision course since they show signs of startle and distress only in the former case (Ball & Tronick, 1971; Bower, 1974).

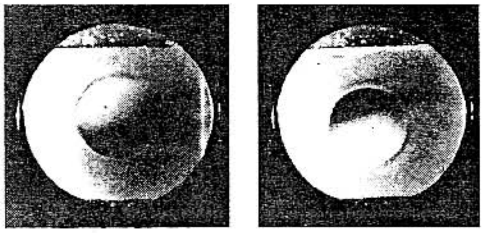
3.3. Prägnanz versus Likelihood

The main feature that distinguishes the Gestalt and Helmholtzean views is surely the opposition of the prägnanz and the likelihood principles. It is worth noting that almost 80 years ago, Mach (1906/1959) drew the same contrast between a principle of economy and a principle of probability in perception. Brunswik, who developed the likelihood principle further than anyone else, discussed this contrast and appeared to endorse the view that the two principles could co-exist and in fact reside at different, sequentially arranged stages of perceptual organization (Brunswik, 1956, pp. 133–134).

3.3.1. Physiology. In retrospect it is unfortunate that the Gestalt position linked its advocacy for prägnanz with strong claims about innately endowed brain processes underlying perception, since the issue of prägnanz is largely orthogonal to the issue of nativism versus empiricism, which in turn is at least partly orthogonal to the issue of brain processes. Humans could acquire through learning a minimum principle for perception in much the same way that problem solvers (e.g., scientists) are putatively trained to adopt the principle of parsimony in their theorizing.

The underlying neural structures that could embody a prägnanz principle are not necessarily different from or incompatible with those that could embody a likelihood principle. Although the Helmholtzean view might seem linked inexorably to brain processes that depend on neural plasticity, functionally equivalent brain mechanisms could evolve either *ontogenetically*, through learning in a single organism of what environmental stimuli are most likely, or *phylogenetically*, through evolutionary adaptation favoring organisms with a perceptual bias toward perceiving likely stimuli (see Kaufman, 1974, p. 411; Rock, 1975, p. 142).

3.3.2. Examples. For example, consider the illusion in which bumps protruding outward from surfaces can be seen either as bumps or as indentations, shown in Figure 36.9. Shading provides a critical clue that determines whether bumps or dents will be perceived. If a vertical surface is illuminated from above, the lower half of a bump will be in shade, as will the upper half of a dent; the reverse will be true, however, if the surface is illuminated from below. Although this effect could be based on an organism's learning through experience that illumination from above (as with sunshine) is more likely to occur than from below in the natural environment, chicks reared



(a) (b)

Figure 36.9. Perceived depth and the assumed direction of illumination; (a) tends to be perceived as a bump extending outward above the page, whereas (b) is seen as a dent extending inward below the page. If the figure is turned upside down, these depth relationships reverse. The effect appears to be due to an assumption within the visual system that the source of ambient illumination is from above, so that shadows are cast toward the bottom of bumps but toward the top of dents. A similar effect can be seen in photographs of craters; if the photographs are inverted, mountains will appear. (From I. Rock, *An introduction to perception*. Macmillan Publishing Co., 1975. Reprinted with permission.)

in cages illuminated only from below show the same bias (Hershberger, 1970). Evidently, organisms are biased from birth onward to presume that illumination comes from above, which suggests that natural selection has programmed an element of the likelihood principle into the nervous system. There may be a further component that is learned from perceptual experience; according to Gregory (1972, p. 185), David Brewster (1847), who discovered the present effect in the nineteenth century, showed that this bias was stronger in adults than in children. Although Brewster's finding is open to varying interpretations, even if the effect is partly learned, any innate component would show that brain mechanisms may serve as embodiments of the likelihood principle. At a minimum, this shows that the prägnanz-likelihood debate is at least partly independent of the nativism-empiricism debate.

The remainder of this section focuses on the deepest difference between the Gestalt and the Helmholtzean view, the prägnanz versus likelihood principles. The issues of brain mechanisms and nativism versus empiricism reappear periodically because of their fundamental importance in understanding perceptual organization, but the particular Gestalt positions on these issues need not be explored further.

Are human perceptions organized in a fashion that maximizes their simplicity or that maximizes their likelihood of matching a probable distal stimulus? When asked in this fashion, the question presupposes that perceptual organization follows from general principles rather than from a conglomeration of ad hoc rules. Further, it presupposes a single, overriding rule governing organization, based either on simplicity or likelihood rather than on a combination of the two. Later in this chapter we address a possible coexistence of the two. Last, the question presupposes the availability of measuring techniques for simplicity and likelihood that will allow us to confirm whether either of these two principles governs organization. Two techniques for measuring simplicity (one based on information theory and one on coding theory) are described at length in subsequent sections of this chapter. No formal measures for assessing likelihood have been proposed, except for Brunswik's concept of *ecological surveys*, in which the frequencies of occurrence of various stimulus configurations and events in the natural environment are assessed (Brunswik, 1956, p. 43). A proper and representative ecological survey would be prohibitively costly, although some less ambitious surveys could be attempted for narrow ranges of stimuli.

To illustrate the problem, consider again Ames' trapezoidal window, oriented perpendicular to the line of sight. The window itself (the distal stimulus) is trapezoidal, but it is seen as a rectangle viewed from an oblique angle. Whenever possible, observers prefer to interpret ambiguous shapes as containing only right angles (Attneave, 1972; Perkins, 1972, 1982; Shepard, 1981). Does this organization of perceived shape and orientation occur because a rectangle is perceptually *simpler* than a trapezoid, or because when the retina receives a proximal stimulus that is trapezoidal the distal stimulus is *more likely* to be a rectangle viewed from an oblique angle than a trapezoid viewed head-on? Both of these propositions are plausible, which makes it difficult to determine whether only one or both of these principles are responsible for the rectangular organization that is perceived.

In Euclidean geometry a rectangle is described more simply (with fewer parameters) than is a trapezoid. A rectangle requires only one parameter (ignoring those irrelevant to its shape, such as its size, orientation, color, etc.), which specifies its height-width ratio. A trapezoid requires three; one for its height-width ratio and two for the two angles that are free to vary. If the prägnanz principle means that the organization with the most economical description is the one perceived (Attneave, 1954), then the principle successfully accounts for the shape perceived. This notion, much simplified here, is the rationale underlying coding theory (Leeuwenberg, 1971, 1978; Restle, 1982), discussed later.

Are rectangles more common in the environment than trapezoids? This is difficult to say, since no satisfactory ecological survey has been performed. Rectangles are rarely encountered in the natural environment; they are mainly artifacts of human civilization. According to the "carpentered world" hypothesis (e.g., Segall, Campbell, & Herskovits, 1966), rectangles are in fact more commonly encountered than trapezoids, at least by the kinds of observers who participate in psychological experiments. If this assertion is correct, then the likelihood principle, too, correctly predicts our perception of a rectangle (as well as predicting that people living in cultures where rectangles are rare will more likely see the shape as trapezoidal). Note that this analysis implies a learned rather than an innate mechanism, since carpentered environments are relatively new on the time scale of evolution.

3.3.3. Globality. The trapezoid example so far has assumed that the prägnanz and likelihood principles operate on the whole shape as their unit of analysis. This appears reasonable, but smaller units could be chosen, such as the lines or angles comprising the trapezoid. As noted previously, the perceptual system may be biased toward perceiving all angles as right angles seen in perspective or all line segments (converging or diverging) as parallel. The corresponding arguments in this case would be that right angles (or parallel lines) are simpler or more probable in the environment than are their alternatives. This tack has its pros and cons. On the positive side, right angles and parallel lines are common in the environment: tree trunks grow at right angles to the ground, dropped objects fall at right angles to the horizon, and so on. Also, in the case of trapezoids, nothing is lost by shifting the locus at which these principles operate, since any trapezoid can be seen as a rectangle viewed from some vantage point; thus, the same final organization will result regardless of which level is chosen.

On the negative side, the unit of analysis should not be reduced to an overly atomistic level. Global scenes vary in simplicity and likelihood, as do the objects and patterns within the scene. Subpatterns too may have these properties, but if stimuli are reduced to their indivisible sensory elements, the organization of the elements is lost; concepts like simplicity and likelihood lose their meaning, for how can an irreducible element be complex? Brain fields and soap bubble models have been postulated specifically to account for global effects that involve whole patterns, not just local regions. Although there are some cases where our percepts are not clearly organized globally by way of either principle (as with impossible figures, discussed later), we must explain the majority of cases where organization *is* global.

The thrust of the Gestalt argument is that perceptions are organized globally to simplify maximally the representation of holistic stimulus configurations. To argue that perceptions are organized to minimize the complexity of *components* might sound distinctly anti-Gestalt. Hochberg's (1981a) recent research, discussed later, has focused on demonstrating purely local determination of perceptual organization. He argues persuasively that his findings are incompatible with the Gibsonean view, and also with the Gestalt view which he and his colleagues now refer to as the "*global* minimum principle" Peterson & Hochberg, 1983).

Still, global organization could be achieved by simplifying all of the local regions or features of the stimulus. In fact, soap bubbles work in this fashion (Attneave, 1982; see also Marr, 1982), since the simultaneous achievement of local equilibria produces the global shape of the bubble. That is, there is no executive process or homunculus that oversees the process to ensure that the final, global organization is satisfactory (see Section 4.3). When viewed this way, a local minimum principle seems less incompatible with the Gestalt position and may help the prägnanz principle explain such phenomena as impossible figures, discussed later.

4. THE GESTALT LAWS

We next consider the Gestalt "laws" of perceptual organization and explore whether they support the prägnanz over the likelihood principle. Again, we are not especially concerned with how the Gestaltists or the Helmholtzeans would implement these laws at the neurophysiological level; although the Gestalt psychologists had ideas about how this might be done for certain of the laws, for others (such as figure-ground segregation) no viable mechanism was developed. At the same time, both views involve not just one but a packet of propositions that ought to be evaluated independently. For example, the Gestalt view holds that the minimization of a form's complexity operates directly, without trial and error. Although this assumption is not logically entailed by the prägnanz principle (witness the problem solver's successive approximations to a parsimonious solution), it is so much part and parcel of the Gestalt approach that evaluating it separately from prägnanz would be difficult.

In 1933 Helson compiled a list of 114 Gestalt laws. Boring (1942) whittled them down to the 14 shown in Table 36.1. Few of them, however, are formulated with sufficient precision to allow an adequate evaluation (Garner, 1981). Consider the fifth law regarding strong and weak forms, of which Boring states, "A strong form coheres and resists disintegration by analysis into parts or by fusion with another form" (p. 253). More recent research (described by Rock, Chapter 33 and Treisman, Chapter 35) has shown that this law (among others) can be operationalized; and in fact when this has been done properly, the laws have been upheld in many cases. But at this time not all the laws in Table 36.1 would be accepted by most perceptual psychologists, nor is there to this day any uniform and agreed-upon listing of these laws.

Consider the thirteenth law concerning fusion of forms, of which Boring states, "Two forms can fuse, giving rise to a new form; or in combination, the stronger one may persist, eliminating the weaker. Simple, poorly articulated forms fuse more easily than complex, good forms" (p. 245). Here Boring links complexity with good configuration and simplicity with poor. This runs counter to the prägnanz principle and to certain information-theoretic accounts of pattern goodness (discussed later) that link simplicity with good configuration (Garner, 1970). This conflict is probably due to the original Gestalt interpretation of prägnanz as entailing both a minimum principle (emphasizing uniformity) and a maximum principle (emphasizing articulation); see Koffka (1935/1963, chap. 4) on "maximum-minimum properties."

The twelfth law, regarding meaningfulness, is described as follows: "A form tends to be meaningful and to have objectivity. The more meaningful the form, the stronger it is, the more easily it is perceived, and the longer it tends to persist." Although it is unclear what "meaningfulness" means here, the law comes perilously close to an empiricist (Helmholtzean) position, to the extent that meaning is acquired through experience. Although the Gestalt psychologists did not deny the importance of learning, they did deny it any role in shaping perceptual organizations.

Finally, some important and easily operationalized laws are missing from Boring's abbreviated list, including: *good continuation*, in which figures are organized to make the fewest changes or interruptions in straight or smoothly curving lines; *area*, in which smaller closed regions of the visual field are more likely to be seen as figure than are larger ones; *convexity*, in which convex regions are more likely to be seen as figure than are concave; *common fate*, in which elements in the field undergoing simultaneous, correlated changes are grouped to-

Table 36.1. Boring's Condensed "Laws" of Gestalten

1. Naturalness of form.
2. Figure and ground.
3. Articulation.
4. Good and poor forms.
5. Strong and weak forms.
6. Open and closed forms.
7. Dynamic basis of form.
8. Persistence of form.
9. Constancy of form.
10. Symmetry of form.
11. Integration of similars and adjacents.
12. Meaningfulness of forms.
13. Fusion of forms.
14. Transposition of forms.

These are the 14 laws that, according to Boring (1942), "represent the major contribution of Gestalt psychology." These laws deal almost exclusively with visual form. Boring credits these laws, or principles, to Wertheimer, Koffka, Köhler, Rubin, and Sander. Certain of these laws are explained in the text. (From E. C. Boring, Sensation and perception in the history of experimental psychology. *New York: Appleton-Century-Crofts, 1942, pp. 253–254. Reprinted with permission.)*

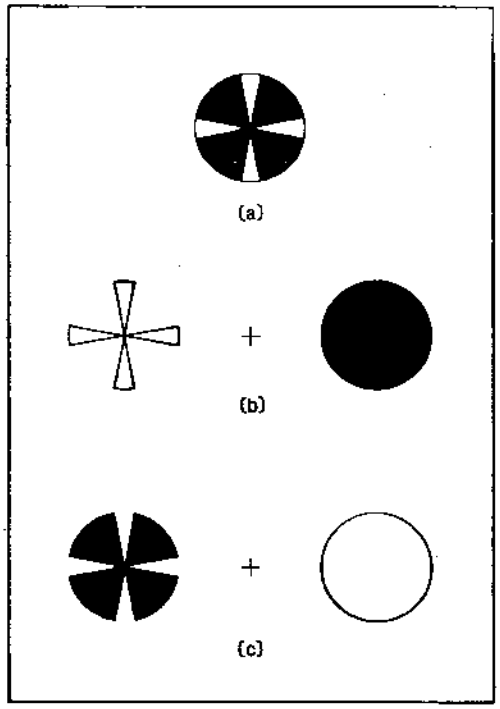


Figure 36.10. A demonstration of the Gestalt law of area. The pattern in (a) is multistable and can be organized with either the white region (b) or the black region (c) as figure. The interpretation in (b) is preferred because, according to this law, the white regions occupy less area than do the black.

gether; the notion, central to the figure-ground phenomenon, that a given contour will be seen as belonging to only one of the two regions it delineates at any one time (called by Rubin the one-sided function of contour); and the notion that the ground is perceived to continue behind the figure. It remains uncertain too whether certain key phenomena of the Gestalt school, such as apparent motion and the multistability of the Necker cube, can be predicted from this list of laws; they probably cannot without substantial elaboration.

Let us examine the Gestalt laws in some detail to see how well they fit with the prägnanz and the likelihood principles (cf. Gregory's 1974 and Hochberg's 1978 analyses). For the time being, we are concerned only with laws describing properties of the stimulus that influence perceptual organization. These include area, proximity, similarity, closure, good continuation, convexity, and symmetry. Our examples are drawn from the visual domain. For comparable phenomena in audition see Bregman (1981), Kubovy (1981), and Vicario (1982).

4.1. Area

First, consider the law of area, previously defined. This law predicts that the white regions forming a cross in Figure 36.10a will be seen as figure, lying on top of a solid black disk (b). (Which regions are white and which are black is arbitrary.) The figure could be organized as a black (Maltese) cross lying on a solid white disk (c), but this should not happen (according to this law) because the black regions occupy more area than the white. Is the predicted interpretation (b) simpler than its alternative (c)? Not in any obvious way. To be sure, there is less total stimulus area in (b) than in (c), but this should not affect complexity any more than a large square should be construed as more complex than a small one. The likelihood principle might explain the result by appealing to the manner in which occlusion occurs in the everyday world. Any opaque object can occlude our view of another object by falling in the latter's line of sight; the relative size of the two objects is irrelevant. However, it may be more often the case that the occluding object is smaller than the occluded one, as when a tree is seen against the sky, a boat is seen against the water, or a set of objects is seen lying atop a desk.

To be sure, larger objects sometimes occlude smaller objects, as when a desk partially blocks our view of a chair. Still, the largest areas in the two-dimensional proximal stimulus often correspond to the largest distal surfaces. For example, when we are seated in a room, the largest bounded regions in our visual field are often surfaces such as walls and desktops that serve as backgrounds for smaller objects lying in front of or on top of them. By definition, a ground must be extended in space (although it may be occluded). But a figure does not have to be extended; it can be arbitrarily small.

To summarize, no complete explanation for the Gestalt law of area has yet emerged. However, the phenomenon seems to have nothing to do with simplicity or prägnanz (even though prägnanz has been suggested as a unitary principle that captures the essentials of the major Gestalt laws). By contrast, it seems to be closely related to the way in which surfaces occlude one another most frequently in our visual field. A survey of the type proposed by Brunswik (1956) would be of great value in clarifying the specific frequencies; but in the absence of such a survey, it does not strike us as being overly speculative to note that small surfaces in our visual image most often correspond to figures that lie in front of larger background surfaces rather than vice versa. Thus area could be a cue, with some limited but nonetheless significant validity, that could be used probabilistically in conjunction with other sources of information to organize our percepts. Clearly this problem has not yet been resolved. But given that the area effect seems unrelated to simplicity, a solution seems more likely to arise from within the likelihood than from within the prägnanz approach.

4.2. Proximity

Second, consider the law of proximity (listed eleventh in Table 36.1). It holds that two regions are more likely to be perceived as belonging to the same form the closer they are to each other, all other factors being equal. This law is usually demonstrated with gridlike arrays of objects, first used by Schumann (1900a, 1900b; Boring, 1942, p. 248) and shown in Figure 36.11. Part

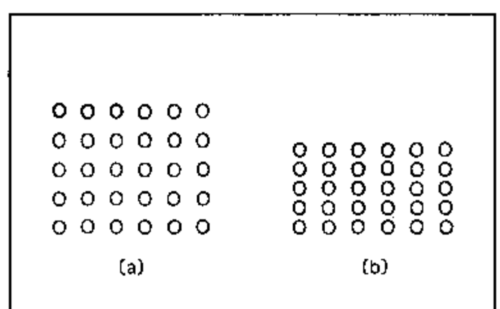


Figure 36.11. A demonstration of the Gestalt law of proximity. (a) The horizontal and vertical interdot spacings are identical, and so the display is readily perceived as grouped into either rows or columns of open circles. (b) The spacing has been altered so that a grouping into columns is more readily perceived.

(a) shows rows and columns that are spaced identically. Because proximity does not bias us to see the objects grouped into rows or columns, both organizations can readily be seen. In Figure 36.11b the spacing has been altered to bias perception toward groupings of columns rather than rows. Is our perception of column groupings in (b) simpler than the alternative row groupings would be? Again, not in any obvious way (cf. Restle, 1982).

This phenomenon might be most readily explained by a model (such as dynamic brain fields) in which neighboring foci would be more likely to interact than distant ones. (Note that it might be simpler to group nearer rather than distant objects in the sense of requiring less effort to accomplish. But the point of prägnanz is to simplify the organization achieved, not to simplify the process of achieving that organization; see Section 2.2.1.)

Alternatively, a spatial frequency model (see Ginsburg, Chapter 34), in which low spatial frequencies determine perceptual grouping, may be capable of accommodating the law of proximity. Indeed, for some theorists the existence of low spatial frequency channels in vision satisfactorily explains grouping by proximity. From the perspective of this chapter, holding forth a physiological mechanism as an explanation ignores the more central and logically prior question of how the grouping of proximal regions serves the purpose of veridical perception. To be sure, once the usefulness of such grouping has been established, a mechanism must be sought; and quite possibly many mechanisms other than low-pass filtering could perform this task. But the particular mechanism involved is secondary to the principle that mechanism subserves, and it would be a mistake to think that the presence of a mechanism automatically explains its *raison d'être*. As explained in Section 1.4, the prägnanz versus likelihood contrast is largely independent of issues concerning the hardware of the perceptual system.

The likelihood principle handles grouping by proximity merely with the claim that the regions of the visual field bounded by a single object are usually close to one another and are usually contiguous. (It might be argued that a single object need not be physically contiguous, but such an argument is specious; even dictionary definitions of the work "object" are based on appeals to human perception.) Occasionally the components of a single stimulus are not contiguous, as when an occluding tree splits a building's retinal image into two parts. Again we lack an ecological survey, but the facts of ecological optics seem clear in this particular case. The prägnanz principle makes no predictions whatsoever about proximity; by contrast, the likelihood view has at least the potential to explain the law of proximity. The same would be true, by close analogy, with the law of *similarity*, which was shown in Figure 36.3 and need not be discussed further here.

4.3. Closure

Third, the law of closure (listed sixth in Table 36.1) is described by Boring (1942) as follows: "An open form tends to change toward a certain good form. When a form has assumed stable equilibrium, it has achieved closure. Thus a nearly circular series of dots may achieve closure by being perceived as a circle" (p. 253).

Closure entails two components. First, closed or bounded regions are preferred to open regions. Second, the perceptual system fills in or closes gaps to convert open regions into closed forms. Each dot constitutes a closed form. These dots are then grouped on the basis of proximity, similarity, good continuation, and the like, and the resulting form is open. The gaps between the dots are "filled in" perceptually and so a "circle" is perceived.

A clearer example of closure might be a real circle broken by a single gap. The law predicts that this gap should be closed perceptually to achieve a fully closed figure. Yet a gap in a circle may either be closed or be accentuated in perception, depending on whether the gap is attended to (for a review, see Zusne, 1970). Because of such complications, Gestalt psychologists never reached agreement on the phenomenon of closure, and most explications of the law are vague.

The law of closure holds that with the row of parentheses shown in Figure 36.7a, adjacent elements should group into left-right parenthesis pairs (which tend toward a closed, circular configuration) rather than right-left pairs (which tend toward an open, hourglass configuration). Figure 36.7b shows a similar demonstration that controls for proximity and good continuation. The contours are not actually seen as closed: the empty spaces separating them are still visible. Rather, the contours are organized as though they were closed.

The likelihood principle handles closure as follows. Three-dimensional objects by definition are closed. Exceptions (stimuli such as the circle with the gap) are not representative of objects likely to be encountered in the environment. Unlike the figure region, the ground need not be closed. The ground often is shapeless, with its proximal shape reflecting only the regions that happen to remain unoccluded by the figures lying in front of it.

The prägnanz explanation for closure works well for Figure 36.7a because a circle is a simpler configuration (in almost any descriptive system) than an hourglass. However, most textbook demonstrations of closure help the phenomenon along by confounding closure with good configuration, good continuation, and convexity, as in the parenthesis example. To test the prägnanz account of closure, we must find whether *any* set of elements will form a simpler configuration when the elements are closed. Figure 36.12 shows a set of figures (Street, 1931) that may be used to test for closure (or "figural completion"). At a minimum, the fragments in each of the patterns of Figure 36.12 appear to form a crude whole or aggregation (Metelli, 1982); but that much would be expected on the basis of proximity and similarity alone (cf. the distinction between grouping and emergent features in Rock, Chapter 33, and in Section 1.2.2).

Does grouping (or mere aggregation) simplify the perception of these patterns as compared with the perception of ungrouped fragments? If only the global outlines of these patterns (and not the internal details) were represented in perception, clearly these outlines could be described more briefly than could the actual stimuli. Indeed, internal details are often missing from our perception of (or at least memory for) complex patterns (Rock, Halper, & Clayton, 1972). But this economy of description is achieved only at the expense of discarding potentially valuable information about the stimulus. *Any* organizational scheme could achieve an economical description by simply deleting information from the stimulus.

One measure of closure (as distinct from aggregation) is whether observers can correctly identify the objects that the fragmented images portray. For three of the four stimuli in Figure 36.12, identification is easily achieved; for the fourth, taken from Attneave (1967), it is not. Thus we can say that closure is achieved for three of the patterns, but only aggregation, not closure, occurs for the fourth. The three that do show closure do not become simpler in any geometric sense; that is, they are

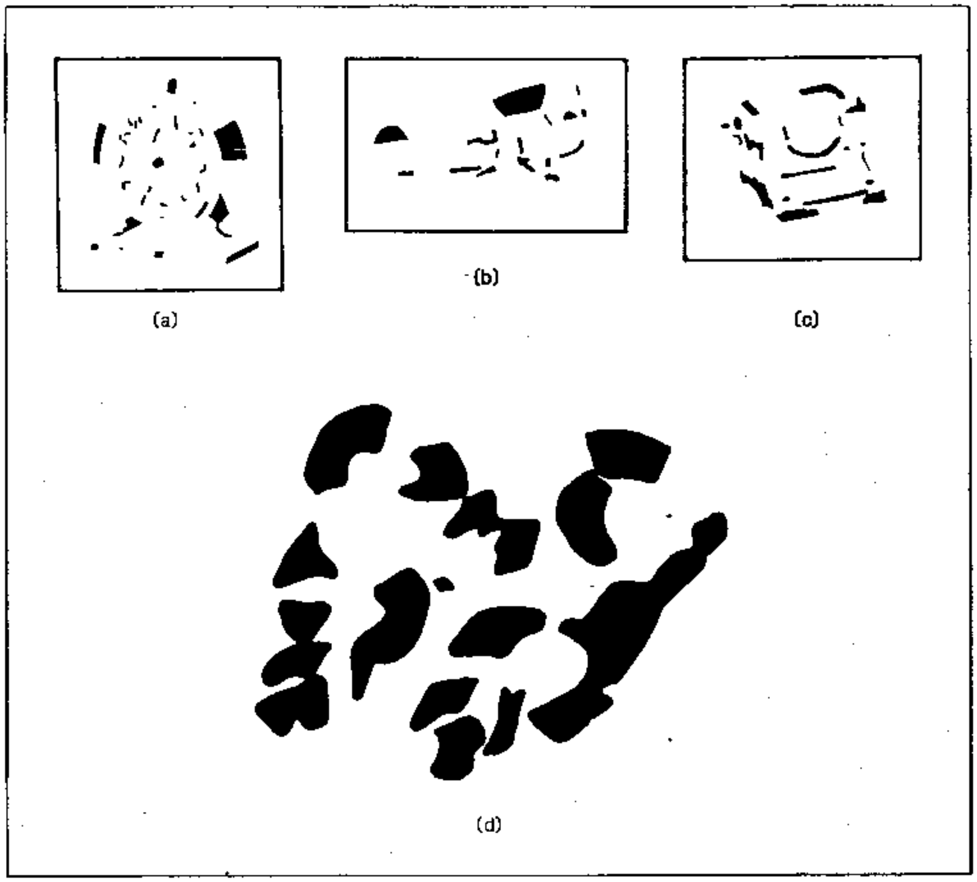


Figure 36.12. The Street figures. With a little effort, the scattered black patches of (a), (b), and (c) can be closed perceptually to reveal familiar (albeit somewhat dated) depictions of a fan, an airplane, and a typewriter. Closure is difficult if not impossible to achieve in (d). [From R. Leeper, A study of a neglected portion of the field of learning—The development of sensory organization. *Journal of Genetic Psychology*, 1935, *46*. Reprinted with permission of the Helen Dwight Reid Educational Foundation. And (a–c) from R. F. Street, *A Gestalt completion test: A study of a cross section of intellect*. AMS Press, 1931. Reprinted with permission. (d) From F. Attneave, Criteria for a tenable theory of form perception. In W. Wathen-Dunn (Ed.), *Models for the perception of speech and visual form*. M.I.T. Press, 1967. Reprinted with permission.]

not like the Ames trapezoid, which becomes more regular when seen as a rectangle. They become "simpler" only in the sense that they can be matched into learned perceptual categories. The situation is in some ways analogous to a string of letters seeming simpler when the letters spell a familiar English word, but this simplification will be enjoyed only by a perceiver who has learned English.

In summary, closure is among the weakest and most vague of the Gestalt laws. To date, we lack any robust demonstration of closure that is free from confounded effects of other Gestalt laws. However, what few phenomena that do exist and that do appear to result from the law of closure seem better explained by the likelihood principle than by prägnanz.

4.4. Good Continuation

Fourth, consider the law of good continuation, which is absent from Table 36.1 but is demonstrated in Figure 36.13. The X-shaped pattern in (a) is usually perceived as two wavy diagonal lines that cross, not as two V-shaped patterns that happen to be abutted at their vertices. Good continuation is an important factor in hidden figures (Gottschaldt, 1926) and other forms of camouflage, as with the hidden digit 5 in (b). It is a powerful law that can easily override the law of closure as in (c), where a sine wave is seen as superimposed on a square wave; closure would predict that we should see the organization shown in (d) (Hochberg, 1978, p. 138). In fact, good continuation, coupled with interposition cues for depth (discussed later) can lead to closure, as is demonstrated with Bregman's (1981) B's in Figure 36.14. The block letter B's are difficult to perceive in (a), but when occlusion information is added in the form of an amorphous ink blot, the collinearity of the B's contours precipitates rapid closure. Figure 36.13*e*, taken from Kanizsa (1979, p. 101), shows five separate crosses. When they are made contiguous at their vertices in (f), the cross becomes harder to perceive. A centrally located square becomes perceptually prominent and is seen as superimposed on the four odd-shaped block figures in the corners. Although the stimulus as a whole retains its global symmetry with this new organization, its regularity or simplicity is diminished; one no longer sees five identical and symmetrical crosses. Thus this figure demonstrates the power of good continuation overriding symmetry in determining perceptual organization.

The prägnanz explanation of good continuation is straightforward: a line or contour whose direction remains constant through an intersection can be described more simply than one

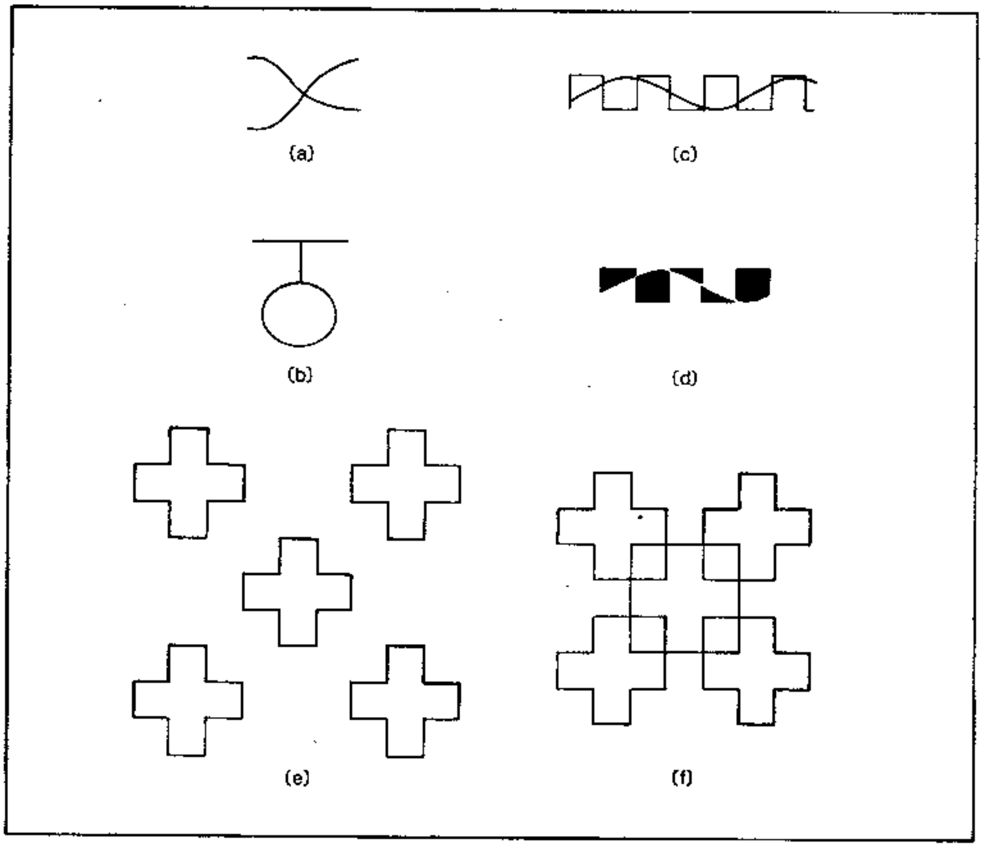


Figure 36.13. Demonstrations of the Gestalt law of good continuation. In (a) the observer is more likely to perceive two smoothly curved lines that cross than to perceive lines containing sharp bends or four lines meeting at a central point. (b) How good continuation can be used to camouflage a familiar figure (the digit 5). (c) Good continuation overcoming closure; the pattern is seen as a sine wave superimposed on a square wave, rather than as a set of adjacent, closed figures as suggested in (d). (e, f) How good continuation can overpower other organizational laws: in (f) the five crosses of (e) have been brought together so they touch each other at their vertices; as a result, the symmetric and identical crosses are no longer seen as primary perceptual units. (From G. Kanizsa, *Organization in vision*. Copyright 1979 by Gaetano Kanizsa. Reprinted with permission of Praeger Publishers.)

whose direction changes or than one that terminates at the intersection and is replaced by another line or contour. Note that in this account prägnanz is applied at a local level, namely, the intersection of lines or contours, with little regard for the consequences at more global levels, as we saw with Kanizsa's crosses. Thus this explanation runs counter to the Gestalt view because prägnanz is supposed to operate at a global level.

The likelihood principle explains good continuation as follows. Given the lines that cross in Figure 36.13a, it is far more likely that the distal stimulus is actually two wavy yet roughly straight lines (or cracks or strings) that intersect than two wavy, V-shaped strings that (1) just happen to have spatially coincident vertices and (2) just happen to be oriented so that the contours of the different strings are roughly collinear at the intersection. To accept both of these coincidences simultaneously would exceed the limits of reasonable doubt.

Figure 36.15 (Kanizsa, 1979, p. 103) appears to demonstrate good continuation even though none of the lines maintains its precise direction through the intersections. Observers tend to organize the pattern in (a) into the two overlapping figures shown in (b) rather than into the two abutting figures in (c). The law of good continuation might be rephrased accordingly to state that when two lines intersect, each continues through the intersection along the path that requires the *smallest change of direction*. However, this reformulation does not favor either prägnanz or likelihood. Given that a line changes its direction abruptly at an intersection, why would a smaller change be simpler than a larger one? Clearly *no* change represents a major simplification, but it is less clear that a change of 60° is more complex geometrically than one of 10°.

How would likelihood handle the smallest-change-of-direction rule for good continuation? Are smaller changes of angle more likely in the environment? The burden of proof falls on the Helmholtzeans to demonstrate this in an ecological survey.

A more promising explanation would claim that Figure 36.15 has nothing to do with good continuation but instead is a demonstration of the law of convexity (in the next section). This law states that convex regions of the field are more likely to be seen as figure than are concave ones. An example is given in Figure 36.16, which is usually seen as a disk on top of a square. Alternatively, it could be seen with the square as figure, containing a round hole (i.e., as a nut), but this is less frequent. Convexity, rather than good continuation, could explain why Figure 36.15a is organized as in part (b) rather than (c), since one of the two component figures in (c) has a substantial concave component.

Thus the law of good continuation need not be modified to include a bias for perceiving small changes of direction over large changes, at least not given the evidence now available. The law need state only that no change is preferred over change. Both the prägnanz and the likelihood principles can handle this law satisfactorily. This in no way implies that both principles are correct; it merely indicates that no experimental method has yet been devised that discriminates between the two principles on this score.

4.5. Convexity

Fifth, what can be said about the law of convexity, which appears to account for Figure 36.15? This law seems to apply only in the plane perpendicular to the line of sight, not in depth, since otherwise we would see dents in surfaces as bumps (holding constant the direction of illumination). The law is further demonstrated in Figure 36.17 (Kanizsa, 1979, p. 112) which shows that convexity is powerful enough even to override the effects of symmetry (Section 4.6). Thus we see the dark, asymmetric regions as figure rather than the light, symmetric ones, because

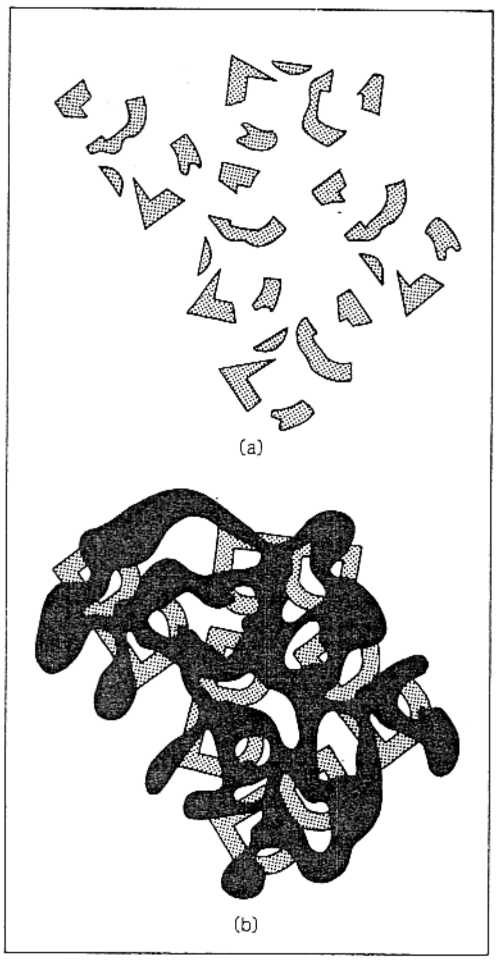


Figure 36.14. Bregman's B's. (a) A seemingly random scattering of irregular shapes that fail to group into meaningful configurations. (b) These same fragments are left intact but an amorphous blob is added that provides clues to occlusion. As a result, it becomes fairly easy to perceive the five B's. This figure thus demonstrates the role of good continuation and of interposition cues in grouping. (From A. S. Bregman, Asking the "What for" question in auditory perception. In M. Kubovy & J. R. Pomerantz (Eds.), *Perceptual organization*. Lawrence Erlbaum Associates, 1981. Reprinted with permission.)

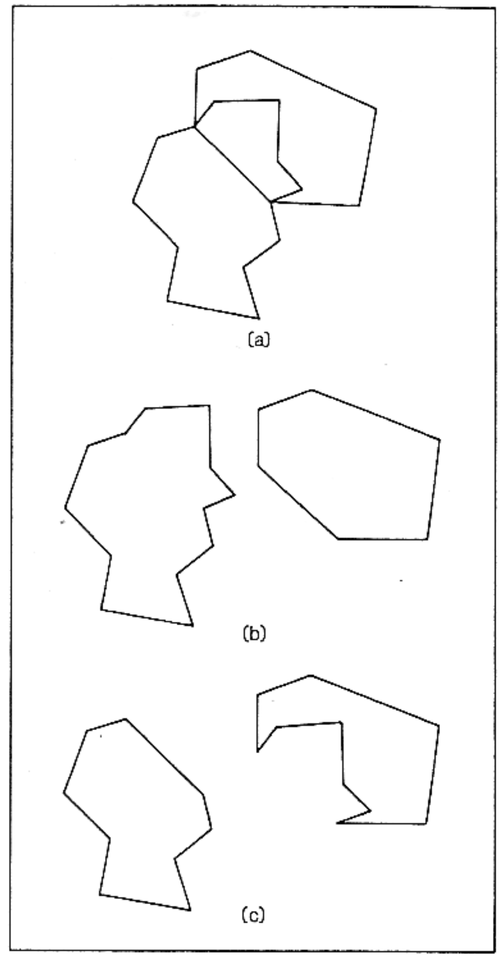


Figure 36.15. Good continuation or convexity? The pattern in (a) is perceptually organized as two superimposed figures as in (b) or, less often, as two figures contiguous at their vertices (c). Although the figure might seem to be a demonstration of the law of good continuation, it is probably a demonstration of the law of convexity, as explained in the text. (From G. Kanizsa, *Organization in vision*. Copyright 1979 by Gaetano Kanizsa. Reprinted with permission of Praeger Publishers.)

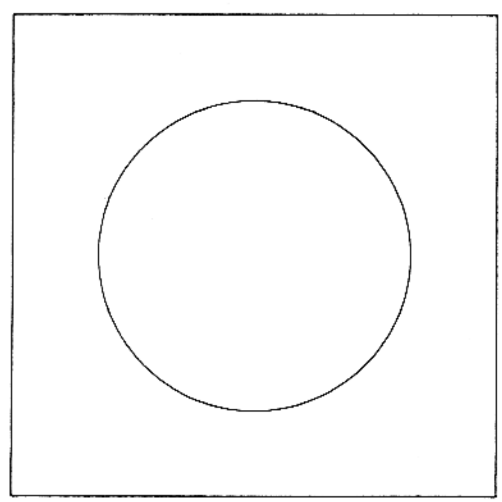


Figure 36.16. A demonstration of the Gestalt law of convexity. This figure is most often perceived as a circle inside of or on top of a square. Alternatively, it could be seen as a square with a circular hole (e.g., a square bolt), but this would require perceiving the circular contour as concave rather than convex.

Figure 36.17. A demonstration of the Gestalt law of convexity prevailing over the law of symmetry. Although the white regions define symmetrical figures, the black regions are more often perceived as figure. Thus the law of symmetry, which has been regarded as the most central to the Gestalt principle of prägnanz, has less effect on perceptual organization than the law of convexity, which is unrelated to prägnanz. (From G. Kanizsa, *Organization in vision.* Copyright 1979 by Gaetano Kanizsa. Reprinted with permission of Praeger Publishers.)

the former are convex whereas the latter are concave. (Note that the areas of the two regions have been equated so the law of area cannot explain the effect; neither does it matter which regions are dark and which are light.) The prägnanz principle would appear hard-pressed to explain the perception of Figure 36.17: the less-favored organization involving symmetrical figures is clearly simpler than the favored one because symmetrical figures are simpler than asymmetric ones.

The likelihood principle fares better than prägnanz with the law of convexity. No ecological survey is required to show that convex edges are more common in the environment than concave ones. Many natural stimuli (the moon, an orange, a smooth stone, etc.) are completely convex, but few if any objects are totally concave. Figure 36.18a shows a figure that is almost fully concave; it resembles little that occurs in nature, save perhaps for a starfish. Moreover, this figure is convex in a net, global sense (in that the figure, not the ground, is on the inside of the contour), although locally it is always concave. Figure 36.18b shows that this shape can readily be seen as figure against a circular background. This suggests that the law of convexity applies to global, not just to local regions, since otherwise the cusped shape should appear as ground. Apertures in surfaces such as a slice of Swiss cheese produce large amounts of concave contour, but even here the outermost contour is usually convex and may be longer than the inner, concave contours. In sum, the law of convexity is not explained well by prägnanz; the likelihood principle provides a more plausible account.

4.6. Symmetry

Sixth and last, consider the law of symmetry, listed tenth in Table 36.1. Boring's (1942) description reads as follows: "A form tends toward symmetry, balance, and proportion. Many of the geometrical 'illusions' illustrate this principle" (p. 254). Beyond this, we may add that, according to this law, elements are likely to group if they are arrayed symmetrically, and symmetrical regions of the field tend to be perceived as figure. Symmetry is a key element in pattern goodness (Garner, 1970); further, there may be specialized detector systems in the nervous system that register symmetry directly (Julesz, 1971). Symmetry exists in a variety of forms distinguished by mathematicians, including axial (symmetry about an axis), rotational (a form can be rotated into itself), and translational (a form is repeated in the visual field). These three classes are not all equally conspicuous to perception (e.g., axial symmetry is more readily detected than translational), nor are the effects of symmetry constant within a class (symmetry is more readily noticed about vertical and horizontal rather than oblique axes, as noted by Mach, 1906/1959 and Rock, 1975).

The law of symmetry is usually demonstrated with stimuli containing alternating symmetric and asymmetric columns. Such figures were first devised by Bahnsen (1928), a student of Rubin (as cited in Kanizsa, 1979, p. 108). An example is shown in Figure 36.19 (Rock, 1975, p. 263) in which the white and black columns have been equated for area, convexity, and other potentially confounding factors. In both panels of this figure, the symmetrical columns tend to be seen as figure, with the asymmetrical ones constituting the ground.

Although symmetry is usually regarded as a preeminent law of organization that stems directly from prägnanz (Koffka, 1935/1963, p. 195), it can be overpowered by other laws, such as convexity and good continuation in Figure 36.20a and b (from Kanizsa, 1979, p. 100). These demonstrations serve as much to reveal the power of good continuation and convexity as to downplay the importance of symmetry. In both cases we perceive two overlapping, asymmetrical figures rather than two abutted, symmetrical ones. The same holds true in Figure 36.21 (Kanizsa, 1979, p. 96, Fig. 5.3c) where a square is perceived as occluding a less symmetrical object rather than dovetailing with a more symmetrical one. Of course all the Gestalt laws refer to tendencies, not absolutes, and they apply only within certain boundary conditions. However, the fact that symmetry

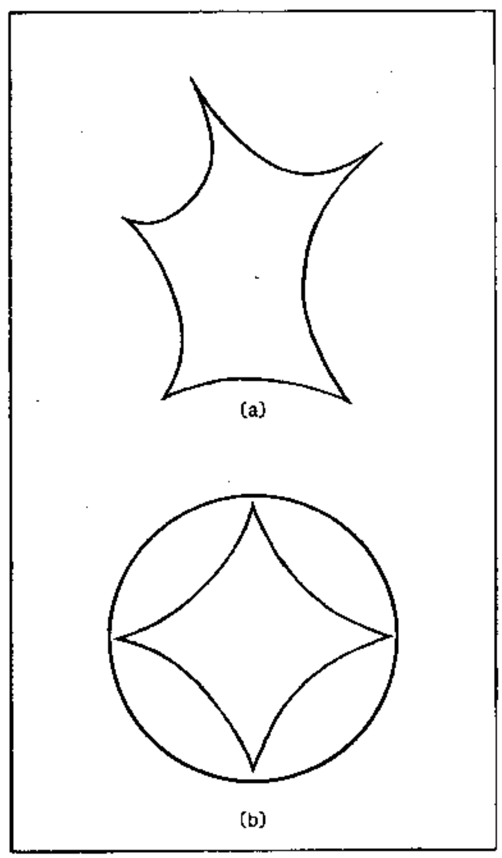
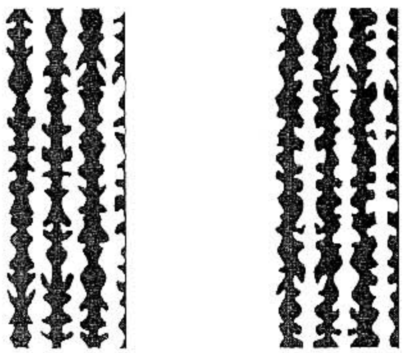


Figure 36.18. Convexity and figure-ground organization. (a) A figure whose perimeter is concave at almost every point. (b) An ambiguous figure: it can be seen as concave, a cuspal figure surrounded by or superimposed on a circle, or as a circle containing a concave hole whose contours are convex at almost every point. The former interpretation is at least as common as the latter, which puts constraints on the convexity principle.



(a) (b)

Figure 36.19. The Bahnsen columns. Although the black columns and the white columns have been equated for area and convexity, the symmetrical columns, black in (a) and white in (b), tend to be seen as figure. This is the most powerful demonstration that exists for the role of symmetry in perceptual organization. (From P. Bahnsen, Eine Untersuchung über Symmetrie und Asymmetrie bei visuellen Wahrnehmungen. *Zeitschrift fur Psychologie*, 1928, *108*. Reprinted with permission of Johann Ambrosius Barth.)

is so easily overcome indicates that it is less important an organizational principle than has been believed.

In Figure 36.22a, from Rock and Leaman (1963), symmetry fails to make its presence known as a factor in perceptual organization. This shape is often perceived as asymmetric even though it is symmetrical about two oblique axes. Figure 36.22b and c, modified from Attneave (1982), shows a related example: (b) tends to be seen as a nearly random distribution of eight dots; (c) shows symmetry *could* be perceived if the dots were interpreted as lying on an oblique plane in three-dimensional space. If the rules of organization placed much weight on discovering an organization that maximizes symmetry, then the symmetric interpretations of (a) and (b) might be easier to achieve than they are. If the perceptual system *is* searching for symmetry, it gives up rather quickly.

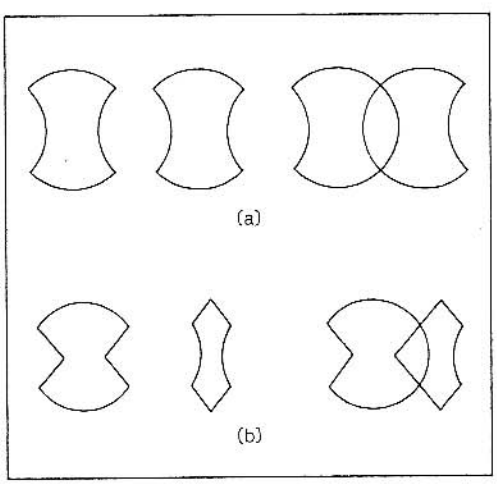


Figure 36.20. A further demonstration of the weakness of the Gestalt law of symmetry. In both (a) and (b) two symmetric figures are superimposed. In each case the composite is organized into two overlapping, asymmetric figures rather than as two abutted, symmetric ones, presumably because of the factors of good continuation and convexity. (From G. Kanizsa, *Organization in vision*. Copyright 1979 by Gaetano Kanizsa. Reprinted with permission of Praeger Publishers.)

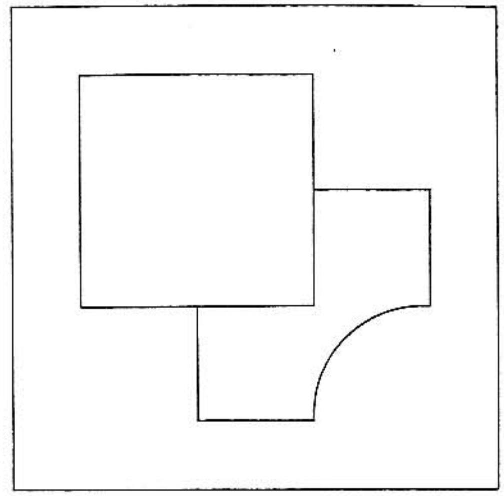


Figure 36.21. Kanizsa's amodal completion phenomenon. This stimulus is usually perceived as a square that is partially occluding a second shape. In addition, observers generally have biases about the shape of the occluded part of the figure; that is, the second figure is amodally completed. With this stimulus, subjects do not complete the second figure in a symmetrical fashion, although this would be possible and is predicted by the prägnanz principle. (From G. Kanizsa, *Organization in vision*. Copyright 1979 by Gaetano Kanizsa. Reprinted with permission of Praeger Publishers.)

Before we interpret symmetry in the light of prägnanz and likelihood, let us note that despite the demonstrations of Kanizsa and Attneave, symmetry is undeniably a salient property of forms and textures (Julesz, 1971; Palmer, 1982; Perkins, 1982; Royer, 1981; see also the discussion of pattern goodness in Section 7.4). Indeed, Palmer, Julesz, and others have formulated models to account for the ease with which symmetry is often detected. On the other hand, Uttal (1975) has demonstrated that symmetry has no role in the detection of dot patterns embedded in dynamic, random dot noise. In any case, the fact that perceivers are adept at detecting symmetry does not imply that symmetry has a major (or even any) role in determining perceptual organization. The same holds true of other properties like coplanarity, rectangularity, and familiarity. This is a subtle but important point that has not been adequately recognized in the literature, so let us elaborate.

Flicker is an extremely salient property of visual stimuli, so much that it is frequently used as an attention-capturing device in visual information displays. Also, flicker can affect the appearance of spatial patterns (see Watson, Chapter 6). Yet to our knowledge, flicker has never been proposed as an organizational factor in vision. It may well be an important organizing factor; but we have chosen it because it has not been proposed as such despite its great perceptual salience. Perhaps flickering elements tend to be grouped into perceptual wholes, but that cannot be taken for granted without empirical evidence demonstrating that it is true and delineating any additional constraints that must be met for such grouping to occur (e.g., common flicker frequencies, phase relationships, or duty cycles). This argument parallels one made by the Gestalt psychologists (and others) about the role of learning in perception. For example, Kanizsa & Gerbino (1982) note that, "the importance of past experience in the interpretation of perceptual data does not legitimize its use as an explicative principle regarding the processes at the basis of the formation of the data themselves" (p. 187).

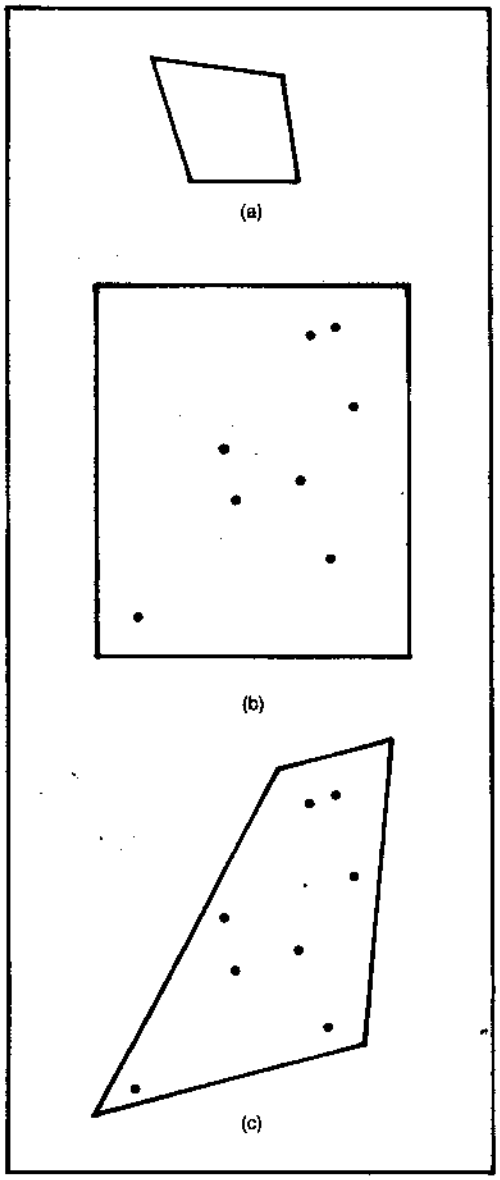


Figure 36.22. Symmetry and orientation. (a) A shape whose symmetry often goes undetected. (b) Dots, usually perceived as a nearly random scattering lying on a surface oriented perpendicular to the line of sight. The scattering could, however, be interpreted as symmetric (about one axis) but viewed at a slant, as indicated in (c) with the help of a reference frame. The latter organization is difficult to achieve in (b), indicating that percepts are not organized spatially to maximize symmetry. (From F. Attneave, Prägnanz and soap bubble systems: A theoretical exploration. In J. Beck (Ed.), *Organization and representation in perception*. Lawrence Erlbaum Associates, 1982. Reprinted with permission.)

The demonstrations of Kanizsa and of Attneave appear to indicate that symmetry will be a detectable property of visual configurations only if symmetry exists in the perceptual units carved out on the basis of other factors besides symmetry. Thus symmetry (like familiarity) may become important only *after* the perceptual organization of the stimulus has been determined.

It is important to note how different this view of symmetry is from other interpretations, such as the soap-bubble concept that symmetry is actively imposed on perceptual organizations, or the notion that the perceptual system actively hunts for a veridical description of the distal stimulus pattern that includes symmetry. The demonstrations just cited are not favorable to either of the latter two explanations. But even if a bias did exist that favored symmetric over asymmetric descriptions of the stimulus, that bias could be accommodated at least as well by the likelihood principle as by prägnanz. Attneave (1982) noted that, "for a given retinal pattern, a possible distal source that contains certain regularities . . . is more probable than one that does not" (p. 21). That is, if one possible interpretation of a proximal stimulus manifests symmetry, it is most likely this interpretation is correct, because it is highly improbable that an asymmetric distal stimulus would lead to a proximal stimulus that could be organized symmetrically without distortion.

Kanizsa (1979) has expressed concern that the effects of symmetry (and of geometric regularity in general) are so easily overridden by other factors in determining perceptual grouping (see Figures 36.20, 36.21, and 36.22). Indeed, the very demonstrations most often summoned to illustrate the law of symmetry are frequently marred by an inadvertent confounding of the effects of convexity or area with those of symmetry; the result has been an exaggeration of symmetry's apparent role in organization. This bias led Kanizsa to conclude, "Although it may be doubtful that there is a tendency to maximum regularity in our perceptual system, it is probable that a 'tendency toward the selection of a regular figure' exists on the part of gestalt psychologists when a perceptual law is being illustrated" (p. 110).

Kanizsa's skepticism is justified. The demonstrable vulnerability of symmetry to domination by other factors forces us to question whether symmetry is as important to organization as traditionally has been believed. However, it does not force us to dismiss symmetry altogether: the Bahnsen columns of Figure 36.19 show symmetry determining perceptual organization when other confounding factors (such as area or convexity) are eliminated. Perhaps symmetry tips the scales of organization only when other, more potent factors are completely balanced and so favor none of the competing organizations.

In any event, the Bahnsen columns *do* show an effect of symmetry in its own right, and so the prägnanz versus likelihood explanations of this phenomenon must be contrasted. The prägnanz explanation is quite straightforward because symmetry is the quintessence of simplicity: having specified one component of a symmetric figure, the remaining components need not be reiterated. The asymmetric columns in Bahnsen's figures need not be represented in perception. The symmetric figure occludes the asymmetric ground, and, as Rubin argued, the ground has no contours or shape of its own but merely continues behind the figure.

Although symmetrical figures abound in the natural environment (as with snowflakes, leaves, faces, etc.), so do asymmetric ones (uneven terrain, jagged rocks, winding streams, etc.), and many natural scenes lack any symmetry whatsoever. An ecological survey would help to resolve the likelihood question, but it is probable that asymmetric objects are more frequently encountered in the environment than symmetric ones. In that case, the prägnanz principle might appear to have prevailed over likelihood in best accounting for symmetry. However as we have noted, if a symmetrical interpretation can be found for a stimulus, it is likely to be a correct interpretation, and so in this fashion the likelihood principle can accommodate the effects of symmetry on perceptual organization (which, as we have seen, are not particularly strong) as well as can prägnanz.

We return to the effects of symmetry in this chapter in the context of information theory and coding theory, which attempt

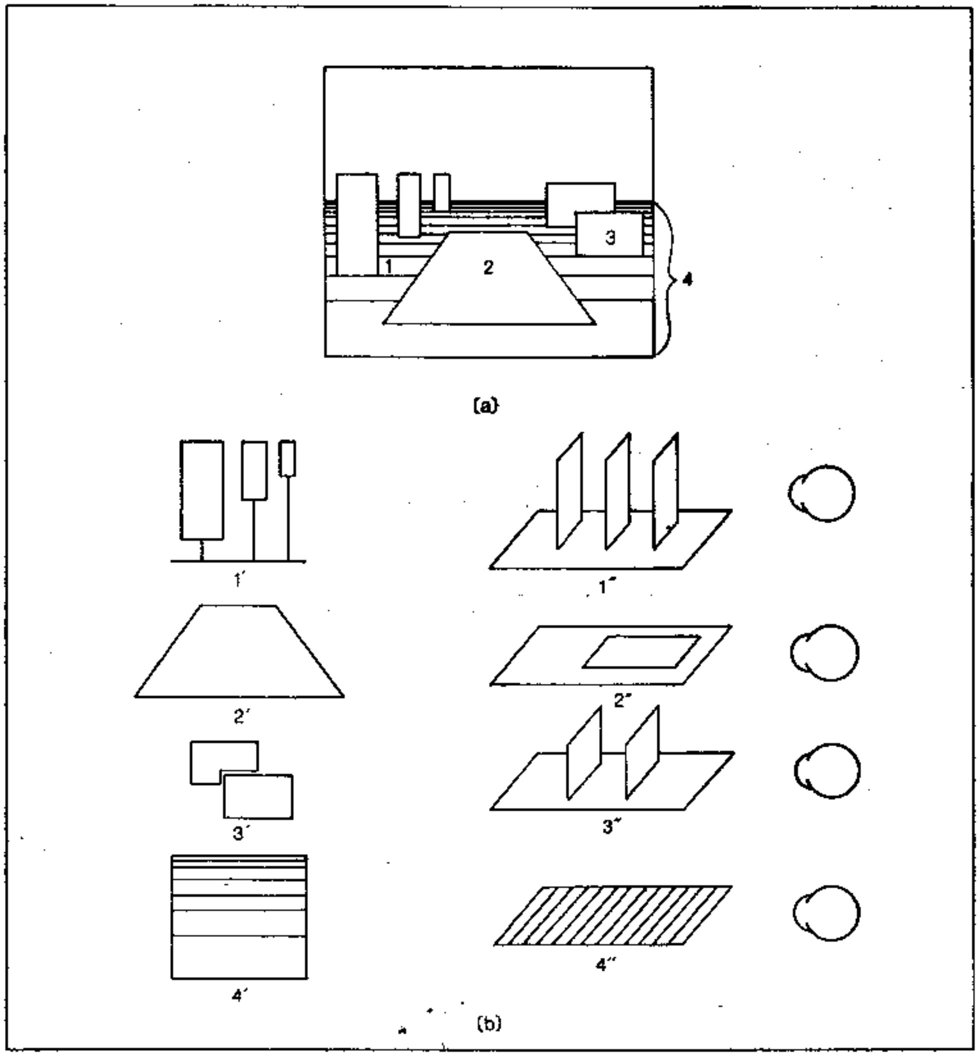


Figure 36.23. Depth cues and prägnanz. (a) A scene containing four monocular depth cues: relative size, linear perspective, interposition (occlusion), and texture-density gradients. (b) Isolation of the four cues, in the left column as viewed in (a) and in the right column as viewed from the side. As the text explains, it is not clear that the depthful interpretation of the scene in any way simplifies the scene. (From J. Hochberg, *Perception* (2nd Ed.). Prentice-Hall, Inc., 1978. Reprinted with permission.)

to deal with symmetries and other forms of regularity (or redundancy) in stimuli in a more formal fashion.

4.7. Assessment

The preceding analyses have focused on the Gestalt principles of area, proximity, similarity, closure, good continuation, convexity, and symmetry. Other principles of some importance not discussed include orientation (Koffka, 1935/1963, p. 190), enclosure or surroundedness (Rubin, 1921), color and contrast (Rock, 1975, p. 261), and common fate (Wertheimer, 1923/1950). Although these and other laws could be analyzed in detail, such an exercise would add little to the picture that has emerged. A rough balance sheet or scorecard (cf. that of Gregory, 1974) shows the following: the likelihood principle provides the better explanation for the effects of closure, area, proximity, and similarity. Both symmetry and good continuation seem to be handled equally well by either. The same is probably true for Rubin's principle regarding the one-sided function of contour, according to which any given contour (a line or edge) is perceived as belonging only to the figure, not to the ground. The law explains why it is difficult if not impossible to perceive the faces and the vase simultaneously in Rubin's famous figure-ground demonstration.

5. ADDITIONAL PERCEPTUAL PHENOMENA TO BE EXPLAINED

Having assessed the various Gestalt laws of organization, let us turn to a series of specific perceptual problems and phenomena that have occupied center stage in theoretical analyses of perceptual organization for many years. These include the perception of space and depth, the Necker cube, impossible figures, subjective contours, and apparent motion.

5.1. Depth Cues

Let us start this analysis with Figure 36.23, drawn from Hochberg (1978, pp. 141–143). Figure 36.23a shows a scene that most observers see as a landscape containing one rectangle lying on the ground and five rectangles standing upright, perpendicular to the receding ground plane. At least four monocular depth cues are contained in this figure: (1) relative size, wherein the proximally larger rectangles are perceived as nearer and not necessarily as larger; (2) linear perspective, wherein distally parallel lines are depicted as converging toward a vanishing point beyond the visible horizon; (3) interposition, wherein nearer surfaces can occlude our view of more distant ones; and (4) texture-density gradients, wherein the parallel, horizontal lines depicting the ground become more dense at greater distances. (Additional cues are contained in this picture, some of which indicate depth, such as height in picture plane, and some of which contradict depth, such as absence of binocular disparity or motion parallax, but we can ignore these factors for the moment.) The figures in the left-hand column of Figure 36.23b depict frontal views of portions of this scene that illustrate these cues; those in the right-hand column show side views depicting the usual three-dimensional interpretation of the scene.

Hochberg (1978) has outlined the Gestalt interpretation of these depth cues as further instances of the prägnanz principle. Considering the topmost pair of figures in Figure 36.23b, is it not simpler to perceive three identical rectangles at three different distances (right column) than three different-sized rectangles at the same distance? Considering the linear perspective cue with the second row of figures, is it not simpler to perceive a square lying flat on the ground than a trapezoid standing upright (cf. the Ames window)? In the third row, is it not simpler to see one complete rectangle partially occluded by another than to see a rectangle abutted in the same depth plane with an irregular, L-shaped figure? Finally, in the bottom row, is not a regularly spaced set of lines receding into the distance simpler than an irregularly spaced set that does not recede? Although these questions are phrased rhetorically, their answers are not at all obvious, for each implies an unstated cost-benefit analysis which must demonstrate that the three-dimensional interpretation is in fact the simpler one (Pomerantz & Kubovy, 1981). Considering the relative size cue as an example, *why* are three identical figures at different depths simpler than three different figures at the same depth? Such a claim entails additional assumptions about the processes and structures used to encode stimuli; the claim does not follow directly from the idea of prägnanz.

The likelihood explanation for these depth cues follows a now-predictable pattern. Concerning relative size, for example, rarely in the natural environment do objects line up in exactly the same depth plane; a typical scene contains numerous objects, most of which are at different depths. However, it is common to see arrays of nearly identically sized objects, as with a field of dandelions or a herd of cattle. In the absence of contradictory information, the perceptual system might assume that several objects of similar shape have the same size. Similar arguments can be made for the other depth cues, but in each case, an ecological survey would be required to settle the matter.

To clarify further the contrast between the two principles, recall the Ames room, shown in Figure 36.24. The room's distal shape is trapezoidal, but when seen monocularly from the proper observation point, it is perceived as rectilinear. When objects of known, familiar size (such as people) are placed within the room, the room is still perceived as rectilinear, and the objects' apparent sizes are therefore distorted. To explain this outcome, prägnanz would hold that a rectangular room is simpler than a trapezoidal one, whereas likelihood would hold that the former is more likely than the latter. Concerning size distortions, prägnanz would claim that altering the sizes of objects does not affect their simplicity; the patterns remain the same even though the elements change size. Some loss in simplicity is incurred by making the people's sizes so variable, but that might be offset partially by making their perceived distances uniform (cf. Figure 36.23) and is certainly compensated for by the perceived regularity of the room. The likelihood principle, on the other hand, must rationalize the size disparity by appealing to the great size variations that exist among human beings, ranging from giants to dwarfs. In sum, each approach does a presentable, albeit not totally convincing, job of handling the Ames room. The tacks taken by the two are similar in that both explain an illusion by appealing to processes that normally foster veridical perception. But no obvious method suggests itself for distinguishing the two empirically.

Hochberg (1978, p. 139) has shown that at least two depth cues cannot be handled by prägnanz. These are *illumination direction*, discussed previously, and *familiar size*. Illumination from above is no simpler than from below; it is only more likely. Similarly, familiar size is by definition dependent on learning, and, although it is in a sense simpler to see objects at their proper sizes, this is not the sense intended by prägnanz. Further, Gregory (1972, p. 183) points to the cue of aerial perspective, in which distant objects appear more blue and less distinct than nearer ones. This effect is due to atmospheric haze, which scatters light and absorbs its constituent wavelengths differentially. It would be farfetched to link this cue with simplicity; more likely this cue is acquired (either phylogenetically or ontogenetically) through experience with the environment.

Returning to our balance sheet, we see again that neither prägnanz nor likelihood has won a decisive victory. Let us next probe some domains in which differences between the two principles may be most apparent, beginning with the perception of the Necker cube and then examining impossible figures, subjective contours, and apparent motion.

5.2. The Necker Cube

This stimulus, discussed earlier and shown in Figure 36.2a, has been at the center of debates about perceptual organization for decades. Why is this figure normally seen as a cube in depth rather than as a flat design? Why does it tend to reverse spontaneously in depth as we observe it, and why is one of the two three-dimensional orientations (where the cube is seen from above) normally preferred to the other? As usual, prägnanz holds that a three-dimensional organization is simpler, whereas likelihood holds that it is more likely. (The relevant arguments have all been presented before.) Multistability is explained (at least in part) by both principles by claiming that both three-dimensional interpretations are viable and so neither should dominate the other. This notion, when combined with neurophysiological account of multistability (in terms of Köhler's satiation processes or Attneave's multistable electronic circuits), has considerable appeal (but see Rock, Chapter 33); and, although the details of such processes need much additional elaboration, neither principle is favored here. The preference for one perceived orientation over the other seems more readily explained by likelihood than by prägnanz; solid objects are viewed from above more often than from below, but it is not clear why the former would be any simpler than the latter.

Hochberg and McAlister (1953) contrasted the two Kopfermann (1930) patterns shown in Figure 36.25 (taken from

Hochberg, 1978, p. 139) and discovered that the traditional Necker cube in Figure 36.25*a* is more likely to be perceived in depth than is the pattern in (b), even though each is an equally correct depiction of a wire cube. The effect was explained by Hochberg and McAlister as follows (see also Hochberg & Brooks, 1960, discussed further later): Part (a) is seen in depth and part (b) as flat because each is simpler when interpreted that way. They devised an objective metric for simplicity based on weighted counts of the number of interior angles, the number of different angles, and the number of continuous lines. Basically, (a) is seen as a cube in depth because all the angles of a cube are right angles; if it were seen as flat, the figure would contain a number of odd angles. On the other hand, (b) is seen as flat because when seen that way all of its angles are identical (60°); further, seeing (b) in depth would entail splitting all three of the internal, continuous line segments into two parts, thereby breaking good continuation and making the figure more complicated than it would be if it were left flat.

The preceding analysis is clearly Gestalt-like, but it goes beyond vague appeals to prägnanz by explaining how simplicity might be measured, at least for drawings of cubes. A likelihood account for the effects in figure 36.25 would note that for the figure in (b) to be a cube it would have to be viewed from exactly the one angle that would make objectively separate contours become continuous in the proximal stimulus. It is more likely, then, that the figure is a flat design. This line of reasoning is not as successful in explaining why the pattern in (a) is seen

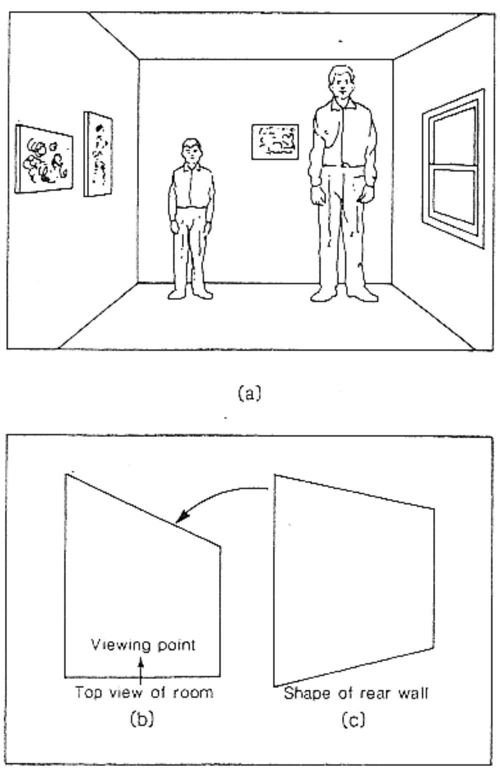


Figure 36.24. The Ames distorted room. Adelbert Ames designed this room which, although it contains no rectangular surfaces, appears normal and "square" to an observer peering in from a properly placed observation hole. (a) What the eye (or camera) would see from this station point. (b and c) Clarification of the the actual layout of the room. Observers perceive the room as square and the two people as stationed at about the same distance but differing greatly in size; in fact, the two people are about the same size but are stationed at different distances. This effect can be explained by either the prägnanz or the likelihood principle. [(a) From I. Rock, *An introduction to perception*. Macmillan Publishing Co., 1975. Reprinted with permission.]

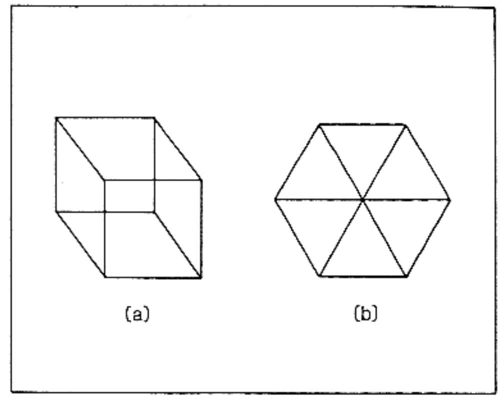


Figure 36.25. Perspective drawings of two Kopfermann cubes. Both of these patterns are equally good perspective drawings of a wire cube, but the design (a Necker cube) in (a) is most likely to be perceived as a cube, whereas that in (b) is most likely to be perceived as a flat design. Hochberg & McAlister (1953) provided a quantitative model to explain why.

in depth, but many of the arguments given before (e.g., that trapezoids, or in this case parallelograms, are likely to represent rectangles) could be applied.

Kanizsa (1979, p. 106) has provided a companion demonstration to the Figure 36.25, which is shown in Figure 36.26 and which places important contraints on either explanation. As with Figure 36.25, (a) tends to be seen in depth whereas (b) is seen as flat. But seeing (a) in depth does not make it simpler than seeing it flat; it is an irregular, asymmetric figure in either case. Similarly, it is not clear that (b) is simpler when seen as flat than if it were seen in depth. [Note that (b) can also be seen in depth as an irregular pyramid viewed from straight above, but it seems neither simpler nor more complicated this way.] Kanizsa's point is that the apparent improvement in regularity seen with the cubes in Figure 36.25 may be only an accidental by-product of other principles that govern perceptual organization. In this case most of the results in both Figures 36.25 and 36.26 may be due to good continuation, which (as we have seen) is in turn explained equally well by likelihood as by prägnanz.

5.3. Impossible Figures

Impossible figures have been treated as interesting curiosities of perception, but their implications for perceptual organization may be profound. Figure 36.27 presents two well-known examples, the three-stick clevis and the impossible triangle. In each instance, our perception tends to organize the figure into a three-dimensional object that could not be realized physically. We tend not to see them as flat designs drawn on paper, although this interpretation would eliminate the problem of impossibility. Figure 36.28 reduces the paradox to perhaps its simplest case. In Figure 36.28a most often we see two rectangles, one of which occludes our view of the other. In (b) we see a multistable organization of two overlapping rectangles containing conflicting depth cues. At times, the left rectangle appears as a nearer figure that occludes our view of the right rectangle, while at other times the converse organization prevails. Following a few such alternations of perceived depth, the conflict becomes apparent to the observer. But despite the conscious awareness of the difficulty of interpreting the figure in depth, the stimulus resists a flat interpretation. Note that this stimulus need not be seen as an impossible figure because the rectangles can be interpreted as possessing horizontal slits that allow them to be

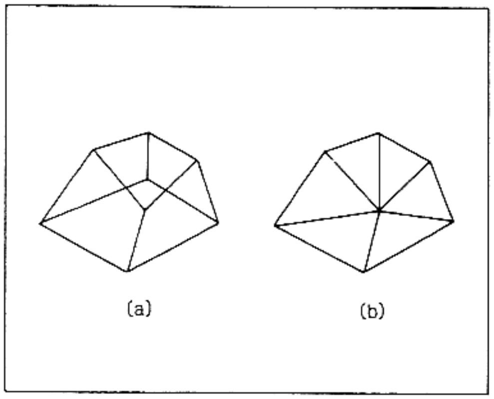


Figure 36.26. Kanizsa's distorted cubes. The two patterns presented here parallel the two in Figure 36.25, except that the object depicted is a distorted cube. Nevertheless, the perceptual effects are the same as in Figure 36.25, with (a) being perceived in depth and (b) as flat. This demonstration indicates that depthful interpretations are not necessarily imposed on stimuli to increase their geometric regularity. (From G. Kanizsa, *Organization in vision*. Copyright 1979 by Gaetano Kanizsa. Reprinted with permission of Praeger Publishers.)

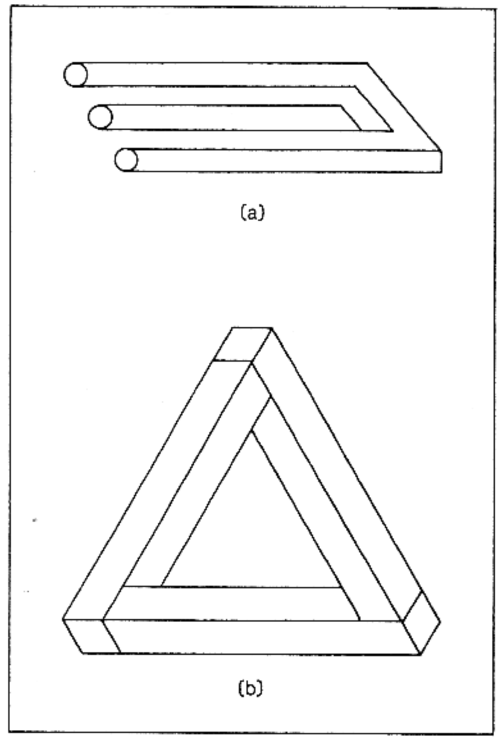


Figure 36.27. The three-stick clevis and the impossible triangle. These are perhaps the best-known of the "impossible figures." Rather than interpreting these patterns as flat designs, the visual system attempts to structure them in depth, which turns out to be an impossible task. These figures present a challenge to all theories of perceptual organization. [(a) From D. H. Schuster, A new ambiguous figure: A three stick clevis. *American Journal of Psychology*, 77. Copyright 1964 by University of Illinois Press. Reprinted with permission. (b) From L. Penrose & R. Penrose, Impossible objects: A special type of visual illusion. *British Journal of Psychology*, 1958, 49. Reprinted with permission.]

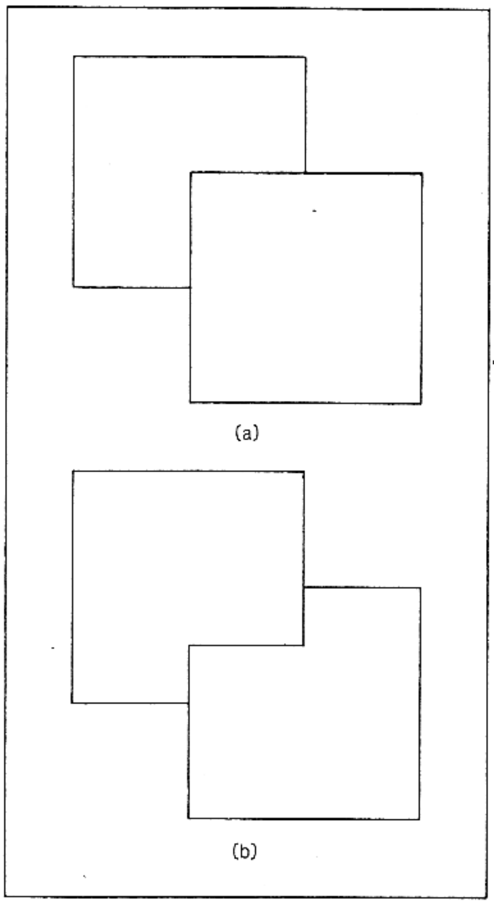


Figure 36.28. Interposition and perceived depth. The stimulus in (a) is most often perceived as one square in front of another. The same is true in (b), but which square is in front of the other is difficult to determine, and the whole figure may appear impossible. For some observers, the display spontaneously alternates in depth like a Necker cube, even though the impossibility would be eliminated if it were perceived as a flat design or as two sheets with slits that have been slipped through one another.

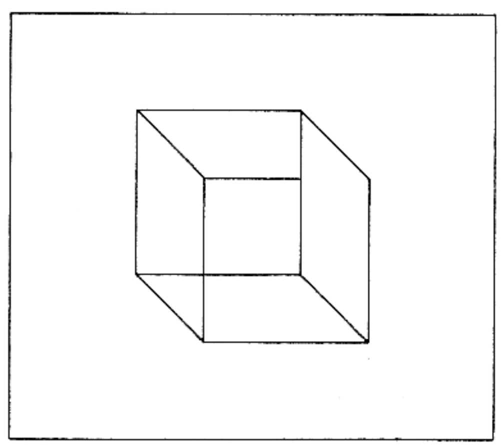


Figure 36.29. Hochberg's incomplete cube. This is a standard Necker cube except for one of the horizontal segments, which has been truncated at the point where it intersects a vertical line. Although this figure has a number of possible interpretations (such as a Necker cube with one opaque wall), many observers perceive it as an impossible figure. (From J. Hochberg, *Perception* (2nd ed.). Prentice-Hall, Inc., 1978. Reprinted with permission.)

slid through one another. But this "possible" interpretation eludes many observers, who experience only the alternating, impossible percepts.

Impossible figures are not easily accommodated by either prägnanz or likelihood because they seem neither simple nor likely. We should note that impossibility per se is unrelated to simplicity, because certain physically impossible structures (such as n-dimensional spaces and Klein bottles) are nonetheless fairly easy to describe mathematically. However, this observation fails to provide much redemption for prägnanz in explaining Figures 36.27 and 36.28; in any geometry these figures remain an enigma. Concerning likelihood, impossible figures clearly lie at the lower limit of the probability scale because they never occur as objects in the environment (Gregory, 1974; Pomerantz & Kubovy, 1981).

Impossible figures thus present a challenge for all existing theories of perceptual organization. One potential resolution of this dilemma would be to dismiss them as anomalies, special cases that could be handled by ad hoc mechanisms, so they would have no impact on general principles of perceptual organization. But a novel demonstration by Hochberg (1981a), shown in Figure 36.29, makes even this route untenable. The figure, which is a minor modification of the Necker cube, is a perfectly "possible" perspective drawing of a wire cube in which either (1) one of the wire edges has been clipped at its midpoint so it stops in midair, or (2) one of the surfaces of the cube is opaque, so the truncated edge is occluded from view. But despite these two "possible" interpretations, observers frequently see the figure as impossible, that is, as an object that could not exist in three-dimensional space. Were either a prägnanz or a likelihood principle operating, the "possible" interpretation should dominate. Yet many observers report spontaneous and in fact indifferent perceptual alternations between the possible and the impossible interpretations. Figure 36.30 (Pomerantz & Kubovy, 1981) shows a variation of this figure in which the "possible" interpretation is perhaps even more likely and plausible than the possible one of Figure 36.29. Even though this figure can easily be seen as an opaque triptych, most observers

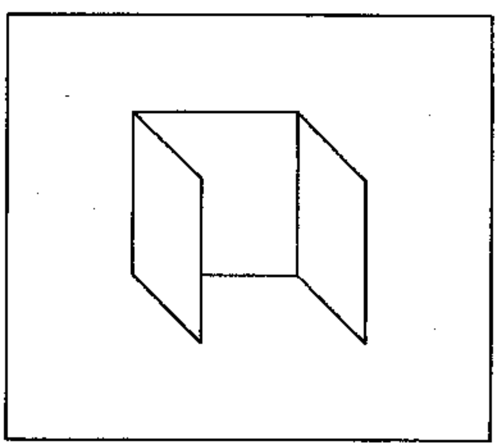


Figure 36.30. The ambiguous triptych. As with Figure 36.29, this modification of Hochberg's incomplete cube is often perceived as impossible even though it has a possible (and in fact quite likely) interpretation: a triptych, that is, a vertically oriented screen folded vertically into three sections. (From J. R. Pomerantz & M. Kubovy, Perceptual organization: An overview. In M. Kubovy & J. R. Pomerantz (Eds.), *Perceptual organization*. Lawrence Erlbaum Associates, 1981. Reprinted with permission.)

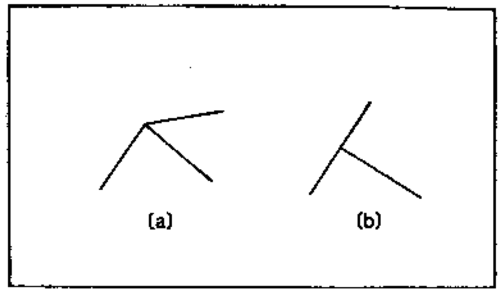


Figure 36.31. Vertices contain structural information. As Guzmán (1968) showed, information relevant to global structure can be gleaned from local regions such as vertices. The intersection in (a) can be interpreted as the corner of a cube, whereas that in (b) suggests depth by means of an occlusion cue (where one line terminates at the point of intersection with another). The principles of prägnanz and likelihood can be applied to local regions as well as to whole objects, although this shift in the level of analysis is not in the spirit of Gestalt theory.

see it equally often as three perpendicular, rectangular surfaces twisted in an impossible manner.

How can these demonstrations be reconciled with either prägnanz or likelihood? As Hochberg (1981a) notes, excluding them as special cases would be gratuitous because both are derived from the same Necker cube that has figured so prominently in the perceptual organization literature. A more forthright reconciliation (alluded to in Section 3.3.3) requires shifting the *unit of analysis* upon which the prägnanz and likelihood principles operate. The literature on perceptual organization has neglected this crucial matter by assuming tacitly that simplicity or likelihood applies to entire stimuli (objects or perhaps entire scenes). But either principle could be applied to smaller units of analysis, such as to the local intersection of contours. Consider the intersections shown in Figure 36.31. In Figure 36.31a the intersection of three line segments can be interpreted as a flat design or as the corner of a cube; in Figure 36.31b the lines can be interpreted as a flat T-shaped configuration or as one contour passing behind an occluding edge (cf. Guzmán, 1968). Without reiterating all the arguments, either a prägnanz or a likelihood explanation could be formulated for perceiving these two intersections in depth. If the global organizations perceived for Figures 36.27–36.30 were determined at the level of local intersections, the dilemma of impossible figures might disappear: considered piecemeal, each narrowly circumscribed region of these figures is organized in a simple, likely fashion.

Thus we can argue that impossible figures are explained satisfactorily by shifting the focus of organizational principles to local regions. This shift might be justified by constraints in the neural underpinnings of perceptual organization, in which interactions are limited to local regions (cf. the soap bubble analogy), or by arguing that organization occurs only within a limited region surrounding our momentary focus of attention (usually the fovea; cf. Hochberg, 1968, 1978). In either case there would be no process that oversees global organization to ensure that the local organizations are compatible with one another. The fact that percepts typically appear to be globally organized and free of internal contradictions, and that impossible figures are only rare curiosities, would then imply that when the perceptual system takes care of all the small details, the "big picture" will take care of itself. Perhaps a highly selective set of rules has evolved to achieve *local* organization that (except in rare, artificially contrived cases such as impossible figures) also gives us *global* organization.

5.4. Subjective Contours

This illusion, first demonstrated by Schumann (1904), involves the perception of contours in regions of homogeneous luminance. Several examples are shown in Figure 36.32. Figure 36.32a reproduces Schumann's original figure; (b) shows what is probably the most common demonstration of the effect, from Kanizsa (1955). In the left half of (b) the perception of a complete triangle that is whiter than the figure's background is especially compelling. Figure 36.32c (Kanizsa, 1955) shows a compelling subjective edge that has a lustrous appearance; in Figure 36.32d (Coren, 1972) most observers perceive the word "FEET," printed in block letters.

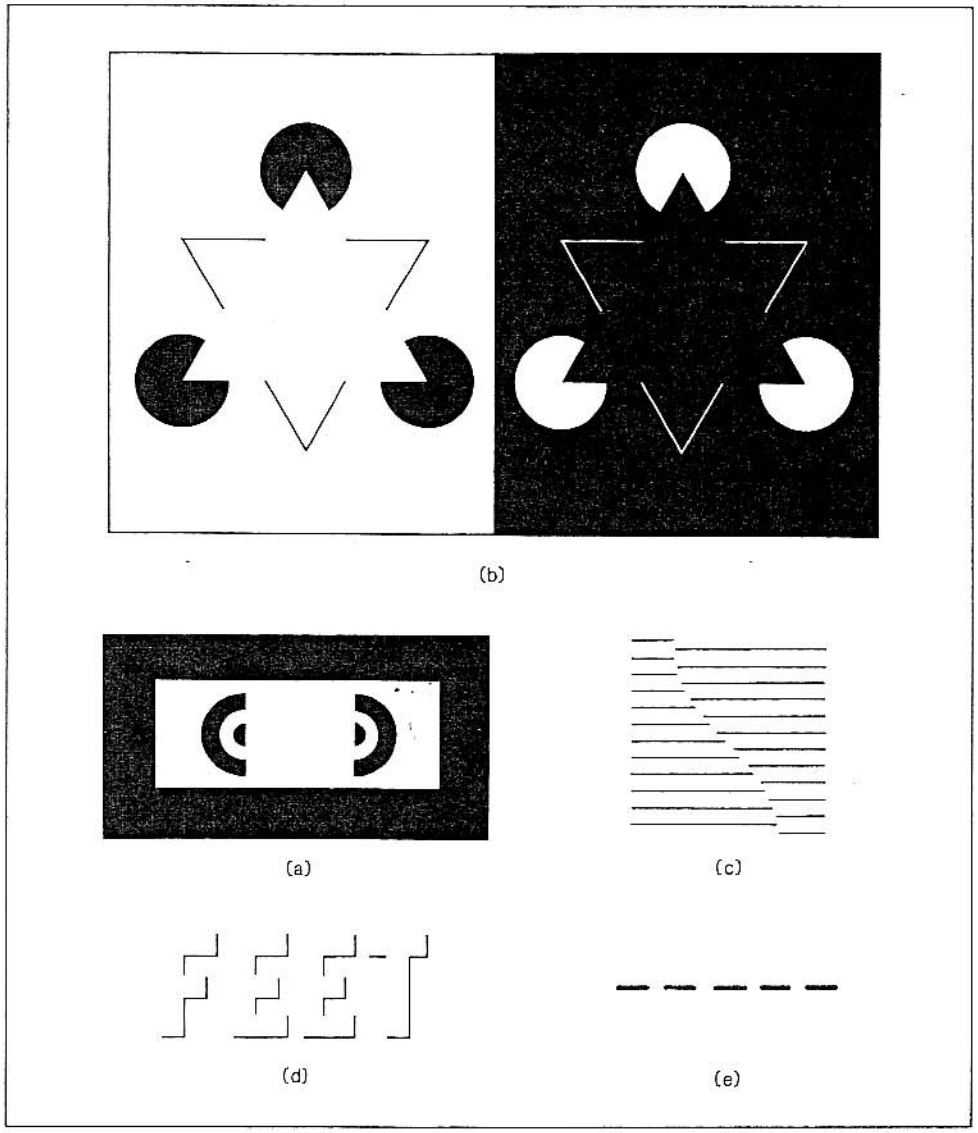


Figure 36.32. Subjective contours. (a) Schumann's (1904) original demonstration of subjective contours; a central square, slightly whiter than the background, can be seen, especially if the stimulus is not scrutinized too closely. The contour of the square seems to be visible throughout its perimeter, although there is no contrast to support the contour for much of its perimeter. (b) Two of Kanizsa's (1955) subjective triangles in which the illusion is stronger than in (a). The subjective triangle appears whiter than the background on the left figure and darker than the background on the right. (c) A subjective contour without differences in brightness due to contrast; the line, however, does have a lustrous appearance. (d) The word FEET spelled using subjective contours. Here, however, the contours do not result from occlusion cues, as in (a–c), but instead arise from cues indicating the presence of unseen objects casting shadows. (e) A simple dashed line. The lines are not filled in perceptually across the gaps, which indicates that subjective contours are not merely a matter of closure or of "filling in." [(a) From F. Schumann, 1904. (b) From G. Kanizsa, Margini quasi-percettivi in campi von stimolazione omogenea. *Revista di psicologia*, 1955, 49.) (c) From G. Kanizsa, *Organization in vision*. Copyright 1979 by Gaetano Kanizsa. Reprinted with permission of Praeger Publishers. (d) From S. Coren, Subjective contours and apparent depth. *Psychological Review*, 79. Copyright 1972 by American Psychological Association. Reprinted with permission.]

Although all of these cases involve the appearance of illusory contours, it is an open question whether they all result from the same underlying mechanism. Coren (1972) has argued that the illusion is due to perceived depth, with the subjective figures in Figure 36.32a and b appearing to lie in front of, and so occluding, the objective inducing areas. Depth is also involved in Figure 36.32d; the physically present contours correspond to the shadows that would result if raised letters (of the same lightness as the background) were illuminated from the upper left.

Subjective contours might be thought of as an instance of the Gestalt law of closure, but this would be incorrect (Coren, 1972). Consider the dashed line shown in Figure 36.32e. Dashed lines are often perceived as equivalent to solid lines, suggesting the operation of closure, but to be consistent with the previous examples of subjective contours, one would have to perceive subjective contours running perpendicular to the dashed line, as though a solid line drawn against a white background were perceived through a white picket fence. (In fact with a little effort, this organization can be achieved.)

To what extent can subjective contours be explained by prägnanz? To be sure, Figure 36.32b is more simply described as three complete black disks and one complete outline triangle partially occluded by a solid white triangle, than as three notched disks and three V's that happen to be oriented with their component edges and line segments collinear. However, Figure 36.33 casts doubt on the prägnanz explanation. Figure 36.33a and b shows irregular, complex figures generated from subjective contours. Figure 36.33c shows that the Penrose and Penrose impossible triangle can be approximated reasonably well with subjective contours (Kanizsa, 1979, p. 218; Pomerantz & Kubovy, 1981, p. 447, Panels c and d). In short, subjective contours can be perceived regardless of whether they simplify the resulting global organization of the distal stimulus.

The likelihood principle can explain Figure 36.32b, since the various occlusion cues strongly suggest the presence of an opaque triangle (Gregory, 1974). The perception of the word "FEET" in Figure 36.32d also is commensurate with a likelihood explanation. Banks and Coffin (1974) questioned whether subjective contours would be perceived by observers unfamiliar with these alphabetic characters; indeed, few observers shown only the leftmost inducing contours of this panel will perceive the letter "F." The complex configurations in Figure 36.33 can be explained either by the operation of local processes that are insensitive to the global figures that emerge from the construction of subjective contours, or by noting that irregular figures are no less probable in the natural environment than more regular ones.

Numerous aspects of the subjective contour problem remain to be explained in detail by either approach. (Some of these are discussed by Ginsburg, Chapter 34.) But the prägnanz approach in particular is greatly damaged by Figure 36.33. The only apparent salvation would require applying prägnanz at the local level (as discussed previously), interpreting terminated line segments more simply as indicating occlusion than as indicating termination without occlusion. But, as we see in the dashed line of Figure 36.32e, terminations do not always lead to subjective contours. Similarly, if one views only a single notched disk from Figure 36.32b, no subjective contours are seen, or will the letter "F" in (d) be seen as such if presented in isolation. Subjective contours are apparently due to *global* organization, not to purely local factors, and so an explanation appealing to a local minimum principle is untenable.

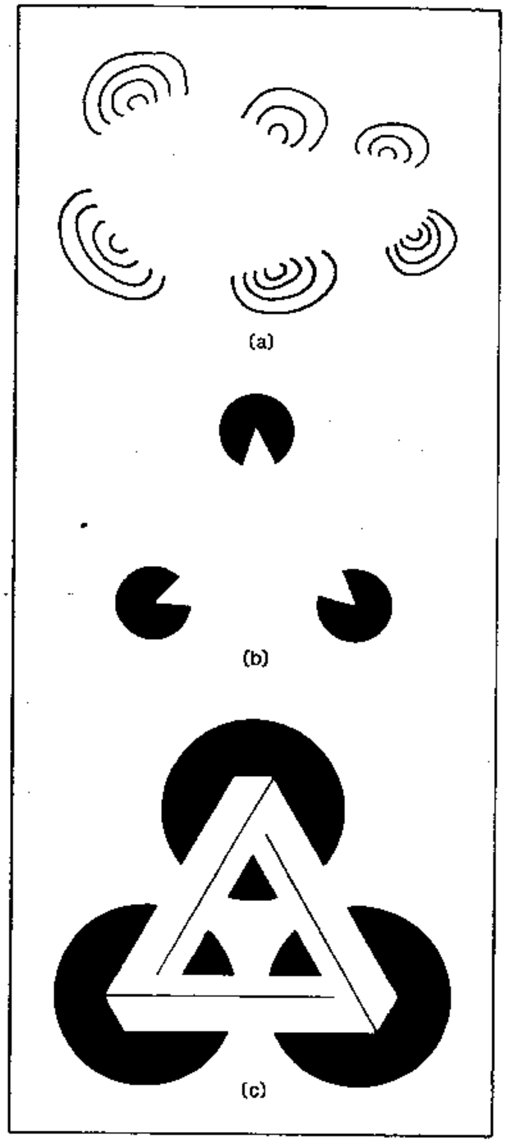


Figure 36.33. Irregular shape and impossible figures produced using subjective contours. (a and b) A demonstration that the subjective figure need not be a good Gestalt for subjective contours to emerge. (c) The Penrose and Penrose (1958) impossible triangle from Figure 36.27 can be approximated reasonably well from subjective contours. These figures all present difficulties for either the global prägnanz or the likelihood principle. (From G. Kanizsa, *Organization in vision*. Copyright 1979 by Gaetano Kanizsa. Reprinted with permission of Praeger Publishers. (c) From J. R. Pomerantz & M. Kubovy, Perceptual organization: An overview. In M. Kubovy & J. R. Pomerantz (Eds.), *Perceptual organization*. Lawrence Erlbaum Associates, 1981. Reprinted with permission.)

It might also be argued that the perception of subjective contours is mediated by highly specific, ad hoc detector mechanisms unrelated to either prägnanz or likelihood. These detectors might be triggered automatically by specific features in the proximal stimulus, such as the collinearity of edges and of terminated line segments. Figure 36.34, from Bradley, Dumais, and Petry (1976; see also Bradley & Petry, 1977), suggests otherwise. If this figure is viewed as a Necker cube floating in front of eight solid black disks, one sees the cube being completed by subjective contours; but if the figure is viewed as a Necker cube floating behind a white surface containing eight circular apertures, no subjective contours are seen. The figure thus

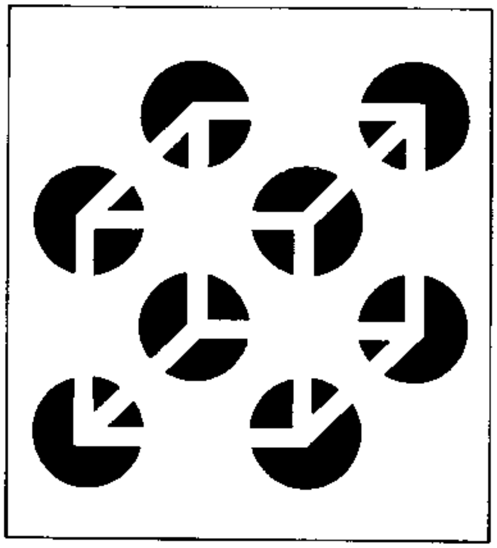


Figure 36.34. The subjective Necker cube. This figure provides a powerful demonstration that subjective contours are not the result of some automatic perceptual process. This figure can be viewed as a white Necker cube floating above a set of eight black disks. If the figure-ground organization is reversed, however, it can be seen as a white Necker cube against a black background as seen through a white screen containing eight round holes. In the former case, subjective contours are seen; in the latter, they are not. (From D. R. Bradley, S. T. Dumais, & H. M. Petry, Reply to Cavonius. *Nature, 261*. Copyright 1976 by Macmillan Journals, Ltd. Reprinted with permission.)

demonstrates that subjective contours are not perceived by the automatic activation of specific detector mechanisms; rather they result from an active ("top-down") and globally oriented organizational process (or schema; see Hochberg, 1978, p. 193).

In summary, the likelihood principle appears to be the only viable contender for explaining subjective contours. The explanation is not complete at this time, however.

5.5. Apparent Motion

This phenomenon, first noted by Exner (1875), formed the cornerstone for Wertheimer's (1912/1961) original notions that launched the Gestalt movement. Several different and perhaps unrelated types of apparent motion exist. Wertheimer's main concern was with the "phi" phenomenon, or objectless motion. If two separated lights are flashed on and off at the proper alternation rate, the observer experiences a strong sense of motion between them, even though no light is seen to move (cf. "beta" motion, in which a moving object is seen traversing the space between the two terminal positions). Wertheimer argued that with phi motion the observer was experiencing "pure" motion (pure in that only motion and no moving object is perceived); thus motion could not be a sensation derived in a structuralist fashion from the combination of the separate sensations produced by the inducing lights. The phi phenomenon seemed to lend itself well to an explanation involving dynamic brain fields (Köhler, 1923; Wertheimer, 1912/1961): each of the two lights produces a specific and local disturbance in the brain, and field effects operating automatically produce a smooth flow of current between them, much in the same manner as when a single light is perceived undergoing real motion.

Can apparent motion be considered a *simple* organization of the distal stimulus event? In the case of beta motion this might be true because one perceives only a single, continuously visible, moving object rather than two flickering, stationary objects. In addition, the trajectory followed by the apparently moving object is often the simplest (straightest, shortest, or most smoothly curved) interpolation between the terminal positions (Foster, 1978); in situations where two or more objects are put into apparent motion simultaneously, the matching (or correspondence) between the multiple objects in the two flashes is often the simplest or most economical one possible (Kolers, 1972; Pantle & Picciano, 1976; Ternus, 1926/1950; Ullman, 1979).

However, two complications arise. First, the perception of beta motion depends on the timing of the stimulus flashes being set within certain limits. If the alternation rate is too fast, two stationary, flickering lights are seen simultaneously; if it is too slow, the lights are again seen as stationary and as appearing and disappearing in succession (Kolers, 1972). Similarly, the kind of motion seen in the Ternus situation just noted is dependent on timing. It is not clear why beta motion would be a simple organization at some alternation rates but not at others. By contrast, it is possible that the temporal bounds on apparent motion reflect some learned or evolved knowledge of the temporal parameters of real motion (Shepard, 1981). Korte's (1915) well-known "laws," which summarize (roughly) the spatial and temporal constraints of apparent motion, could be viewed as the internal representation of these learned boundaries, an interpretation consistent with the likelihood principle. Kaufman, Cyrulnik, Kaplowitz, Melnick, and Stoff (1971) showed that the velocity range over which apparent motion is perceived does not overlap with the range for real motion; apparent motion is perceived only at velocities that are above the upper threshold for seeing real motion. Kaufman (1974, p. 401) has suggested that apparent motion arises from stimulation of detectors whose function is to respond to real motion that occurs at velocities too great for ordinary, real-motion detectors. According to this reasoning, motion (rather than succession or simultaneity) is the organization of the stimulus event that is most likely to be correct.

The second complication is that beta motion can be perceived just as easily between two alternating stimuli that differ in shape as between two identical shapes (Kolers & Pomerantz, 1971; Orlansky, 1940). In the former case, the observer usually perceives the two objects undergoing a plastic deformation such that the moving object transforms its shape smoothly as it moves between the two termini. Again, it is not clear why a single object changing in shape is any simpler an organization than the veridical perception of two different objects flickering in place. Nor for that matter is it clear why the former is more likely than the latter. Many objects change their shape as they move (as with a bird in flight), but often they do not (as with a gliding bird or a rigid object); just which is the more likely state of affairs is anyone's guess, so the likelihood principle neither wins nor loses on this score. However, it is relatively rare that objects abruptly appear out of nowhere (or disappear abruptly), although this does occur occasionally in nature, as with fireflies at nighttime. More likely, an image that disappears from one location and reappears at another signifies a moving object that either has passed behind an occluding surface or has been interrupted by a saccadic eye movement or a blink. Thus apparent motion detectors may have evolved as a mechanism for preserving the perceptual continuity of objects continuously present but not continuously represented in the proximal stimulus.

A likelihood explanation for the standard alternating-lights demonstration of apparent motion might predict that the observer would perceive subjective contours forming an opaque subjective figure occluding the space between the two terminal locations. However, subjective contours are not seen in this situation (although they are seen in other cases where further dynamic cues to occlusion are present). Furthermore, if a solid, opaque object is placed in the path of apparent motion, one might expect the observer to perceive the moving object to pass *behind* the occluding surface rather than in front of it, since the former provides a likely explanation of the disappearance of the object from the proximal stimulus. In fact, however, these two alternatives are perceived with approximately equal frequency (Pomerantz & Kubovy, 1981). Although facts such as these do not present insurmountable obstacles for a likelihood explanation, they do force an element of arbitrariness in any eventual model by requiring it to explain our sensitivity to some aspects of the stimulus event but an insensitivity to other aspects that would seem to be of equal importance.

In sum, our conclusions for apparent motion parallel those for subjective contours. The prägnanz explanation is weak; simplicity does not seem to be relevant to our perception of apparent motion. By contrast, the likelihood approach seems more promising. The stimulus information associated with this phenomenon is a likely indicator of an object moving under conditions that cannot be sensed by detectors of real motion because the velocity of motion is too great, because the moving object was occluded, or for some other reason. Clearly we need more information about the ecological optics of visual motion, but this approach seems far more promising than one based on prägnanz.

6. ASSESSMENT AND RECONCILIATION OF PRÄGNANZ AND LIKELIHOOD

At this point we have considered an extensive sample of the perceptual phenomena on which claims about perceptual organization have been based. Our discussion has necessrily excluded many important effects, especially those in modalities other than vision, and we have focused on qualitative aspects of these phenomena at the expense of quantitative details and models. However, we are now in a position to evaluate the evidence and ask whether there are any common features to be found within our sample of phenomena that could serve as a foundation for a general theory of perceptual organization.

6.1. Gestalt Psychology and Prägnanz

The evidence favoring the prägnanz principle is somewhat thin. Whereas the dominant view of perceptual organization held by psychologists in general is most often centered around the Gestalt approach (as witnessed by most textbook treatments of perception), the Gestalt explanations of Gestalt phenomena are often inadequate, vague, or simply wrong. The various Gestalt laws of organization are on fairly safe ground when considered as descriptions of organizational tendencies, although even here they often fail to give us predictions of everyday perception or (in the absence of a formal model) to tell us when one law will prevail over another. The law of symmetry, which can be regarded as the keystone of prägnanz, lacks the kind of clean and robust demonstration one should expect of so preeminent a principle. It is clear that symmetry can be detected in visual patterns, but so can countless other physical properties; it remains to be demonstrated, however, that symmetry either is actively imposed upon our organizations in soap bubble fashion or is sought after in an extensive search of alternative organizations. To be sure, certain effects described previously lend themselves to a Gestalt explanation, but in many such cases alternative explanations appear to do at least as well.

6.2. The Helmholtzean View and Likelihood

The Helmholtzean approach, with a few exceptions, has provided a more promising and potentially testable explanatory framework for a number of organizational phenomena. To be sure, these phenomena can hardly be said to be *explained* by the likelihood principle unless a specific mechanism can be put forth to model how the phenomenon occurs. In addition, in many cases we lack the necessary ecological survey to inform us about critical information in the proximal stimulus. Despite these limitations, the likelihood approach seems far more promising than the prägnanz approach, which failed to make predictions of any sort for many important phenomena.

Certain robust effects, such as familiar size and illumination direction (Hochberg, 1978), are completely unrelated to simplicity and so demand an account based on adaptations to likely correspondences between proximal and distal stimuli. These adaptations could be based either on ontogeny (i.e., on learning during the lifetime of the organism) or phylogeny (i.e., on evolutionary trends). Most of the Gestalt laws can be regarded as indicators (of varying validity) of what distal stimulus is most likely to have given rise to the proximal stimulus. The major drawback to this approach is the practical difficulty of performing the ecological surveys required to substantiate the claim that our organizational rules capitalize on properties of proximal stimuli that mirror the most likely properties of distal stimuli.

The primary requirement for any plausible theory of perceptual organization is to account for the veridicality of perception. Schemes based on prägnanz must recognize that our distal environment shows only a weak bias toward geometric regularity. A perceiver who, for the sake of economical encoding of the environment, imposes regularity where it does not exist would suffer a distorted, Pollyanna-like representation of the world that would be counterproductive to survival (Attneave, 1982). The likelihood principle, by contrast, is better suited for representing the world veridically.

The likelihood approach is not free of difficulties, however. One problem lies in explaining why certain likely organizations do not occur, as in the case of apparent motion along a path blocked by an opaque object. A second problem concerns the perception of impossible figures, such as the Penrose triangle. Gregory (1974) has maintained that paradoxical percepts pose no special problem for the Helmholtzean view: perceptions, by this approach, are only hypotheses, and "Hypotheses, or descriptions, can be logically impossible. Paradoxes may be generated by following false assumptions, which turn out to be incompatible" (p. 277).

This tack seems overly forgiving, for why should a system founded on likely hypotheses generate ones that are impossible? The only way to justify this stand would be to shift the scope of the perceptual unit to more microscopic levels, where the perceptual system works independently on more local aspects of the total stimulus pattern to arrive at likely hypotheses (Hochberg, 1981a). This would allow sets of simultaneous hypotheses, each of which is highly probable, to contain internal contradictions. When such contradictions are tolerated, it indicates that no executive process or homunculus is supervising the assembly of local hypotheses into a unitary, global representation free of contradictions.

Our assessment leans toward the likelihood principle as the best overall description of how perceptual organization operates. However, an acceptance of likelihood does not mandate a rejection of prägnanz, because the two are not mutually exclusive. As we have seen, certain phenomena support prägnanz, so a compromise could be sought that captures the essentials of both positions without diluting the positive contributions of either or endangering the parsimony of any definitive framework for perceptual organization. Indeed, Mach (1906/1959) was certain that, "The visual sense acts therefore in conformity with the principle of economy, and, at the same time, in conformity with the principle of probability . . ." (p. 215).

6.3. Economical Coding

Information theory (see Attneave, 1959; Garner, 1962) and structural information theory (also known as coding theory; Leeuwenberg, 1971, 1978, 1982; Restle, 1982) may provide a basis for such a compromise. Consider Attneave's (1954, 1981) concept of *economical coding*:

> Suppose that what the system *likes* is short descriptions and that the image is progressively changed, within the constraints of the input, until its description is minimized. This way of looking at the matter, which is considerably different from the classical Gestalt point of view, has the advantage of taking into account not only intrinsic stimulus properties—that is, redundancy, uniformity, or homogeneity in the stimulus itself—but also schemata corresponding to familiar objects. If an input can be brought into conformity with a well-formed schema that is frequently used and to which a short symbol has been assigned, it might be described quite as economically as if it were intrinsically simple (Attneave, 1981, pp. 417–418).

Attneave's observation points to two concepts that are the primary focus of the balance of this chapter: information theory as applied to human perception, and structural information theory, which attempts to devise schemes for representing patterns in a fashion that reflects their perceptual organization. Structural information theory is discussed at length in Section 8. For the moment, let us focus upon information theory.

Information theory allows both prägnanz and likelihood to be translated into the common framework of brief codes. In information theory the information value of a stimulus is inversely related to its predictability, and the lower the information value, the shorter the description or encoding of the stimulus can be. The predictability (or redundancy) present in symmetrical patterns can be exploited in a number of ways (some of which are described later) to produce briefer descriptions. Less obvious is the fact that frequently occurring stimuli are also redundant in that they are more predictable than rare stimuli; this redundancy can be exploited in a similar fashion as well. For example, the most frequently occurring words in English tend to be the shortest words (e.g., a, the, of, is; this principle is known as Zipf's law). Similarly, in electronic communications, more frequently occurring characters (such as the letter E) are best transmitted using fewer bits than rarer characters (such as Q), as in Huffman coding. If this approach is correct, then certain potential conflicts between likelihood and prägnanz can be avoided, and any scheme of perceptual organization that exploits redundancy in the stimulus may be accommodated.

7. INFORMATION THEORY AND PERCEPTUAL ORGANIZATION

Information theory (IT) provides a formal model for measuring the amount of information in a signal or stimulus. The theory was developed outside the field of psychology (in communication engineering) and is completely neutral with respect to psychological issues. In fact, Garner's (1962) book, *Uncertainty and Structure as Psychological Concepts*, avoided using the term "information theory" whenever possible to prevent confusion between IT as a mathematical theory and IT as a descriptive model of human information processing. Thus a caveat is in order for those who would apply IT to human perception.

As Garner (1974) has made clear, IT is most useful as a *normative* model of human information processing, that is, as a benchmark against which to compare human performance, since it prescribes theoretical limits on the efficiency of information encoding and transmission in an ideal information-processing system. IT has not been taken as a literal (or descriptive) model for perception, although there was a time when many psychologists were optimistic that it would serve that function. But IT has proven useful both in providing improved dependent variables for measuring perceptual processes and in guiding the development of psychological models. Recent years have seen a decline in its use for quantifying the amount of information processed by the perceiver, although the earlier research on that topic has not declined in importance over time. Rather, IT has been used successfully as a tool to answer certain questions about human information transmission, and once those questions were answered, interest naturally turned to other matters. At a minimum, IT places constraints on any plausible model of perception, and so no perceptual psychologist should be ignorant of it. IT has also proven useful in studies of manual control (see Wickens, Chapter 39) and of workload monitoring and supervisory control (see Moray, Chapter 40).

7.1. Basic Concepts

The essence of IT is that the information value of a stimulus is related directly to its predictability: a completely predictable or redundant stimulus conveys no information, whereas an unexpected stimulus or event does convey information. Information is defined as that which reduces uncertainty; a completely redundant stimulus has zero uncertainty associated with it, and so when it occurs, no reduction in uncertainty takes place. The connection between IT and perceptual organization derives from the fact that frequent or simple (e.g., symmetric) stimuli are predictable and thus are redundant. But translating likelihood or prägnanz into a language commensurate with IT is not entirely straightforward.

An important concept in IT is that the meaning of a stimulus derives entirely from its alternatives, that is, the stimuli that might have occurred but did not. Given this orientation, IT has proven most useful in understanding how people perceive and process stimuli drawn from clearly defined sets. For example, IT's best-known application has been the channel-capacity experiments (summarized in Miller, 1956) that measure how well observers can identify stimuli drawn from sets that vary in only one dimension, such as circles varying in size, tones varying in amplitude, and color patches varying in lightness.

It is much more difficult to apply IT to describe either an individual stimulus or stimuli that lack a clear dimensional structure or other means from which the parent set of stimuli can be inferred. For example, it is impossible to assess the complexity (or information load) of a scribble drawn on paper without knowing the dimensions along which the scribble was free to vary, or in other words, what other alternative scribbles might have occurred instead of the one actually produced. Scribbles seem quite complex perceptually, and indeed they are hard to encode, describe, copy, and remember. Scribbles are ill-defined patterns produced with very few constraints. Thus every scribble has a large number of alternatives and so carries a high information load. But unless the few constraints that do exist can be stated precisely, the exact information load (or uncertainty) of scribbles is infinite, since with no constraints an infinite number of scribbles can be generated.

Similarly, it is not obvious from IT that so simple a stimulus as a circle has a low information load, since a circle is a unique pattern. Circles are well-defined patterns with numerous constraints; they vary in only one dimension (their diameter), and so they have few alternatives and a low information load. Yet unless the number of possible diameters is specified, an infinite number of circles is possible (albeit a smaller order of infinity than with scribbles), and information load is again infinite. An ellipse, by contrast, is perceived as slightly more complex than a circle, since an ellipse is free to vary in one or two additional dimensions (its proportions and perhaps its orientation as well). In each of these cases, it has been the assumed constraints, inferred by the perceiver, that allow the alternatives to a stimulus to be enumerated. This step is necessary for using IT, but it does not come from the theory itself.

Garner (1962) has discussed the problem of the "unique stimulus" at length. The problem is particularly important for perceptual organization, where the focus of attention is often on the unique stimulus and where the observer's perceptual processes are often different from those engaged by the performance tasks where IT has proven most successful. We return to this problem, and some solutions to it, after reviewing the fundamentals of IT.

7.2. A Primer on Information Theory

This section is provided for readers who are either unfamiliar with the basics of the theory or who may need a brief review of its essentials. It concentrates on only those concepts relevant to perceptual organization. This brief overview cannot substitute for more complete discussions, which are provided in Attneave (1959), Garner (1962), and Coombs, Dawes, and Tversky (1970).

Fundamentally, the information value of a stimulus is determined by its predictability or probability of occurrence. This proposition accords well with the common-sense definition of information as *news*; when one receives a message that is completely predictable, nothing new is learned, and so the information value of the message is zero. Conversely, when an unexpected message is received, we experience surprise, and the information value of the message is high. In the limiting case of a *totally* unexpected message, the information value would be infinite; but such an event rarely if ever occurs. Technically, the information value of a stimulus is specified by its uncertainty U: when you receive information, your uncertainty is reduced by some amount (all the way to zero if the information received uniquely specifies the stimulus in question).

7.2.1. The Guessing Game. To illustrate, let us borrow from the guessing game experiment used by Shannon (1951), the originator of IT (Shannon, 1948). Suppose you are receiving a passage of text over a communication channel (e.g., a computer terminal), one letter at a time. Your task is to predict each successive letter in the sequence before you may proceed to the next letter. Since there are 26 different letters possible at each step in the sequence (ignoring punctuation marks and other nonalphabetic symbols, case distinctions, and the like), you will often experience considerable uncertainty about what letter will occur next. In fact, if we were to begin this game at some randomly selected point in the text, you might resort mainly to guesswork, because you would have little basis on which to form an educated guess.

One obvious but inefficient strategy would be to guess at specific possibilities until you hit upon the correct answer (e.g., is it an A? . . . a B? . . ., etc.). Because there are 26 alternatives, on average you would hit upon the correct answer midway through the list, after 13 guesses or so, depending on chance factors. A more efficient strategy would be to ask more general questions, beginning with, "Does the letter fall between A and M (in the first half of the alphabet)?" Although neither a "yes" nor a "no" answer pinpoints the identity of the unknown letter, you can eliminate exactly 13 alternatives in either case. Following an optimal strategy (in accordance with IT), you can arrive at the exact identity of the letter after 4.7 guesses, on the average. (The first guess reduces the number of possibilities to 13; the second to 6.5; the third to 3.25; the fourth to 1.625; and the fifth to 0.8125, at which point the stimulus is overdetermined. Thus somewhere between the fourth and fifth guess you arrive at just one possibility, which corresponds to a state of complete certainty). Ignoring chance variations, 4.7 guesses is the logical minimum needed to arrive at the correct answer. Accordingly, the information value of a single letter sampled at random from 26 letters is 4.7 bits ("bits" is a contraction of "binary digits," and it reflects the fact that the answer to each question is binary in nature because it must be either a yes or a no). Each additional binary guess allows you to choose among double the number of alternative possibilities. It follows that the uncertainty U of a signal is proportional to the logarithm (to the base 2, for convenience) of the number of equally likely alternative stimuli that could occur. If there were 32 equally likely stimuli, $U = 5$ bits, since

$$U = \log_2(32) = 5 .$$

If there were 16 stimuli, $U = 4$ bits, since

$$U = \log_2(16) = 4 .$$

In the case of 26 equally likely alphabetic characters:

$$U = \log_2(26) = 4.7 \text{ bits} .$$

If you knew that the message you were receiving was a normal English sentence, you could arrive at the correct answer after fewer than 4.7 binary guesses because of the redundancy of the language. This redundancy comes from two basic sources. First, the 26 letters in English do not all occur with equal frequency: the letter E, for example, is much more common than the letter Z. The calculations above all assume that each alternative stimulus is as likely as the next, but when the probabilities of the alternatives vary, uncertainty is reduced and redundancy increases. Second, the sequence of letters in English text is constrained by orthographic rules that prohibit certain sequences (such as zq), mandate other sequences (such as u following q), and less dramatically favor certain ordered pairs over others (gh is more common than hg). Similarly, syntactic and semantic rules constrain what words are likely to follow others in normal text, which in turn increases predictability. In general the average uncertainty that exists when a variety of alternatives (with differing probabilities) is possible is as follows:

$$U = -\sum_i p_i \log_2 p_i , \qquad (1)$$

where p is the probability of occurrence of each of the i alternative stimuli. Stated verbally, the average uncertainty is given by the sum of the logarithms of the alternatives probabilities, each weighted by the negative of the alternative's probability.

7.2.2. Information Transmission and Channel Capacity. The best-known application of IT to perceptual processes came in the well-known channel-capacity experiments (Miller, 1956), which attempted to measure the maximum amount of information that could be conveyed over a single sensory channel. Subjects were presented with stimuli, one at a time, that varied along a single dimension, such as tones varying in amplitude. The task was one of absolute judgment; that is, subjects were asked to respond to each stimulus with a label (typically a digit) that uniquely identified the stimulus. The number of alternative stimuli possible was varied, so the average uncertainty of the stimuli varied as well. Channel capacity was measured by the maximum amount of information that subjects could transmit about the stimuli in their responses.

The procedure for measuring information transmission from such an experiment is as follows. First, a two-dimensional confusion matrix is created to summarize the subjects' data. In this matrix the rows correspond to the different stimuli and the columns to the different responses. The entry in each cell of the matrix is the probability of occurrence of that particular stimulus-response combination (e.g., the proportion of trials on which a given response was produced for a given stimulus). The entries in all the cells in the matrix must sum to unity. The marginal row and column totals of the matrix indicate the relative frequencies of the stimuli and of the responses without regard to their co-occurrence or correlation.

The uncertainty of the stimuli U_s, which is entirely determined by the experimental design, can be computed by applying Eq. (1) in Section 7.2.1 to the row marginals. Similarly, the uncertainty of the responses U_r, which is entirely determined by the subjects' responses, can be computed from the column marginals. Last, the uncertainty of the total set of co-occurrences (called the *joint* uncertainty, or $U_{s,r}$) can be calculated in identical fashion. Given these three terms, information transmission $U_{s:r}$ is then computed as

$$U_{s:r} = U_s + U_r - U_{s,r} . \qquad (2)$$

In effect, information transmission is a measure of the nonmetric correlation between stimuli and responses. If each stimulus is invariably assigned its unique response, then all four quantities in Eq. (2) will have equal values. That is, U_r will equal U_s because the different responses occur with frequencies identical to the different stimuli, and $U_{s,r}$ will have the same value as well because each row and column of the matrix will have only one nonzero value. It follows from simple algebra that $U_{s:r}$ will have the same value as the other three terms, and information transmission will be perfect since all the information contained in the stimuli has been conveyed with perfect, one-to-one correspondence in the responses. However, should each stimulus be associated with more than one response, the correlation will drop; the $U_{s,r}$ term will increase (indicating more alternative stimulus-response pairings), and $U_{s:r}$ will decrease. Finally, should there be no correlation between stimuli and responses, the $U_{s,r}$ term will be equal to the sum of U_s and U_r, and $U_{s:r}$ will become zero, indicating that no information has been transmitted.

7.2.3. Experimental Data. A vast literature on channel capacities for various perceptual dimensions has yielded a remarkable convergence on an estimated capacity of between two and three bits for virtually all unidimensional continua (Garner, 1962; Miller, 1956). This estimate corresponds to perfect performance in identifying between four and eight equiprobable alternative stimuli. For example, Garner (1953) found a channel capacity of 2.1 bits for identifying tones that varied in loudness. This indicates that as long as there were no more than four or five different tones presented, subjects could identify them consistently without error. But beyond five stimuli, information transmission remained at a ceiling of 2.1 bits, indicating that a channel capacity limit had been reached, as depicted in Figure 36.35. (This figure also indicates the unique ability of the information transmission measure to reflect a channel's maximum capacity. Other measures, such as overall percentage correct identification, show perfect performance at low levels and declining performance at higher levels of stimulus uncertainty. Thus the percentage correct measure fails to capture the manner in which a channel conveys increasing amounts of information until its capacity limit has been reached.)

When the stimuli employed in these absolute judgment experiments are multidimensional, higher estimates of channel capacity are obtained. If the information conveyed by each dimension (or channel) could be processed independently, we would expect that the total information transmission estimate would equal the sum of the capacity estimates for each component dimension. However, the total is generally lower than this

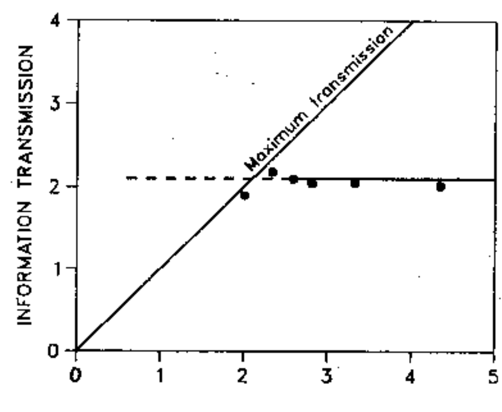


Figure 36.35. Channel capacity for auditory loudness judgments. This figure shows a typical function demonstrating a channel capacity of between two and three bits for absolute judgments of stimuli varying along a single sensory continuum. In this case the stimuli were tones whose intensities ranged from 15–110 DB, and 4–20 stimuli were used in each judgment task. The abscissa indicates the amount of stimulus uncertainty (in bits) over the different tasks; the ordinate indicates the amount of information transmitted (in bits) for each task. Although no tasks were tested in this experiment using fewer than two bits of stimulus uncertainty, the figure shows an idealized, bilinear function that levels off abruptly at about 2.1 bits. In other words, subjects continue to identify all test stimuli correctly as long as there are no more than four stimuli to be judged; beyond four, information transmission does not continue to increase. (From W. R. Garner, *Uncertainty and structure as psychological concepts*. John Wiley & Sons, Inc., 1962. Reprinted with permission.)

(Miller, 1956). For example, Egeth and Pachella (1969) had subjects judge either the horizontal or vertical position of a dot on a card and found a channel capacity of 3.4 bits for each dimension. But when subjects judged both dimensions, total capacity was measured at 5.8 bits, considerably higher than 3.4 but lower than the 6.8 predicted by additivity. One contributing reason for this underadditivity is that the dimensions of horizontal and vertical position were not being processed independently, which is consistent with evidence that these two dimensions are *integral* (Garner & Felfoldy, 1970; see also Treisman, Chapter 35).

7.3. Pattern Perception and Redundancy

A good Gestalt, as we have seen, is one that possesses a simple structure and whose components are (1) few in number, (2) regular in shape, and (3) arranged in a symmetrical fashion. Whereas poor patterns are presumed to be complex in structure, good ones are redundant; for that reason good patterns are thought to be perceived more quickly and remembered more accurately than poor patterns. Many experiments on pattern perception inspired by IT have failed to corroborate these claims. Mixed results have arisen in part because of IT's focus on sets of stimuli rather than on the individual stimulus and in part from confusion about the meaning of redundancy.

7.3.1. Experimental Evidence. Let us consider three experiments that Garner (1962) analyzed in detail to explain this problem. The first experiment, by Bricker (1955), required subjects to learn verbal labels for the visual patterns shown in Figure 36.36 (Garner, 1962, p. 188). The stimulus display consisted of five pairs of lights (denoted as a, b, c, d, and e in Figure 36.36, which shows all eight displays tested), one light above the other. Patterns were created by illuminating either the upper or the lower light of each pair. The dependent variables were the speed of learning the pattern-label pairs and the speed of responding to the briefly flashed light patterns. In one condition, only the three rightmost light pairs (c, d, and e) were illuminated, while in another condition all five pairs were used. As Figure 36.36 reveals, the three rightmost lights are illuminated in all possible combinations over the eight stimuli. Thus these three-light displays involve three bits of uncertainty, one for each light pair. The five-light displays also involved just three bits of uncertainty, even though they contain five lights. The reason may be explained in two equivalent ways. First, light-pairs a and b are completely redundant because pairs c, d, and e alone uniquely identify each of the eight patterns; thus the two bits of information provided by pairs a and b are redundant and need not be attended to. A second way to understand this logic is that while five pairs of lights can be used to generate 32 possible patterns (with an uncertainty of five bits), only eight patterns were actually used in the experiment (with an uncertainty of just three bits); thus, the selection of just eight of the 32 possible patterns creates two bits of redundancy.

Bricker's results were clear-cut: the redundant, five-light patterns were both learned and responded to more slowly than the three-light patterns. In short, redundancy hurt performance rather than helped it. The only way to increase redundancy in a set containing a fixed number of patterns is to increase the number of dimensions along which they are free to vary. Increasing redundancy thus makes the patterns more *complex*, not more simple. The added redundancy will often make the patterns more discriminable from each other (because they will

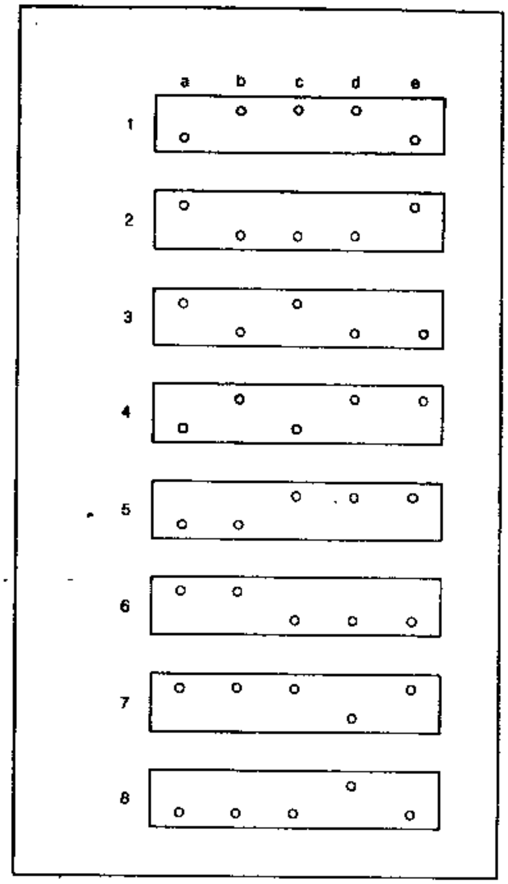


Figure 36.36. Bricker's (1955) stimuli. The stimuli were presented in a display containing ten lights, arranged as two rows of five lights each. Patterns were created by illuminating one of the two lights in each of the five columns. In one condition only the lights in the three rightmost columns (c, d, and e) were illuminated; in the other condition, the lights in columns a and b were added, but these were completely redundant with the other three lights. The dependent variables were the speed of learning verbal labels for the eight patterns used, and the speed of responding with these labels to the briefly flashed light displays. (From W. R. Garner, *Uncertainty and structure as psychological concepts*. John Wiley & Sons, Inc., 1962. Reprinted with permission.)

differ in more ways than will less redundant sets), but their added complexity may require *more* time, not less, to perceive and to learn, as Bricker apparently discovered. In a similar experiment by Deese (1956), complex figures were responded to more slowly but also more accurately than the simple ones (see Figure 36.37). In this case redundancy did lead to greater discriminability, but only at the cost of increased processing time. That is, subjects could exploit the redundant information in the complex patterns, but it took them extra time to do so. In short, the effects of redundancy on human perception and performance are not always obvious.

A third experiment by Attneave (1955) is especially useful for contrasting the information-theory meaning of redundancy as applied to sets of patterns and the less formal Gestaltist meaning of the term as applied to individual patterns. This experiment required subjects to identify (by labeling or by reproducing) dot patterns that were created by filling in cells of two-dimensional matrices. The cells of the matrices were filled in either at random or in a fashion constrained to produce symmetrical (mirror-reflected) patterns. Attneave's main results were that the symmetrical patterns were identified more ac-

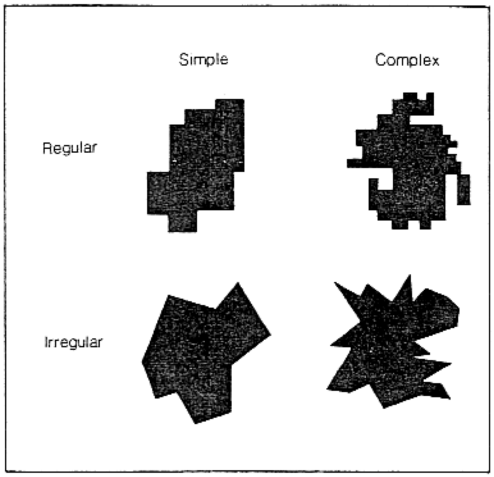


Figure 36.37. Deese's (1956) stimuli. The four patterns shown are a representative sample of Deese's stimuli, which varied in (1) "simplicity," measured by the number of sides the pattern contains, and (2) "regularity," measured by whether the pattern was constrained to contain only right angles or could contain angles of any magnitude. Subjects were shown individual patterns and then were required to select that same pattern from a group of patterns of the same level of simplicity and regularity.

curately than the random (asymmetrical) ones, and that patterns created within smaller matrices were identified better than those created with matrices containing more cells.

From the Gestalt viewpoint, Attneave's results are quite reasonable, because they show superior performance with symmetrical patterns and with less complex patterns created with smaller matrices. From an information-theory viewpoint, Garner notes, quite different conclusions may be drawn. First, Attneave's symmetrical patterns are no more (or less) redundant than his asymmetrical patterns in the technical sense of the term. That is, *any* pattern created within a matrix of a given size is as predictable as any other, regardless of its symmetry, for the same reason that in flipping coins a sequence of five heads in a row is no more or less predictable than any of the other 31 possible sequences. Selecting only symmetrical patterns has no bearing on the *amount* of redundancy, which is solely a function of the number of patterns actually selected relative to the maximum number that could have been selected. Instead, selecting symmetrical patterns affects only the *form* of that redundancy. Second, the decrease in performance as the pattern matrices grew larger shows the same deleterious effect of redundancy on performance that was demonstrated by Bricker (1955). Because the same number of visual patterns were employed at each matrix size, the patterns from larger matrices were more redundant (that is, they differed from each other in more ways; or equivalently, they were drawn from a larger parent set) than those from the smaller matrices.

see Garner '62

7.3.2. The Unique Stimulus. A major obstacle in applying IT to pattern perception has been that IT allows us to measure the redundancy of sets of patterns but not of an individual pattern such as a single circle or a particular polygon. Indeed, redundancy (like correlation) applies only to sets of items and in particular to constraints on the way in which they vary. A single item has no variability and therefore can have no measure of redundancy.

Several ways around this obstacle have been attempted with some success, although no general solution to the problem has been proposed. One approach has been to abandon the framework of IT for other formal methods of measuring pattern complexity; this approach is discussed in Section 8 under the topic of structural information theory and elsewhere in this volume in the context of autocorrelation techniques. The other kind of approach, which stays within the framework of IT, was proposed by Garner (1962) and developed by Garner and his colleagues (Garner & Clement, 1963; Royer & Garner, 1966). The essential idea is that when a simple, regular, and symmetrical pattern is said to be redundant, this means that the perceiver infers that the pattern has been drawn from a small subset of alternative patterns. That is, the perceiver makes an inference about what dimensions were free to vary in the pattern, or equivalently what constraints were used in the process of generating the pattern.

7.3.3. Inferred Subsets. This concept of inferred subsets has been developed most fully for simple dot patterns like those shown in Figure 36.38 (Garner, 1974, p. 12; see Palmer, 1982, for a recent expansion of Garner's ideas). These patterns are produced by filling in selected cells of an imaginary 3×3 matrix. Because the matrix contains nine cells, there are 512 (i.e., 2^9) patterns possible. However, only patterns containing at least one dot in each row and each column of the matrix were used. This constraint reduces the number of possible patterns to 120. The two stimuli in the leftmost column of Figure 36.38 are judged by subjects to be the "best" Gestalts and are most likely to be described as redundant. Further, they are the most symmetrical patterns possible because they show symmetry around four axes (horizontal, vertical, and the two diagonal axes) and are rotationally symmetrical as well. The patterns

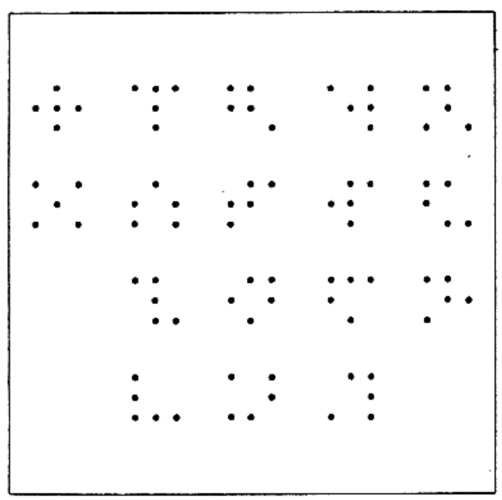


Figure 36.38. The Garner-Clement dot patterns. The patterns shown are a representative sample of the stimuli used first by Garner and Clement and subsequently by a large umber of investigators. The patterns are created by filling in five of the nine cells of an imaginary 3×3 matrix, subject to the constraint that each row and column in the matrix contain at least one dot. The patterns in the leftmost column are the "best" configurations and come from an R & R subset of one, which means that only one pattern results as the stimulus is rotated in 90° increments or is reflected. The patterns in the next two columns are of intermediate goodness and come from an R & R subset of size four. The patterns in the two rightmost columns are poor and come from R & R subsets of size eight. The results of numerous experiments show that the better patterns are easier to remember than the poor ones and so show superior performance in a variety of perceptual information-processing tasks. This figure demonstrates the concept of inferred subsets. (From W. R. Garner & D. Sutliff, The effects of goodness on encoding time. *Perception and Psychophysics*, 1974, *16*. Reprinted with permission.)

in the next two columns are judged to be less "good," and physically they are symmetric around fewer axes than the previous stimuli. Finally, the patterns in the two rightmost columns are judged to be the "poorest" patterns, and objectively they contain no symmetry.

According to Garner, perceivers infer that the better patterns are drawn from smaller subsets of equivalent stimuli than the poorer ones. He also has shown that a pattern's equivalency subset can be regarded as the set of patterns produced when that pattern is subjected to all possible combinations of rotation (in increments of 90°) and of reflection. When the two best patterns in Figure 36.38 are so rotated and reflected, the patterns remain unchanged. Thus they are said to come from a subset of just one pattern. In Garner's notation, their R & R (rotation and reflection) subset size is one. The patterns of intermediate goodness yield four different variations when rotated and reflected, and so they come from an R & R subset of size four. Last, the poor patterns yield eight variations and so come from an R & R subset of size eight.

The notion of an inferred subset takes us from the realm of unique stimuli to the realm of sets of stimuli, and so the information-theory concept of redundancy now becomes meaningful. The best patterns are maximally redundant, whereas the poorer patterns possess progressively less redundancy. This kind of redundancy *does* facilitate pattern discrimination and pattern memory in a variety of information-processing tasks; as we demonstrate later, good patterns are better remembered and more rapidly discriminated from one another than are poor patterns.

7.3.4. Perceived Subsets. Whereas the R & R method was used to identify *inferred subsets* of equivalent dot patterns, a second method uses the number of perceived organizations that a given stimulus can possess to identify *perceived subset* sizes. The more alternative organizations an observer can impose on a stimulus, the larger is that stimulus's perceived subset size. Royer and Garner (1966) first applied this method to temporal auditory patterns. These patterns are produced by alternating between two distinguishable sounds (e.g., two tones of different frequency) according to a specified pattern. This experiment used patterns of eight elements, as shown in Figure 36.39 (Garner, 1974, p. 50), where the two auditory elements are represented by X's and O's. The patterns were presented in cyclical fashion wherein the eighth element would be followed by the first element in an unbroken tempo. Subjects were asked to describe the patterns by tapping them out on a pair of telegraphic keys as they were hearing them.

Because the patterns were presented repeatedly in an uninterrupted loop, there is no inherent starting point to the pattern. In principle, subjects could begin tapping at any of the eight positions within the sequence. The data show, however, that subjects perceive clear starting points for most such patterns because they start tapping only at certain of the eight possible positions. Subjectively, too, the patterns appear to be strongly organized, with distinct beginnings and ends. A major finding from this research is that some patterns have only a small number of perceived starting points, whereas other patterns have many. This fact provides the necessary link to measure the size of a pattern's perceived subset and thus to assess its redundancy. In agreement with the results on dot patterns, Garner and his colleagues found that the more redundant temporal patterns (that is, those with few perceived alternatives) were perceived more rapidly and accurately than the less redundant ones.

```
...X X X O X O X O...
  ...X X O X O X O X...
    ...X O X O X O X X...
      ...O X O X O X X X...
        ...X O X O X X X O...
          ...O X O X X X O X...
            ...X O X X X O X O...
              ...O X X X O X O X...
```

Figure 36.39. Royer and Garner's repeating auditory patterns. Shown is one binary auditory pattern of length eight, which consists of a continuing alternation of two auditory stimuli (e.g, a bell and a click), represented here by an X and an O. Because the patterns are repeated indefinitely, they can be described using any of eight possible starting points, as shown here by the eight rows. The subject's task is to learn the patterns and to respond to them by tapping out the sequence on a pair of telegraph keys. Although subjects could begin tapping out the pattern at any of the eight starting points, for many patterns subjects used only one or two, indicating that they had perceptually organized the pattern with a clear starting and ending point. For other patterns, however, many more starting points were used, indicating that these patterns were less organized perceptually, or in other words were poorer patterns. In agreement with the work on visual configurations, the poorer patterns were more difficult to learn and to perceive. This figure demonstrates the concept of perceived subsets. (From W. R. Garner & D. Sutliff, The effects of goodness on encoding time. *Perception and Psychophysics*, 1974, *16*. Reprinted with permission.)

The perceived subset approach has been shown to be applicable to dot patterns as well as to temporal patterns (Pomerantz, 1981). When subjects are asked to indicate their perceived organization of a dot pattern by drawing connecting lines between the dots to indicate the pattern's perceived structure, the "good" patterns yield many fewer alternative organizations than do the "poor" patterns. Thus the perceived subset technique may have some generality for assessing the redundancy of many different types of pattern.

7.4. The Role of Pattern Goodness in Information Processing

At this point, we have established that information-theoretic constructs can be adapted to capture the psychologically relevant properties of good Gestalts such as simplicity and symmetry. We have also seen that patterns that are good Gestalts can lead to superior perceptual and memory performance. Let us now examine in more detail the precise nature of these performance effects to see when they do and do not appear and to gain a clearer conception of how and where they arise in the perceptual and memory systems. This discussion is limited to dot patterns because these are the patterns that have been studied most exhaustively in the laboratory.

7.4.1. Memory. Attneave (1955), discussed briefly before, showed that good (symmetrical) dot patterns are not necessarily remembered better than poor ones. Subjects reproduced patterns in an empty matrix immediately following their presentation. One set of patterns was produced within a 3×4 matrix. A second set was produced within a 5×4 matrix, either by filling in cells at random or by reflecting the pattern of the 3×4 matrix about the vertical axis to yield a pattern with vertical symmetry. The third set was produced within a 5×7 matrix, either by filling in cells at random or by reflecting the pattern of the 5×4 matrix about the horizontal axis to yield a pattern with both horizontal and vertical symmetry. The results showed superior performance for symmetrical patterns over asymmetrical patterns within the same-sized matrix; and superior memory for patterns in the smaller matrices than in the larger. But the doubly symmetric patterns within the 5×7 matrix were remembered more poorly than the singly symmetric ones within the 5×4 matrix, which in turn were remembered more poorly than the random (asymmetric) patterns in the smallest 3×4 matrix. Thus symmetry does improve memory when the total matrix size is held constant; but a small, asymmetric pattern is remembered better than a larger pattern produced by reflecting it about an axis.

7.4.2. Perceptual Discrimination. Clement and Varnadoe (1967) tested the discriminabilities of pairs of dot patterns. They used the Garner-Clement patterns shown in Figure 36.38 in a speeded card-sorting task. The dependent measure was the time required to sort a shuffled deck of cards into two piles (one for each of the two different patterns in the deck). The main finding was that sorting times were shortest when two good patterns were discriminated and longest when two poor ones were discriminated; discriminating a good from a poor pattern required an intermediate amount of time.

Subsequent experiments have attempted to localize the stages of processing responsible for Clement and Varnadoe's discriminability effect. Although their result might suggest that the effect is due to slower pattern comparison for poor patterns, it could also be due to either slower encoding of poor patterns or to a more difficult memory load in tasks involving poor patterns. (Because subjects must keep the patterns to be discriminated in memory while performing the task, a greater memory load for poor patterns could impair performance.) Garner and Sutliff (1974) repeated the Clement and Varnadoe experiment using a discrete reaction time (RT) procedure to obtain RTs to individual patterns (something not possible with the card-sorting technique). Besides replicating the earlier findings, Garner and Sutliff found faster RTs to the good pattern than to the poor one in the tasks requiring discriminating one good from one poor pattern. This asymmetry suggested that good patterns were perceived or encoded faster than poor ones. Consistent with this interpretation is Bell and Handel's (1976) finding that under conditions of poststimulus masking, good patterns are identified more accurately than poor ones, even though no such difference is apparent when no mask follows the stimulus presentation. The logic here is that good patterns are perceived more quickly and thus stand a better chance of being encoded fully before the appearance of the mask.

Checkosky and Whitlock (1973) used Sternberg's (1969) additive factors method to localize the effect of pattern goodness in a memory-scanning task. In this task subjects memorized sets of two or three patterns, which comprised the memory set. The patterns in the memory set were either all good patterns or all poor patterns. Probe patterns were then presented one at a time; subjects were to make one response if the probe was a member of the memory set and a different response if it was not. In addition, probes were presented under conditions of either high or low contrast (visibility). Checkosky and Whitlock found an interaction of memory set goodness and memory set size (two versus three patterns) such that the slope of the function relating RT to the size of the memory set was greater when poor patterns comprised the memory set. Following Sternberg (1967), this indicates an effect of goodness on the speed of memory comparisons, and it is consistent with the findings reviewed previously showing that good patterns are remembered better than poor ones.

Checkosky and Whitlock further found no interaction between probe goodness and probe contrast. Following additive factors logic, two factors that affect the same stage should yield interactive effects on RT; presuming that probe contrast affects the encoding stage, this logic dictates that pattern goodness does *not* affect encoding. However, Garner (1974) analyzed Checkosky and Whitlock's data further and discovered that probe goodness affected the y-intercept of the function relating RT to memory set size, with good probes showing smaller intercepts than poor ones. Such a result indicates an effect of goodness in some stage of processing separate from memory operations, perhaps in the encoding stage.

Pomerantz (1977) attempted to clarify this conflict about whether pattern goodness affects speed of encoding with a discrete RT experiment in which the positive (memory) set consisted of only a single pattern (good or poor), while the negative set contained either two or four patterns, which could be all good or all poor. The results were as follows: the goodness of probes that were in the positive set had a large effect on RTs (indicating a goodness effect on memory), but the goodness of probes in the negative set (which had to be encoded but were not held in memory) did not matter. Accordingly, Pomerantz's (1977) con slusions were in agreement with those of Checkosky and Whitlock (1973) that good patterns are perceived no more quickly than poor ones. Good patterns are processed better than poor ones in a variety of performance tasks, but the advantage held by good patterns appears to be due to the memory component of processing.

This conclusion is important for theories of perceptual organization because it is simple to imagine models in which good patterns would be encoded more quickly than poor ones. Good patterns are symmetrical, contain fewer perceived parts, and contain other structural properties that might allow them to be encoded more rapidly than their poorer counterparts. Perhaps this conclusion that goodness does not affect encoding speed should be tempered by noting that these discrimination time tasks may not require as detailed an analysis of the stimulus as do other tasks that have a more substantial memory requirement. That is, in discrimination tasks patterns must be encoded only to the point where the subject can determine whether they match another pattern held in memory. In Bell and Handel's (1976) experiment, subjects presumably had to encode patterns into a more lasting form of memory representation so they could reproduce them a few moments later. This experiment showed a substantial goodness effect, which suggests that good patterns can be recoded into memory more quickly than poor ones.

7.5. Summary

As noted at the outset of this section, IT has proven a useful, and in several applications a necessary, tool for understanding the nature of the stimulus and how stimulus information is processed perceptually. IT describes limits on the processing capabilities of an ideal observer who retains and integrates information without error and who knows the objective, a priori probabilities of occurrence of the various alternative stimuli. IT does not address how information is processed in human perception and so cannot be used as a descriptive model for the human perceiver. But it can serve as a useful guide once we know how subjects derive their own sets of alternative stimuli. More important, IT has provided essential measurements of perceptual performance and has helped us understand what is meant by such otherwise ill-defined concepts as simplicity and redundancy. Those concepts are difficult enough to make operational even with the aid of IT; without such a formal model, our level of confusion would be far greater than it currently is.

Ultimately we want a model that describes both the functional information load carried by a stimulus (and its alternative organizations) and the processes through which the stimulus is organized and perceived. The next section describes an approach that addresses the first of these two goals. Known both as structural information theory and as coding theory, this approach is not a descriptive model of the processes by which perception operates. But it does provide a framework for developing models for how complex stimuli may be described, models that would make testable predictions of how these stimuli are organized perceptually.

8. STRUCTURAL INFORMATION THEORY

Previously called *coding theory*, structural information theory (SIT) was developed by E. L. J. Leeuwenberg and H. F. J. M. Buffart, and in recent years by the late Frank Restle. The theory is a descendent of the work of Simon and his colleagues (Simon, 1972, 1978; Simon & Kotovsky, 1963), of Restle (1970b), and of Vitz and Todd (1969). Our presentation does not follow in all particulars the accounts of the theory written by Leeuwenberg and his co-workers because as it has evolved the theory has undergone changes both in form and in substance, ranging from the notational system used to the predictions generated. SIT is more difficult to evaluate than information theory, in part because the theory is still in a state of flux, because some of the theory's components have not yet been formalized, and because some of the main papers appear not to have been adequately translated from Dutch into English.

The key papers we have used are Buffart and Leeuwenberg (1981, Note 1); Leeuwenberg (1978); Buffart, Leeuwenberg, and Restle (1981); and Leeuwenberg (Note 2). We also consulted Leeuwenberg (Note 3) and Butler (1982). (For additional discussion of Leeuwenberg's work, see Chase, Chapter 28.)

8.1. Overview

SIT is designed to deal with a class of problem illustrated in Figure 36.40. The pattern in the center of the figure (a) is ambiguous: there are at least four ways to decompose it into parts. The most common interpretation is that labeled (b), two overlapping squares. Why is this interpretation more frequently perceived than the others? We have discussed some earlier approaches to this problem, most notably Hochberg and McAlister's (1953) analysis of the perception of perspective drawings of cubes. SIT differs from Hochberg's approach only in its degree of elaboration and formalization and its strategy of translating spatial patterns into list form.

The theory consists of the following five parts (note that these parts are not hypothetical stages of perceptual processing because SIT is not a process model):

1. Preliminary data. A set of mutually exclusive interpretations of a stimulus is obtained from phenomenological reports of

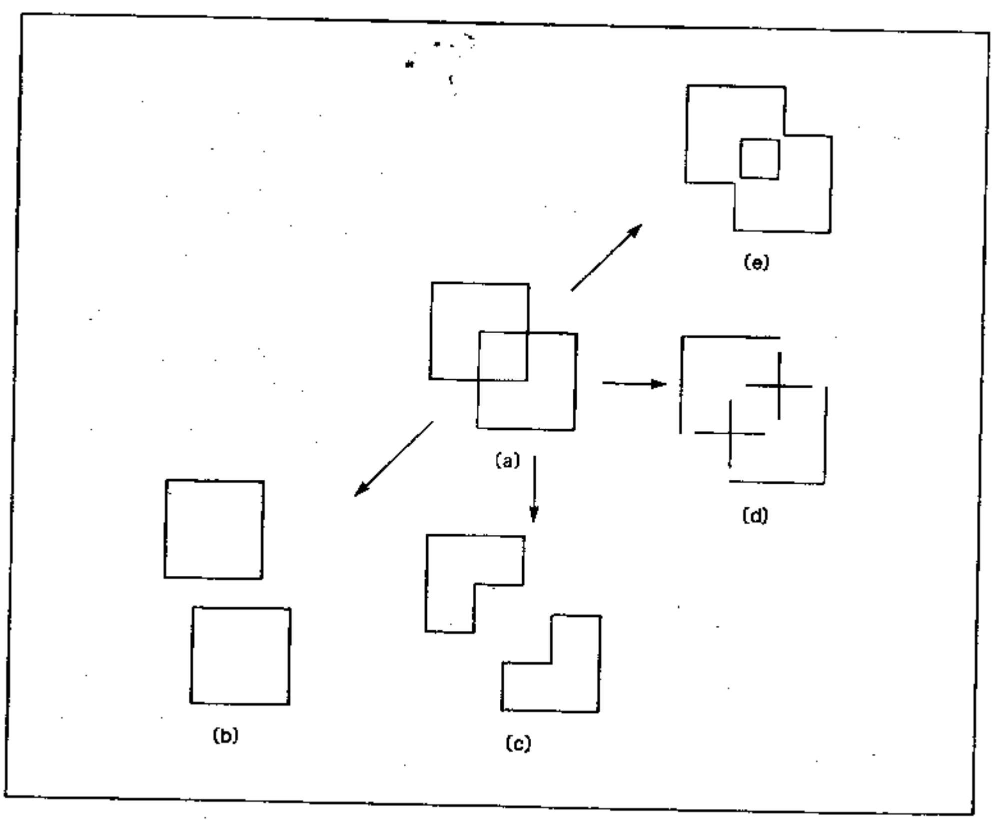


Figure 36.40. Four interpretations of a visual pattern. The central pattern shown at (a) can be interpreted by structural information theory in at least four ways (b–e). These four interpretations will result in four unique codes as described in the text. (Adapted from Leeuwenberg, 1978, Figure 1.)

observers. SIT assumes that the perceptual system considers more than one interpretation before the stimulus is perceived in a fashion consistent with one of these interpretations. The process by which the perceptual system constructs these alternative interpretations is called *perceptual inference*.

2. Semantics. A primitive code is computed for each interpretation. The procedure for generating a primitive code from an interpretation is embodied in the *semantics* of SIT, which consists of a set of *semantic operators* and *rules* for their application.
3. Structural information load. The number of parameters in the code, or the code's *structural information load* (SIL), is calculated.
4. Syntax. Rewrite rules are used to extract all redundancy from the primitive code of each interpretation. This is equivalent to reexpressing a primitive code to minimize its SIL. The product of this process is called an *end-code*.
5. Perceptual decision. A procedure to calculate the *strength of interpretation preference* underlies SIT's prediction of the outcome of the *perceptual decision* process, that is, the likelihood of a given interpretation's being assigned to the stimulus.

8.2. Semantics

Each interpretation of a stimulus can be coded, that is, represented symbolically. An interpretation of a line drawing is usually coded in terms of two kinds of *primitive elements*, line segments and angles, after an origin (a starting point and a starting direction) has been specified. The resulting string of symbols is called a *primitive code*. Each symbol in a primitive code can be viewed as an instruction to a draftsperson, and the whole string can be viewed as a program to reconstruct the entire figure. For instance, Figure 36.41a, is coded

$$\overline{1}\ \widehat{90}\ \overline{1}\ \widehat{90}\ \overline{1}\ \widehat{90}\ \overline{1}\ , \qquad (3)$$

where $\overline{1}$ represents the length of the side of the square, and $\widehat{90}$ is a counterclockwise 90° angle.

It is unclear from available accounts of SIT whether the code of an interpretation is or is not unique. For example, in Figure 36.41b, the starting direction associated with the origin is different from that in Figure 36.41a. The corresponding primitive code is

$$\widehat{90}\ \overline{1}\ \widehat{90}\ \overline{1}\ \widehat{90}\ \overline{1}\ \widehat{90}\ \overline{1}\ . \qquad (4)$$

Similarly, the primitive codes for Figure 36.41*c* and *d*, respectively, are

$$\overline{i}\ \widehat{90}\ \overline{1}\ \widehat{90}\ \overline{1}\ \widehat{90}\ \overline{1}\ \widehat{90}\ \overline{j}\ , \qquad (5)$$

and

$$a\ i\ \widehat{90}\ j\ i\ \widehat{90}\ j\ i\ \widehat{90}\ j\ i\ \widehat{90}\ j\ , \qquad (6)$$

where i and j represent line segments such that $i + j = \overline{1}$, and a is an acute counterclockwise angle. Given the current state of the theory, it is unclear whether these four expressions should be considered as primitive codes for a single interpretation or for four different interpretations of the square; on the basis of parsimony, we assume the latter.

The semantics of SIT are not limited to the coding of straight-line patterns. For a brief treatment of the coding of drawings that contain curved segments see Buffart, Leeuwenberg, and Restle (1981). Restle (1979) developed the semantics for the coding of motion displays of the kind used by Johansson (1950). In these dynamic displays each of a small number of lights was displayed either in uniform circular motion or in a parallel projection of a uniform circular motion. When the trajectory of a light was not circular, it was either elliptical (in which case the dot moved most quickly at the minor axis and most slowly at the major axis) or linear (in which case its velocity was a sinusoidal function of time). Figure 36.42 illustrates the parameters required to specify these motions. The projected uniform circular motion that underlies each light in the display requires three parameters to be specified completely: its amplitude (the radius of the circular trajectory, a, in units of length); its phase (the position of the light on its trajectory at some reference instant, ϕ); and its frequency (f in Hertz). Two more parameters (the angles b and t) are required to specify the orientation of the plane in which the underlying circular motion is taking place relative to the picture plane. Thus if the motion of a system composed of a single light p is interpreted as the

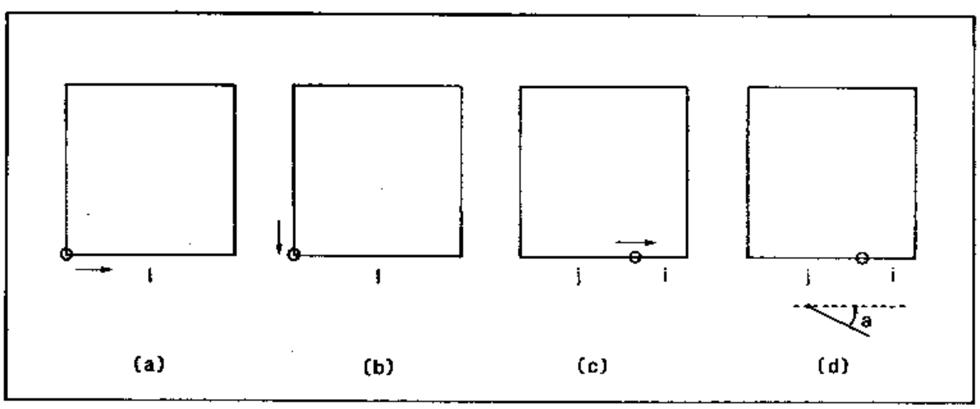


Figure 36.41. Four ways to code a square. The coding process begins with the selection of an origin, defined as a starting point and a starting direction. The four codes shown differ in their origin. As the text explains, it is unclear whether these different origins will all result in unique, different codes. The origin is indicated by a circle. The primitive elements are the line segments *l*, *j*, and *i* and angles a. The arrow shows the starting direction.

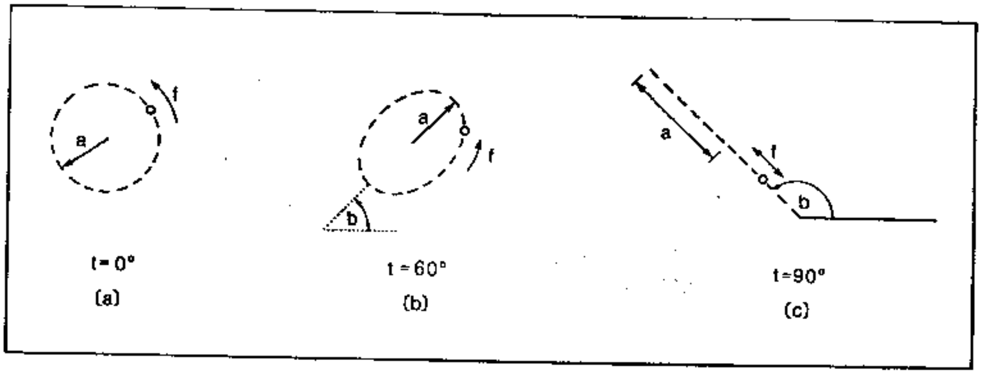


Figure 36.42. Restle's coding of motion configurations. The motion parameters required to code three types of motion along trajectories are indicated by dotted lines. (a) Uniform circular motion of a single light taking place in a plane parallel to the picture plane (t = 0°). (b) Elliptical motion represented as the projection of uniform circular motion in a plane that is tilted 60° to the picture plane (t = 60°) and that is also tilted 45° with respect to the horizontal plane (b = 45°). (c) Linear motion represented as the projection of uniform circular motion in a plane that is tilted perpendicular to the picture plane (t = 90°) and that is also tilted 135° with respect to the horizontal plane (b = 135°). The remaining parameters are a, which indicates the amplitude of the motion, f, indicating the frequency of the motion, and the phase of the motion, which is represented implicitly by the position of the light on its trajectory. (Adapted from Restle, 1979).

projection of a uniform circular motion, its primitive code will be

$$M_{a\phi fbt}(p)\ . \tag{7}$$

But if the motion is perceived as uniform circular motion in a context in which all motions are uniform, circular, the primitive code will consist of only three parameters:

$$M_{a\phi f}(p)\ . \tag{8}$$

For displays containing more than one moving light, the motions may be interpreted as being unrelated, with each light's trajectory being coded to the same stationary frame of reference; or the motions may be interpreted relative to each other in a hierarchical organization. An example of the latter is the case of a ball bouncing on the floor of a moving train. If the moving configuration is interpreted hierarchically, the train would be perceived as moving horizontally and the ball as bouncing on a vertical trajectory relative to the frame of the train, even though the motion of the ball relative to the stationary ground below the train follows a damped sinusoidal trajectory.

8.3. Structural Information Load

When dealing with primitive codes, the SIL is easy to calculate, because it is simply the number of primitive elements (parameters) in the code. Thus the SIL of the code in Eq. (3) is 7, and that of Eq. (7) is 5. We show later, however, that the SIL of end-codes is not equal to the number of primitive elements they contain.

8.4. Syntax

SIT proposes certain formal devices for reducing the length of codes, which in turn reduces their SIL. Consider the following reduction of a primitive code of a line drawing by use of the *symmetry* (SYM) operator:

$$n\,a\,n\,n\,a\,n\,n\,a\,n\,n\,a\,n = \mathrm{SYM}[n\,a\,n\,n\,a\,n]\,, \tag{9}$$

which is further reduced as follows:

$$\mathrm{SYM}[n\,a\,n\,n\,a\,n] = \mathrm{SYM}[\mathrm{SYM}\{n\,a\,n\}]\,, \tag{10}$$

where a and n are arbitrary primitive elements. Equation (9) reduces the SIL of the primitive code from 12 (12 primitive elements) to 7 (6 primitive elements + 1 operator), and Eq. (10) reduces it further to 5 (3 primitive elements + 2 operators). These examples show that each SYM operator adds (by definition) 1 to the SIL; for an explanation, see Buffart and Leeuwenberg (1981). Another symmetry operator SYMM is used to condense patterns that are symmetric around a pivotal element or sequence (where n, a, p, q, and r, are arbitrary primitive elements):

$$n\,a\,p\,q\,r\,a\,n = \mathrm{SYMM}[n\,a\,(p\,q\,r)]\,. \tag{11}$$

Further reductions are made possible by using the *distributive property*, indicated by the use of triangular brackets ⟨⟩. For example:

$$a\,n\,a\,n\,n\,a\,n\,n\,a\,n\,n\,a\,n$$

$$= \langle a\rangle\langle(n)\,(n\,n)\,(n\,n)\,(n\,n)\,(n)\rangle\,, \tag{12}$$

which reduces the SIL from 13 to 9. The *iteration operation*,

$$\langle a\rangle\langle(n)\,(n\,n)\,(n\,n)\,(n\,n)\,(n)\rangle =$$

$$\langle a\rangle\langle(n)\,3{*}[(n\,n)]\,(n)\rangle\,, \tag{13}$$

further reduces the load from 9 to 6. (Note that the various types of parentheses and brackets, as well as the iteration symbol *, do not add to the SIL.)

In the case of Restle's primitive codes for motion perception, there is only one rule for syntactic elimination of redundancy:

if the motions of two lights are interpreted as sharing a parameter (for instance, if they have the same frequency, or are in phase, or are both linear harmonic motions, and hence have the same tilt), reduplicated parameters are suppressed from the primitive code, yielding an end-code with only one token of each parameter. In other words, in this context the SIT reflects the number of *different* parameters in the primitive code of an interpretation.

8.5. Perceptual Decision

On the basis of the SIL of the several possible interpretations of a figure, SIT proposes a measure of the strength of the preference for the most common interpretation of a stimulus. If $I(A)$ and $I(B)$ are the SILs of interpretations A and B of a given stimulus, then the preference of interpretation A over B, denoted as $P(A > B)$, is a monotonic function of the ratio $I(B)/I(A)$. Evidence in favor of this prediction can be found in Buffart, Leeuwenberg, and Restle (1981); Restle (1979); and Leeuwenberg (Note 2). None of these experiments has studied the functional relation between the ratio of SILs and the probability of an interpretation being perceived. Thus this part of SIT has remained merely ordinal to the same extent as Hochberg and McAlister's (1953) scheme.

8.6. Critique of Structural Information Theory

The most innovative parts of SIT are the rules that allow the shortening of a primitive code into a parsimonious end-code. These have not yet been submitted directly to empirical test; indeed, such tests would probably be quite indirect in that they would be based on comparing the loads of alternative interpretations against people's preferred organizations of the stimuli. Any discrepancy between these two could indicate a problem with the rules employed or, more ominously, an error in the underlying assumption that human perception strives for economical descriptions of stimuli. Moreover, assuming that the general approach of using rules is correct, it is not clear in the absence of alternative sets of rules whether the rules just described are optimal or whether all the rewrite rules used in applications of SIT to line drawings are in fact necessary.

In Figure 36.43, adapted from Buffart, Leeuwenberg, and Restle (1981, Figure 19, display 1), a stimulus pattern is shown at (e), along with illustrations of the two most common interpretations of the stimulus. The top pair, (a) and (b), show the features required to present Buffart et al.'s code; the bottom pair indicates an alternative coding scheme devised by the present authors and explained later.

The codes obtained by Buffart and his colleagues use two new context-dependent operators. Both are continuation operators, and they have the form $@;(x)$ where x can either be any string of symbols or an &, which represents an infinitesimal element and is called the *grain*. The first operator $@;(x)$ means, "repeat x until a part of the figure already specified in the code is encountered." If the x is a string of primitive elements, the meaning of $@;(x)$ is made clear by the following reduction of the code of a square of side $\bar{1}$, where a stands for a right angle:

$$\bar{1}\,a\,\bar{1}\,a\,\bar{1}\,a\,\bar{1} = \bar{1}\,@;(a\,\bar{1})\,. \tag{14}$$

The resulting end-code has a lower SIL than

$$\bar{1}\,3*(a\,\bar{1}) \tag{15}$$

because the continuation operator is considered not to add to the SIL. The second operator $@;(\&)$ means, "draw a straight line until a part of the figure already specified in the code is encountered." This device makes it possible to code a square

$$\bar{1}\,a\,\bar{1}\,a\,\bar{1}\,a\,\bar{1} = \bar{1}\,a\,\bar{1}\,a\,\bar{1}\,a\,@;(\&) = 3*(\bar{1}\,a)\,@;(\&)\,. \tag{16}$$

We propose to show that these two continuation operators sometimes produce codes that are obscure because they are not

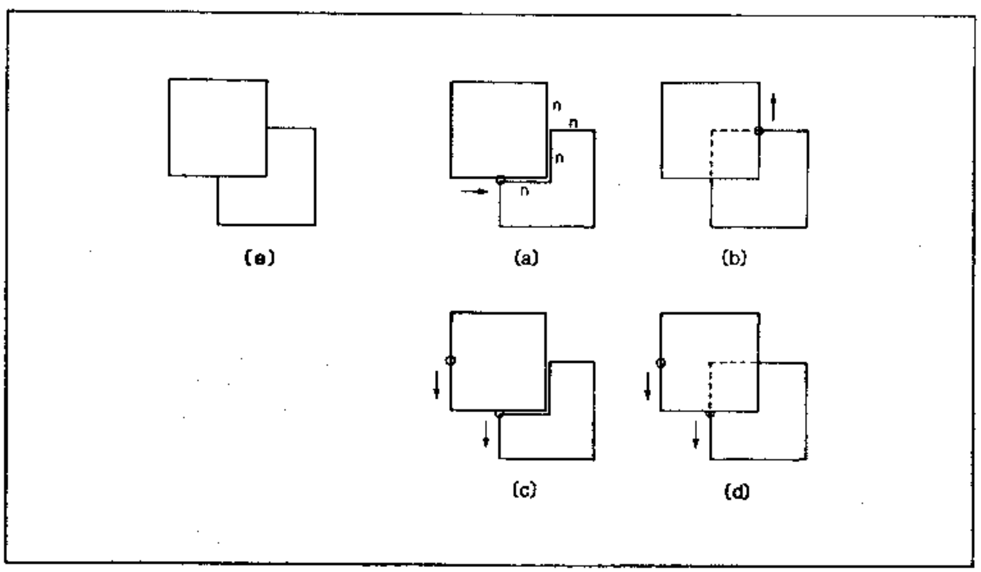


Figure 36.43. An alternative coding scheme to SIT. (e) The pattern to be coded. This pattern can be interpreted either as a mosaic in which one square is abutted with another square whose upper-left quadrant has been removed, (a) and (c), or as two squares, one of which occludes the other, (b) and (d). Parts (a) and (b) are labeled for the Buffart, Leeuwenberg, and Restle (1981) coding; (c) and (d) are labeled for the present authors' alternative coding. It is argued that the latter coding is more faithful to observers' perceptual organizations of the original pattern. [Parts (a) and (b) are adapted from Buffart, Leeuwenberg, and Restle, 1981.]

readily translatable into verbal descriptions that people might produce. In addition, the SIL of other codes, based on different primitives and operators, can be just as effective in predicting the verbal descriptions of human observers. From this we conclude that SIT in its current state lacks an adequate criterion for selecting recoding operators.

The two interpretations of the stimulus pattern at the top of Figure 36.43 are, first, a mosaic composed of one complete square and another square missing its upper left quadrant; and second, one complete square overlapping another complete square. Letting $-a$ stand for a clockwise angle of magnitude a, Buffart, Leeuwenberg, and Restle's (1981) code for the interpretation shown in Figure 36.43a is

$$n\,a\,n\,n\,a\,n\,n\,a\,n\,n\,a\,n - a\,n\,a\,n\,n\,a\,n\,n\,a\,n\,a\,n - a\,n \quad (17)$$

$$= @;(n\,a\,n) - a\,@;(n\,a\,n)\,a\,@;(\&) - a\,@;(\&) \quad (18)$$

$$= \langle @;(n\,a\,n)\rangle\langle(-a)\,(a\,@;(\&) - a\,@;(\&))\rangle\,. \quad (19)$$

Similarly, Buffart et al.'s code for the interpretation in Figure 36.43*b* is

$$n\,a\,n\,n\,a\,n\,n\,a\,n\,n\,a\,n\,a\,n\,a\,n\,n\,a\,n\,n\,a\,n\,n\,a\,n \quad (20)$$

$$= @;(n\,a\,n)\,@;(a\,n)\,@;(n\,a\,n)\,@;(\&) \quad (21)$$

$$= \langle(@;(n\,a\,n))\rangle\langle(@;(x))\,(@;(\&))\rangle\,, \quad (22)$$

where $x = a\,n$.

If we forgo the context-dependent continuation operator and we code each part of an interpretation (such as the complete and the incomplete squares in the mosaic interpretation) separately as a chunk, while taking care to use the same primitive elements as did Buffart et al., the mosaic interpretation shown in Figure 36.43c is coded in a far more transparent fashion:

$$(n\,a\,n\,n\,a\,n\,n\,a\,n\,n\,a\,n)(n\,a\,n\,n\,a\,n\,n\,a\,n\,a\,n - a\,n) \quad (23)$$

$$= [4^*(n\,a\,n)]\,[(3^*(x))\,\langle a\ -a\rangle\,\langle n\rangle]\,, \quad (24)$$

where $x = n\,a\,n$. The code of the two overlapping squares interpretation in Figure 36.43d is

$$4^*(n\,a\,n) + y\,, \quad (25)$$

where $y = 4^*\,(n\,a\,n)$.

According to Buffart et al., the SIL of the interpretation in Figure 36.43a, Eq. (19), is 6, and the SIL of Figure 36.43 b, Eq. (22), is 4. By contrast, our coding scheme yields an SIL of 9 for Figure 36.43c, Eq. (24), and an SIL of 5 for Figure 36.43d, Eq. (25). According to the data reported by Buffart et al. from three experiments, almost all subjects selected the interpretation shown in Figure 36.43b and d. Even though the end-codes proposed by Buffart et al. are quite different from the alternatives we have presented, as are their respective SILs, the ordering of the SILs is the same. Thus the data are consistent with both sets of end-codes. It is possible, however, to choose between the two pairs of end-codes on the grounds that those we have developed here attempt to mimic more closely the verbal descriptions subjects might produce for the original stimulus. For instance, in Eq. (24), $3^*(x) = 3^*(n\,a\,n)$ represents the intact part of the square (that is, its three quadrants), and $\langle a\ -a\rangle\,\langle n\rangle$ represents the missing quadrant.

Our purpose here is not to propose an improved version of SIT. Indeed, we are not certain that our proposal is entirely consistent with the spirit of SIT. Nevertheless, we consider it imperative for SIT to formulate explicit criteria for assessing the adequacy of primitive codes and end-codes.

8.7. The Influence of Context

As Garner (1974) has noted, the verbal description of a stimulus given by an observer will depend upon what other stimuli are present, have been present recently, or are suggested by the original stimulus. A stimulus that when presented alone might be called simply "a circle" is likely to be called "a single circle" if it follows presentation of a pair of concentric circles, or "a black circle" if it follows presentation of other stimuli varying in color. Although SIT does not address the issue of the relation between verbal descriptions of forms and end-codes, we have suggested that the cause of uniqueness of end-codes would be served well by using verbal descriptions as empirical data to which end-codes must conform in some fashion. If this suggestion is correct, the end-code of a figure will depend on other figures that comprise its context. Restle (1979) recognized this need explicitly in his discussion of the number of parameters required for the description of circular motion. It is difficult to see how SIT can accommodate this sort of context dependence without introducing further assumptions about the nature of contexts and their effects on verbal descriptions.

8.8. Prägnanz versus Likelihood

SIT was conceived in the spirit of the simplicity or prägnanz principle. Its authors state this explicitly, and they designed SIT specifically to produce end-codes that maximally exploit the symmetries and other regularities in the stimulus. Their measure of complexity of a pattern in its SIL, and their approach has been to search for coding rules such that organizations that are preferred by observers have smaller SILs than nonpreferred organizations. In this search coding rules that fail to produce minimal SILs for preferred organizations are rejected.

By way of assessment, we support SIT's approach of viewing perceptions as structural descriptions, and we applaud its goal of formalizing the codification of these descriptions. At the same time, this approach might benefit if its links with the prägnanz principle were weakened for the reasons cited, and if means could be found by which codes for *likely* elements would require fewer parameters than for unlikely elements, as the earlier quotation from Attneave (1981) suggests. With these modifications, SIT also would become capable of handling the many cases where the likelihood principle prevails over prägnanz. Finally, if the coding of patterns were tied more directly to the actual organizations of stimuli that are perceived by human observers, the result would be a theory of perceptual organization that is formal, testable, and congruent with phenomenology.

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