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Enduring Interest in Perceptual Ambiguity: Alternating Views of Reversible Figures

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Research favoring the so-called *bottom-up* and *top-down* classes of explanations for reversible figures that dominated the literature in last half of the 20th century is reviewed. Two conclusions are offered. First, any single-process model is extremely unlikely to be able to accommodate the wide array of empirical findings, suggesting that the "final" explanation will almost certainly involve a hybrid conceptualization of interacting sensory and cognitive processes. Second, the utility of distinguishing between 2 components of the observer's experience with reversible figures is emphasized. This distinction between the observer's ability to access multiple representations from the single stimulus pattern (*ambiguity*) and the observer's phenomenal experience of oscillation between those representations (*reversibility*) permits the literature to be segregated into useful categories of research that expose overlapping but distinctive cortical processes.

In the study of form perception, an intriguing class of stimuli has played a powerful recurring role because of the special insights they have been thought to provide into the array of processes underlying this complex visual ability. These stimuli are known as *reversible, or ambiguous, figures* (see Figure 1), and their curious multistable character putatively reveals critical sensory, motor, cognitive, and physiological processes involved in form perception. Although it is true that any reasonably complete theory of form perception must be able to accommodate the observer's unusual experience with this class of figures, that fact does not explain either the extent or longevity of the popularity of these figures in the psychological literature. Since the 1800s, researchers and theorists have returned to these phenomenally unstable figures time and time again because of the oft-cited belief that they offer a unique window to the involvement and interplay of critical underlying processes in the visual system. The basic observation that, in the case of reversible figures, the information in the retinal array is insufficient to produce a single stable phenomenal experience is thought to provide a useful tool in identifying the kinds of processes (and their nature) that allow the human observer to extract form from an indeterminate retinal stimulus. Many visual theorists over the years (e.g., Ames, 1951; Andrews, Schluppeck, Homfray, Matthews, & Blakemore, 2002; Frisby, 1980; Gregory, 1974; Medin, Ross, & Markman, 2001; Rock, 1975) have argued that ambiguity is the hallmark of the retinal stimulus in nearly all visual perception and that the visual system must routinely resolve the ambiguity for the organism's effective adaptation to its environment. Within this commonly expressed view, the phenomenal instability of reversible figures provides an especially dramatic and compelling example of this more general ambiguity; but the underlying processes are believed to be essentially the same as those involved in observers' normal perception of form.

As we summarize below, the certainly incomplete list of processes hypothesized over the past 170 years to be revealed by the reversible figures shown in Figure 1 includes fluctuations in attention, eye-movement changes, accommodation changes, stimulus complexity effects, natural cortical rhythms, expectancy effects, volitional effects on perception, satiation in the flow of cortical activity, fatigue of localized neural channels, cyclical decision processes, perceptual learning, perceptual hypothesis-testing, preference for novelty, cyclical cortical "search" processes, and more. In all cases, the hypothesized processes are not cited as unique to the reversible-figure situation; rather, these processes are proposed as normal visual processes that are more clearly revealed in the reversible-figure situation.

In the following pages, we review what we believe are the critical classes of empirical findings in the long history of research with reversible figures, and we evaluate the current status of the many often-competing claims regarding the processes revealed by reversible figures. On the basis of this evaluation, we conclude that the wealth of empirical work with reversible figures sets clear parameters on likely theoretical accounts and that, more specifically, there is incontrovertible evidence for both bottom-up and top-down processes that must be incorporated in any complete theoretical treatment of the reversible-figure literature. Finally, we offer an alternative manner of conceptualizing reversible-figure effects that identifies distinguishable aspects of figural reversal, thereby allowing a consideration of the separable perceptual phenomena involved with reversible figures. And we present a theoretical framework that we believe provides a useful conceptualization of the interactive roles of sensory and cognitive processes.

Hypothesized Processes Underlying Figural Reversal

As the story goes, in 1832 L. A. Necker, a Swiss naturalist, described in a letter to Sir David Brewster the interesting changing character of a two-dimensional drawing of a rhomboid crystal (see Boring, 1942). This depiction of the now-famous "Necker cube"

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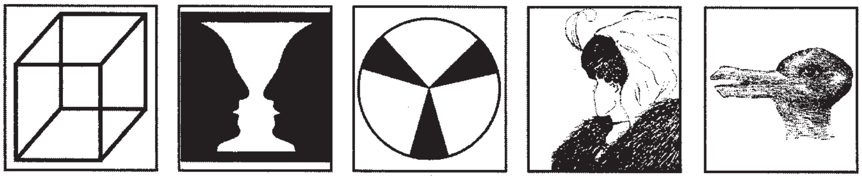

(a)
Necker Cube

(b)
Vase / Faces

(c)
Maltese Cross

(d)
Wife / Mother-In-Law

(e)
Duck / Rabbit

(f)
Schroeder Staircase

(g)
Man / Girl

(h)
Rat / Man

(i)
Ambiguous Triangles

(j)
Overlapping Squares

Figure 1. Several common examples of reversible figures that have been used throughout the long history of research with perceptually unstable figures. a: Boring (1942); b: Rubin (1915/1958); c: Kohler (1940); d: Boring (1930); e: Jastrow (1899); f: Boring (1942); g: Fisher (1967); h: Bugelski and Alampay (1961); i: Attneave (1968); j: von Grunau, Wiggin, and Reed (1984).

formally introduced reversible, or ambiguous, figures to the scientific literature, although, as Boring (1942) and earlier Helmholtz (1910/1962) have both noted, isolated descriptions of naturally occurring reversible figures such as the rotating vanes on a windmill had predated Necker's observation by many years.[1] Rubin's (1915/1958) famous research with the vase–faces and the Maltese cross figures and Boring's (1930) description of the well-known wife/mother-in-law figure, which was previously printed in the English magazine *Puck* in 1915 (see Wright, 1992), are often cited as other landmark events for the study of reversible figures. In these two latter classes of reversible figures, the perceptual instability involves reversals in figure-ground organization and changes in meaning, respectively, rather than the fluctuations in perspective (depth) observed with the Necker cube. Dozens of reversible figures (of all three types) have since been described in the perception literature, and some of the best known examples are shown in Figure 1.[2] Viewing any of these physically stable figures produces a multistable experience for an observer in which different interpretations of the figure are quite strong, and these interpretations alternate perceptually as the figure is inspected by the observer. It is not surprising, then, that a perusal of general psychology or sensation/perception or cognition texts published over the past 50 years testifies to the continuing interest in this type of visual figure.

Early Explanations: Peripheral Versus Central Processes

As revealed by early descriptions of the reversible-figures literature (e.g., Flugel, 1913; Glen, 1940; Vicholkovska, 1906), from the very beginning of research with this class of figures a variety of explanations for perceptual instability have been proposed involving both central and peripheral processes.[3] According to Boring (1942), Necker (1832/1964) favored an early version of what we refer to as the *focal-feature hypothesis,* in which different points on a figure are assumed to foster one or the other perceptual alternative. Hence, the perceived interpretation of the figure depends on the set of features receiving primary processing. In Necker's view, eye movements were critical because the foveated portion of the figure ("the point of distinct vision of the retina") was "naturally supposed [by the observer] to be nearer and foremost" (p. 337). This early interpretation placed the locus of figural reversal in "optical" rather than "mental" processes (Necker, 1832/1964). Other early theorists such as Wundt, Titchener, and Loeb

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[1] Boring (1942) also mentioned that Wheatstone observed the reversibility of outline drawings of solids in Euclid's work, which dated to approximately 300 B.C. Smith, Imperato, and Exner (1968) claimed that decorative tiles in the Temple of Apollo in Pompeii contained figures that reverse in perspective.

[2] Another class of reversible figures involves ambiguity in the direction of motion of a stimulus. This work, too, has a long history and most likely involves many of the same processes as the static figures. Examples of studies with ambiguous motion include the early work by Brown (1955) and Fisichelli (1947) with the Lissajous figures, work with the rotating Necker cube (Howard, 1961; Long et al., 1983, 1992), work with ambiguous rotary motion (e.g., Nawrot & Blake, 1989; Petersik et al., 1984), and ambiguous apparent motion (e.g., Hock, Kelso, & Schoner, 1993; Ramachandran & Anstis, 1985).

[3] Some clarification of terms as we use them in this article seems appropriate. *Peripheral processes* refer to factors related to the operation of the sense organ, whereas *central processes* refer to brain (and, especially, cortical) mechanisms. *Bottom-up* and *top-down processes* refer to whether processing is driven, respectively, by lower order or by higher order information. Finally, *local processes* are limited to particular retinal-spatial locations, whereas *global processes* are more flexible and transcend such limitations. We conceive of these terms as describing aspects of information processing that are conceptually independent, although in practice there may be correlations and asymmetries among them. For example, local processing typically implies bottom-up processing because it seems to be driven by localized stimulus information. However, one can conceive of bottom-up processing that would not necessarily be narrowly localized (e.g., when processing proceeds from the inferotemporal cortex of the visual system to areas of the prefrontal cortex).

preferred a similar interpretation of the cause of figural reversal (see Glen, 1940; Price, 1969b; Vicholkovska, 1906).[4]

In addition to the intuitive appeal of this claim (see Figure 2a), there is considerable experimental work demonstrating that eye movements (or variable eye position) can indeed be related to figural reversals. Ellis and Stark (1978) demonstrated that changing eye fixations is associated with reported reversals, and Ruggieri and Fernandez (1994) reported particular eye movements to be correlated nicely with instructions to produce a particular interpretation of a reversible figure. Several studies have shown that fixation at different locations of a figure tend to favor one or the other perceptual response (e.g., Chastain & Burnham, 1975; Garcia-Perez, 1989; Hochberg & Peterson, 1987; Kawabata, Yamagami, & Noaki, 1978; Peterson & Gibson, 1991; Tsal & Kolbert, 1985). However, there is also strong evidence to conclude that eye movements, while clearly conducive to figural reversal, are not necessary for figural reversal. The simple introduction of a fixation point does not stop reversals (see Figure 2b); and the rapid presentation of a reversible figure such that eye movements are excluded does not eliminate perceived reversals (Wallin, 1910, as cited in Glen, 1940). Moreover, formal eye movement recording work has not found that a change in eye fixation necessarily follows or precedes a reversal (e.g., Gale & Findlay, 1983; Pheiffer, Eure, & Hamilton, 1956). Perhaps even more convincing, it has been shown that the elimination of eye movements through the use of an afterimage of the figure (Gregory, 1970; Washburn & Gillette, 1933) or through artificial retinal stabilization (Pritchard, 1958) does not eliminate reversals. The reader can demonstrate this fact of figural reversals without eye movements for him- or herself with Figure 3.

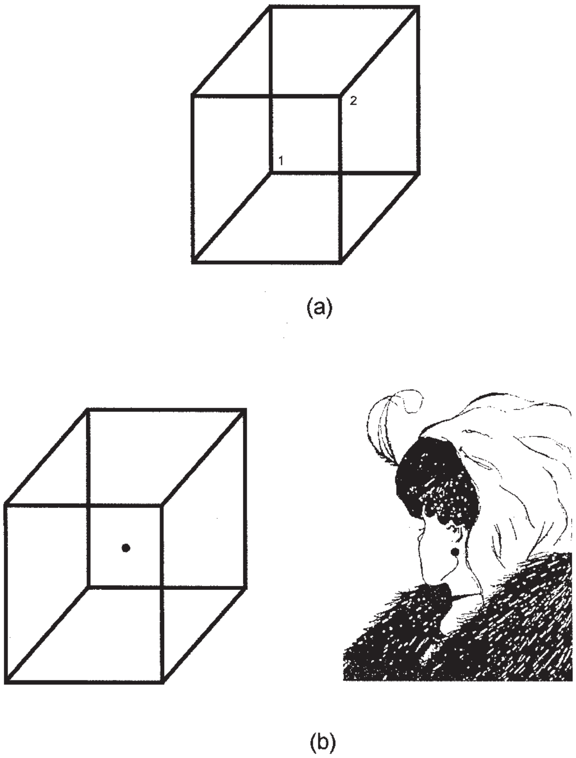

Figure 2. Effects of fixation location on figural reversal. In (a), fixation at Position 1 favors the perception of the cube as "front face up to the right"; fixation at Position 2 favors the perception of the cube as "front face down to left" (see Kawabata et al., 1978). In (b), maintaining steady fixation on the black dot does not eliminate perceived reversals of either the Necker cube or the wife/mother-in-law figure.

Even by the early 1900s, then, the research evidence clearly did not favor a necessary role for peripheral mechanisms in figural reversal. And, as noted above, subsequent work with more sophisticated procedures has shown that conditions that essentially eliminate changes in eye movements and accommodation were still quite conducive to reports of reversals. Other early hypotheses put forward involved central or "psychological" explanations invoking such concepts as will, imagination, and attention. For example, Flugel (1913) proposed a variation of the focal-feature hypothesis mentioned previously in connection with Necker's (1832/1964) eye-movement interpretation of figural reversal. Anticipating the more modern view in which eye movement and attention can be decoupled (e.g., Posner, 1980; Posner, Snyder, & Davidson, 1980; Tsal, 1994), Flugel proposed that the direction of attention rather than eye fixation per se is critical for the experience of one or the other interpretation of an ambiguous figure. He considered the attended features of a stimulus to enjoy a "clearness in consciousness" (Flugel, 1913, p. 391). Others such as Lange in the late 1800s (as cited in Vicholkovska, 1906) and Gordon (1903) similarly had invoked changes in attention to explain the "inversions" of the reversible figures that shift in perspective. These fluctuations of attention were, in turn, conceptualized as reflecting global characteristics of the observer's higher cortical structures. Finally, according to Vicholkovska (1906) and Flugel, several 19th century investigators such as Hering, Helmholtz, and Becher cited the observer's expectation and imagery as critical to determining the perspective seen. In Helmholtz's (1910/1962) words,

> The same kind of effect [figural reversal] may be observed in numerous perspective line-drawings which are intended to represent geometrical projections of regular objects, models of crystals, etc., as viewed from a great distance. Corners or edges which appear at one time to stand out from the plane of the paper may appear at another time to be behind it. The idea we get frequently changes involuntarily. Still my experience is that we can produce the changes at pleasure, provided we are bent on getting a different picture. (p. 286)

Thus, there was relatively clear consensus that the locus of figural reversal was to be found in central rather than peripheral processes.

Later Research: Sensory Versus Cognitive Explanations

For the next several decades, it appears that reversible-figure research was relatively quiet except for the notable series of

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[4] We are grouping Necker's (1832/1964) explanation with that of Wundt and others as eye-movement based interpretations. Technically, Necker's interpretation involved an additional component of perceived depth changing with the foveated portion of the figure. Vicholkovska (1906) also argued that refractive changes accompanied reports of figural reversal. Such an explanation would be limited to figures that reverse in perspective (e.g., the Schroeder staircase, Mach card, overlapping rings) but would not appear applicable to the many figures exhibiting reversals in meaning (e.g., Boring's, 1930, wife/mother-in-law; Botwinick's, 1961, husband/father-in-law; Jastrow's, 1899, duck/rabbit; and see Brugger, 1999). Later work has shown that there are no accommodative changes during figural reversal with the Necker cube (Ellis, Wong, & Stark, 1979).

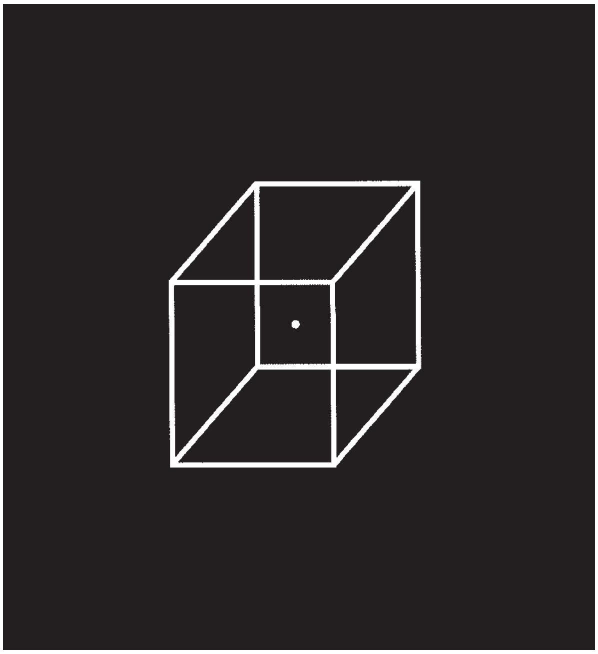

Figure 3. Demonstration of figural reversal in a negative afterimage. Maintain fixation on the fixation point for a count of 10; then shift one's gaze to a blank sheet of white paper. Notice the perceived reversals of the afterimage occur even though scanning of the figure has been eliminated through the production of an afterimage.

studies conducted at Vassar College by Washburn and his colleagues. In this work, the impact of numerous stimulus and viewing conditions were examined, including figure size, instructional effects, afterimage production, and figural complexity (Washburn & Gillette, 1933; Washburn, Mallay, & Naylor, 1931; Washburn, Reagan, & Thurston, 1934). Then, after World War II, there was an explosion of interest in the phenomenon because of the impact of the new school of thought in psychology represented by the Gestaltists (Kohler, 1940; Kohler & Wallach, 1944). The new Gestalt conceptualization of brain functioning, particularly the constructs of flowing electrical fields and changing resistance (*satiation*) to the flow of these fields, provided a new theoretical model to be applied to this curious class of visual figures. In fact, Kohler's (1940) work with reversible figures, most notably the Maltese cross, played an important role in the development of his theoretical model of form perception, which invoked field effects in the brain. He believed that figural reversal could be attributed to a gradual build up of resistance ("electrotonus") in the brain to the field flow underlying the percept first seen. Specifically, Kohler (1940) suggested,

> Prolongation of continuous observation—with constant fixation of the center [of the Maltese cross]—tends to decrease the average time during which the figure will stay in a given part of the pattern; repetition of observation periods tends to have the same effect. These facts point to the possibility that prolonged occurrence of a figure process in a given area leads to gradual changes in this area which oppose the further existence of the process in the same place; in other words, a figure process seems to have some effect by which it tends more and more to block its own way. Moreover this effect seems to persist beyond the time during which the figure process actually occurs; it may not completely disappear in a minute or more, and thus with repeated observation a progressively stronger after-effect will be obtained by summation. (pp. 70–72)

Within this view, what renders reversible figures unique—and particularly valuable as research tools—is the fact that the perceptual reversals provide special insights into the nature of these dynamic brain processes. Kohler (1940) argued that the increasing pattern of reversals reported over time reveals increasing "satiation" in those regions underlying the initial percept, which results in a phenomenal reversal to the second interpretation. This second percept presumably dominates until its field flow is also satiated to a point where the brain areas underlying the first percept can again dominate after having recovered from their original satiation. The perceptual alternations were thought to mirror the alternating field flows underlying the two perceptual phenomena that were undergoing successive periods of activation and satiation.

With the findings of subsequent research that did not support the conceptualization of flowing electrical fields in the brain (e.g., Lashley, Chow, & Semmes, 1951), and especially with the application of more advanced research techniques such as single-cell recording of cortical regions (e.g., Hubel & Wiesel, 1959), the Gestalt model of brain physiology has since been abandoned. However, the dominant approach of modern research (and theory), which is based on the notion of neural channels selectively tuned to particular characteristics of the retinal stimulus (see Anstis, Verstraten, & Mather, 1998; Braddick, Campbell, & Atkinson, 1978; R. L. DeValois & DeValois, 1988; Graham, 1992; Regan, 1982), has incorporated the critical concept of *neural adaptation* (e.g., Blakemore & Campbell, 1969; Blakemore & Sutton, 1969; K. K. DeValois, 1977; Maffei, Fiorentini, & Bisti, 1973). On the basis of both physiological and psychophysical evidence, it is now believed that continued stimulation of selective neural channels temporarily alters their response profiles, thereby reducing their sensitivity and altering their ability to respond to subsequent stimuli until they have recovered from this adapted state. Concerning the phenomena of reversible figures, current explanations based on the neural-channel model share much of the flavor of the older Gestalt model. Figural reversal depends on relatively automatic brain processes that are (a) stimulus driven (i.e., critically dependent on the features of the stimulus); (b) localized to those retinal regions undergoing excitation, adaptation, and recovery; and (c) largely independent of the observer's higher order cognitive processes (see Orbach, Ehrlich, & Heath, 1963, for one early variation of this type of theoretical conceptualization). As Toppino and Long (1987) have argued, this view places reversible figures within a broader class of well-known visual phenomena, which includes reduced sensitivity effects and numerous visual aftereffects, that are presumed to depend on the selective adaptation of localized visual channels. These channels have been identified by electrophysiological and psychophysical research as sensitive to specific, retinally localized stimulus features such as size (spatial frequency), orientation, motion, motion in depth, and so forth (see R. L. DeValois & DeValois, 1988).

In contrast, the other mainstream approach of post-Gestalt research into form perception has essentially rejected both the Gestalt and the neural-channel models of passive neural processes underlying figural reversal and has favored the critical role of more active, cognitive processes such as learning, decision making, and attention. Although different researchers have favored or emphasized different cognitive processes (reviewed below), they have in common a rejection of the automaticity of figural reversals in favor of the pliability of the observer. The observer actively processes the retinal pattern, applying internal resources of attention, learning, and expectation to the ambiguous retinal pattern. This theoretical approach is captured nicely by Gregory's (1974) characterization of "perceptions as hypotheses, based on stored and sensed data" (p. 280). Gregory (1974) described reversible figures thusly:

> Each alternate perception is regarded as a hypothesis. The Necker cube (or the duck-rabbit figure) have features which select not one but two or more reasonably likely hypotheses, which are entertained in turn (perhaps for testing) and which are the perceptions. (p. 277)

As he noted, while not rejecting the obvious criticality of physiological processes, this view emphasizes "'software' logical processes without specific reference to underlying neural processes" (Gregory, 1974, p. 280). In contrast, the neural-channel model described above seeks to place the locus of reversibility squarely within the hardware of the system.

In the current vernacular, the neural-channel approach favors so-called *bottom-up processes* in explaining figural reversals; the alternate approach, which arose from the cognitive, information-processing revolution of the late 1960s and 1970s, favors so-called *top-down processes* in explaining figural reversals. As several investigators have argued (e.g., Horlitz & O'Leary, 1993; Long & Toppino, 1994, 2002; Long, Toppino, & Mondin, 1992; Struber & Stadler, 1999; Toppino & Long, 1987, 1996), most of the explanations offered for reversible figures over the past 50–60 years can be categorized as either bottom-up or top-down theories in terms of their reliance on passive (automatic), sensory versus active, cognitive processes. Let us try to summarize the evidence cited in favor of these two currently dominant classes of explanations.

Evidence for Sensory, or Bottom-Up, Theories of Figural Reversal

Pattern of reversals over time. Table 1 presents several well-replicated classes of empirical findings that have been used to support the critical presence of passive, sensory processes in figural reversal. First, the pattern of reversals over time has been thought to reveal an automaticity to figural reversals that is most easily conceptualized as resulting from the interplay of excitatory and fatiguelike processes. As indicated in the table, numerous investigators since at least Kohler (1940) have been struck by the fact that the number of reported reversals increases systematically over a viewing period of a few minutes. More specifically, the number of reported reversals exhibits a negatively accelerated pattern over time. If one assumes (a) that the neural activity underlying each of the perceptual responses goes through recurring periods of transient fatigue (or satiation) and recovery,[5] (b) that there is incomplete recovery from the fatigue during each recurring cycle, and (c) that the observer's experience depends on whichever neural activity is strongest at a given moment, then an increasing pattern of reversals that exhibits an asymptotic response rate as the figure is viewed is the predictable result.

Figure 4 presents a schematic depiction of the competing neural processes progressing through successive periods of fatigue and recovery in such a manner that a negatively accelerating pattern of reversals over time would be produced. In the figure, the duration of each successive percept (t_1, t_2, t_3, . . .) is determined by the time it takes for the automatic fatigue process that is building during the experience of that percept to reach some critical level (θ). When that threshold value is attained, the neural processes underlying the alternate percept dominate, and a phenomenal reversal is experienced by the observer. While the second set of neural processes is dominant, the fatigue that had built up in the first set of neural structures begins to dissipate. However, when the neural processes underlying the second percept reach their threshold level, resulting in an alternation back to the first set of neural processes, the latter processes will not have recovered completely. As a result, these structures will attain their threshold level of fatigue more quickly, and the duration for the related percept (t_3) is briefer than in its first occurrence (t_1). This progressive shortening of the length of time for each set of structures to reach its fatigue threshold until some asymptotic rate of rapid alteration is achieved is thought to be the basis for the negatively accelerating pattern of reversals over time (see Dornic, 1967).[6]

Localization of reversal pattern. As we revisit below, this negatively accelerating response pattern by itself is not necessarily incompatible with other processes such as learning; but there is a further aspect of this work that many believe is especially indicative of passive neural processes—the localized character of fatigue effects demonstrated with reversible figures (see Table 1). For example, Kohler (1940) discovered that if observers were shown a Maltese cross figure with small and large sectors (see Figure 1c), the increasing pattern of reversals described above was

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[5] As has been noted elsewhere (e.g., Long & Toppino, 1994), it is probably safest to use the term *adaptation* rather than *fatigue* in this context, although the latter is clearly more common in the literature. The term *adaptation* permits the possibility of within-channel fatigue or "autoinhibition" (Howard, 1961) or between-channel inhibitions or some combination of these neural processes. In much of our work, we have favored the term *fatigue* because it most readily captures the sense of automatic, passive activity within the nervous system, which is the major tenet of this class of theories being discussed. A second point worth noting in this discussion of adaptation or fatigue is that the locus of the fatigue could (also) occur in the reciprocal connections between the neural networks underlying the two percepts, thereby producing slowly progressing decrease in the inhibition. This view was favored by Attneave (1971), who attributed the reversals to fatigue in the "suppressive linkage" that allows only one neural network to be dominant at any moment. Nonetheless, the same negatively accelerating pattern of reversals over the viewing period is predicted.

[6] Although the conceptualization in Figure 4 is extremely simplistic and assumes fixed threshold levels and linearly increasing and decreasing rates of fatigue, it is quite useful in suggesting a number of predictions beyond the negatively-accelerating pattern of reversals. For example, consider the predictions if the threshold level for fatigue of Percept A is made quite a bit higher than that for Percept B. This would correspond to the situation when one of the percepts of the reversible figure is much stronger than the other percept, which is quite common with reversible figures (e.g., Brugger, 1999; Fisher, 1967). The relative dominance of one set of neural structures would allow the fatigue in the alternate set of structures that occurs in t_2 to fully recover while the first set is again dominant in t_3. This would result in the duration of Percept B remaining relatively unchanged at least initially in the viewing period while that of Percept A would systematically decrease. In fact, this result has been reported by some investigators, although, ironically, it has been cited as a serious difficulty for a passive neural-fatigue model of reversals (Price, 1967, 1969b; Sadler & Mefferd, 1970).

Table 1

Classes of Results and Representative Studies That Are Typically Cited to Support a Sensory, or Bottom-Up, Model of Figural Reversal

Class of result	Representative studies
Increasing number of reversals over time	Brown (1955), Cornwell (1976), Fisichelli (1947), Kohler (1940), Philip & Fisichelli (1945), Price (1969a), Virsu (1975)
Evidence for localization of increasing reversal rate	Babich & Standing (1981), Cohen (1959b), Long et al. (1983), Spitz & Lipman (1962), Toppino & Long (1987)
Reverse-bias effects (adaptation effects) on figural reversal	Carlson (1953), Dornic (1967), Harris (1980), Hochberg (1950), Long et al. (2002), Long et al. (1992), Nawrot & Blake (1989), Orbach et al. (1963), Petersik et al. (1984), Virsu (1975)
Evidence for localization of reverse-bias effects	Howard (1961), Long & Olszweski (1999), von Grunau et al. (1984)
Multiple-figure presentation	Adams & Haire (1958, 1959), Babich & Standing (1981), Flugel (1913), Gillam (1972), Long & Toppino (1981), Long et al. (1983), Toppino & Long (1987)
Stimulus effects on figural reversal	
Intensity/luminance	Cipywynk (1959), Lynn (1961)
Figural completeness	Babich & Standing (1981), Botha (1963), Cornwell (1976), Fisichelli (1947)
Continuity of presentation	Fisichelli (1947), Leopold et al. (2002), Orbach et al. (1963), Philip & Fisichelli (1945), Spitz & Lipman (1962), Thetford (1963)

Note. Some studies are cited in multiple categories because their results have implications for more than a single category of bottom-up processes in figural reversal.

revealed. But he also determined that simply rotating that figure to a new position after several minutes of observation so that the small sectors now fell on different retinal regions caused the reversal pattern to revert to its original slow level of reversals. This same localized effect has been reported by other researchers and with other reversible figures. If a Necker cube is viewed for several minutes but then moved to a different location in the visual field, reversal rate returns to baseline (Spitz & Lipman, 1962). Similarly, Howard (1961) and Toppino and Long (1987) used the rotating Necker cube figure and demonstrated that a change in retinal location produces a return to baseline in the response pattern. In a closely related vein, Toppino and Long (1987) also demonstrated that adaptation to a figure of one size and then viewing a cube of a different size shows no carryover from the adaptation phase to the test phase. To many researchers, these demonstrations are especially strong evidence for the involvement of relatively localized processes, which is easily modeled with known cortical structures receiving input from restricted retinal regions (i.e., localized receptive fields).

Reverse-bias (adaptation) effects with reversible figures. A second class of findings that have been interpreted to strongly support a bottom-up model of figural reversal involves a *reverse-bias,* or *adaptation effect.* In this paradigm, the researcher determines the effect of exposing an observer to an unambiguous version of the reversible figure before presenting the standard ambiguous version. Examples of the kinds of ambiguous and unambiguous figures used for this demonstration are shown in Figure 5. Using figures of this type, several researchers have adopted what in the current neural-channel vernacular is referred to as the *selective-adaptation technique* to attempt to adapt those neural structures underlying one of the perceptual responses by exposing (adapting) the observer to an unambiguous version of the figure for a period of time before presenting the usual ambiguous figure (e.g., Carlson, 1953; Cohen, 1959b; Harris, 1980; Hochberg, 1950; Long et al., 1992; Nawrot & Blake, 1989; Petersik, Shepard, & Malsch, 1984; Virsu, 1975). The consistent finding from these studies has been that the observer, after adaptation to one of the unambiguous versions, reports the alternate version of the reversible figure. This reverse-bias effect is interpreted to result from the selective adaptation of one set of neural networks underlying figural reversal, thereby allowing the unadapted set of neural networks to then dominate. Furthermore, this research has also shown that the effectiveness of the adaptation depends on both the duration of that adaptation period and the correspondence between the retinal regions stimulated during the adaptation and test periods (e.g., Harris, 1980; Howard, 1961; Long et al., 1992; Virsu, 1975; von Grunau, Wiggin, & Reed, 1984). This time dependency and restricted localization of the reverse-bias effect are readily incorporated with a model of neural adaptation in cortical structures receiving input from localized retinal regions.

Viewing multiple reversible figures simultaneously. The third class of results favoring a sensory model for figural reversal also has an impressively long history and involves an extremely simple observation with very powerful theoretical implications for the relative likelihood of a host of explanations that have been offered for figural reversal. In 1913, Flugel reported an interesting observation with a multiple-figure presentation that has been repeated and elaborated by several researchers since, most notably Long and Toppino (1981; Long, Toppino, & Kostenbauder, 1983; Toppino & Long, 1987; see also Adams & Haire, 1958, 1959; Cohen, 1959b). If, for example, two Necker cubes are presented simultaneously with one inside the other or in a side-by-side format (see Figure 6), an observer is able to see the cubes reverse independently of each other.

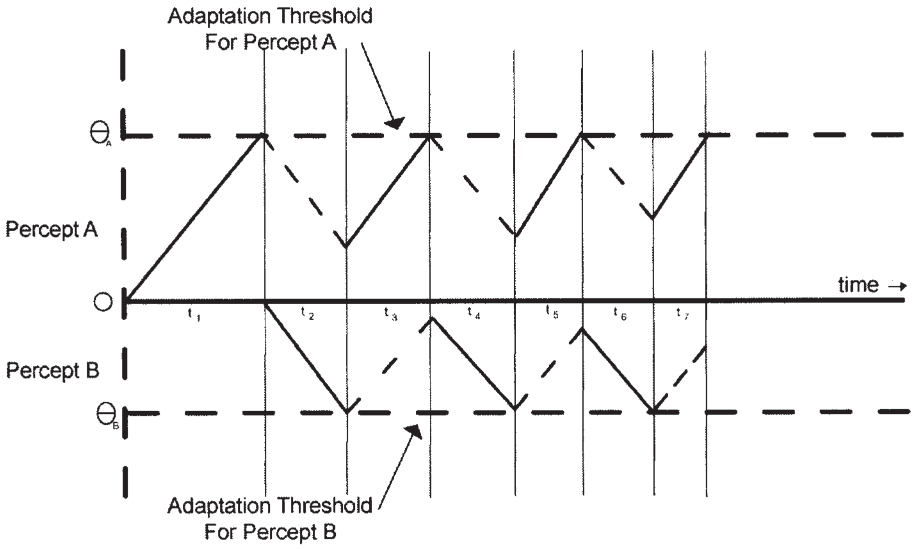

Figure 4. A schematic representation of fatigue and recovery processes in the competing neural networks underlying the alternate perceptions of a single reversible figure. The solid horizontal line represents a time line. Activity above the line refers to the fatigue and recovery of those structures underlying Percept A; activity below the line refers to the parallel processes for Percept B. The horizontal dashed lines represent fatigue thresholds (t, where the duration of each successive percept is t_1, t_2, t_3, etc.) at which point the dominant neural structures are unable to respond further and the alternate set of neural structures are activated. The solid oblique lines represent linearly increasing levels of fatigue in the activated structures; the dashed oblique lines represent linearly decreasing levels of fatigue (i.e., recovery) that occur while the alternate set of structures dominate. In interval t_1, Percept A is dominant as the level of fatigue grows until a maximum level for functioning is achieved and the dominance of Percept 1 ceases. In interval t_2, Percept B is dominant while the fatigue in the neural structures underlying Percept A begins to dissipate. In interval t_3, Percept A is dominant again while the fatigue in the neural structures underling Percept B dissipate, and so on. The different absolute levels of the two fatigue thresholds indicate that Percept A is the "preferred" interpretation of the reversible figure. This representation is from "Measurement of Satiation in Reversible Figures," by S. Dornic, 1967, *Studia Psychologica, 9,* p. 21. Copyright 1967 by Slovak Academic Press. Adapted with permission.

In an especially powerful demonstration of this independence of multiple figures, Toppino and Long (1987) incorporated the multiple-figure presentation with the adaptation procedure described previously. Their experimental procedure is shown schematically in Figure 7. Specifically, the observer viewed a single reversible figure that was presented to the left or right of a fixation point during a 2-min adaptation period and depressed a response key for each perceived reversal. The typical negatively accelerating pattern of reversals over the 2-min viewing period was revealed. Then, in an immediately following test period, two identical reversible figures were presented, one in the same retinal location as the figure in the preceding adaptation period and the second in the other visual field. Observers reported the reversals of both figures. (Previous work had demonstrated that observers are able to report the reversals of two cubes simultaneously with little interference; e.g., Long et al., 1983.)

The results from this experiment (see Figure 8) were quite striking. Observers reporting reversals for the test figure located in the same retinal location as the adapting figure maintained the high reversal rate attained by the end of the adaptation period. In contrast, observers reporting reversals for the test figure in the different retinal location exhibited a new negatively accelerating response rate as if no prior inspection of the figure had occurred during the adaptation period. That is, the figure in the "fresh" retinal (and cortical) location revealed no effect of the adaptation period. Observers reported seeing the two side-by-side figures reversing at different times and at very different rates. Toppino and Long (1987) concluded, consistently with Flugel's (1913) argument 70 years earlier, that this multiple-figure demonstration renders much less plausible peripheral factors such as eye movements and accommodation as well as global rhythmic processes such as vaso-motor changes or brain waves (e.g., Bonser, 1903). That is, the relative independence of reversals reported for simultaneously viewed figures—and especially the fact that the individual cubes in the retinal field can be adapted separately and, consequently, reversed at different times and different rates—rules out "some physiological factor which must affect the whole of the cortex simultaneously" (Flugel, 1913, p. 360) and implicates "strictly localized conditions" (p. 361). In short, a single globally configured, top-down process would appear to be excluded as necessary to figural reversal (although a moderating role cannot be excluded). A list of the proposed global processes that are rendered problematic would include a centralized neural switching process (e.g., Leopold & Logothetis, 1999), perceptual learning (e.g., Ammons, 1954), attention (e.g., Kawabata & Mori, 1992; Tsal & Kolbert, 1985), rhythmic metabolic processes such as pulse rate and brain waves (Flugel, 1913; Vicholkovska, 1906), and a central decisional or problem-solving process (Rock, 1975; Vickers, 1972).[7]

Stimulus effects on figural reversal. Finally, Table 1 presents a final category of findings that have been cited by various investigators to support a model of figural reversal that is dependent on sensory processes. These findings involve stimulus effects whose role is predicted for a stimulus-driven model involving early cortical processes. More intense figures reverse more rapidly than less intense ones; complete figures reverse more rapidly than incomplete ones; and continuous viewing produces more reversals that intermittent viewing. Each of these manipulations has been interpreted to impact relatively early cortical structures which analyze stimulus features and in which slowly building adaptation effects critically dependent on these stimulus characteristics are believed to occur.

Evidence for Cognitive, or Top-Down, Theories of Figural Reversal

Volitional effects on figural reversal. Table 2 presents four classes of results that are most frequently cited in support of a cognitive, or top-down, locus to figural reversals. The first involves volitional effects on figural reversals. It has been demonstrated since the 1800s that observers have some degree of control over figural reversals. For example, Helmholtz claimed that an observer can produce intentionally a "change of inversion" in a figure like the Schroeder staircase (see Figure 1f) if "we recall vividly the image of its contrary form" (as cited in Vicholkovska, 1906, p. 276).

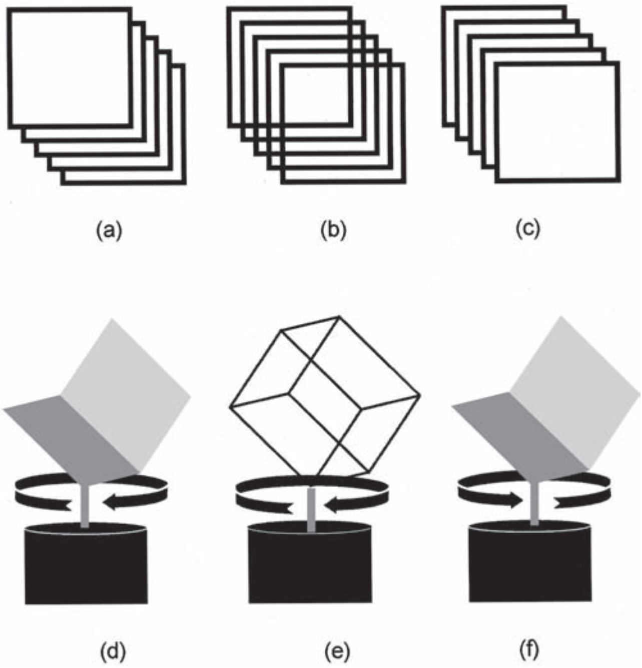

Figure 5. The adaptation and test figures used by Long et al. (1992). The upper three figures depict the normal ambiguous overlapping square figure (b) and the two unambiguous versions of the figure, (a) and (c), that the observer viewed for varying durations prior to viewing the ambiguous figure. The lower three figures depict the corresponding patterns for the rotating Necker cube figure (e), which was preceded by solid "boxes" rotating unambiguously to either the left (d) or the right (f). From "Prime Time: Fatigue and Set Effects in the Perception of Reversible Figures," by G. M. Long, T. C. Toppino, and G. W. Mondin, 1992, *Perception & Psychophysics, 52,* p. 611. Copyright 1992 by the Psychonomic Society. Reprinted with permission.

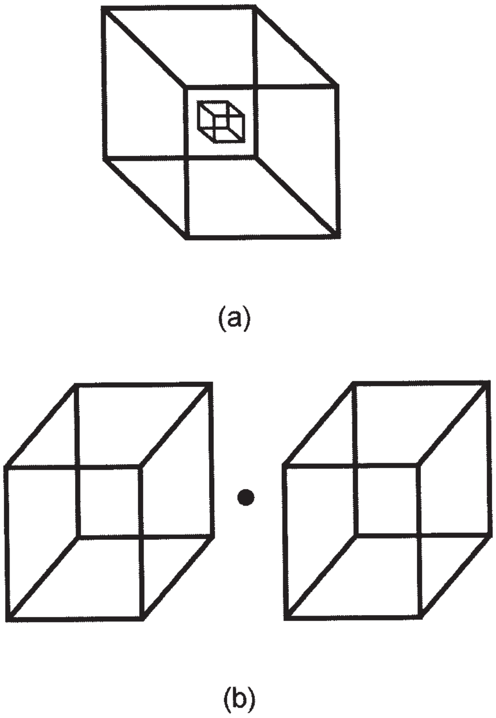

Figure 6. Effects of viewing multiple reversible figures simultaneously. In (a), note that it is possible to see the large and small cubes in different orientations at the same time. The upper figure (a) is reprinted from *Vision Research, 19,* S. R. Ellis, J. H. Wong, and L. Stark, "Absence of Accommodation During Perceptual Reversal of Necker Cubes," p. 953, Copyright 1979, with permission from Elsevier. In (b), note that the side-by-side cubes need not be seen in the same orientation at any given point in time. The lower figure (b) is from "Multiple Representations of the Same Reversible Figure: Implications for Cognitive Decisional Interpretations," by G. M. Long and T. C. Toppino, 1981, *Perception, 10,* p. 232. Copyright 1981 by Pion Limited, London. Adapted with permission.

The empirical investigation of volitional control has taken several forms in the literature. In some studies, observers are instructed to "hold" a particular interpretation of the figure (e.g., Liebert & Burk, 1985; Peterson & Gibson, 1991; Washburn &

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[7] Theories based on decisional, problem-solving, or hypothesis-testing processes conceptualize perception in terms of the influence of top-down processes that are subject to the attentional limitation that is characteristic of higher order cognition. This limitation seems to account for why people can consider (and, thus, perceive) only one interpretation of a reversible figure at a time (e.g., Rock, 1983). If multiple simultaneously viewed figures are perceived to reverse largely independently, it would seem necessary to postulate an independent attentional or decisional process for each figure added to the array. As Long and Toppino (1981) observed, "the notion of innumerable . . . attentional processes working largely independently in the multiple-figure situation is neither very appealing nor very consistent with the general conceptualization of these processes" (p. 233).

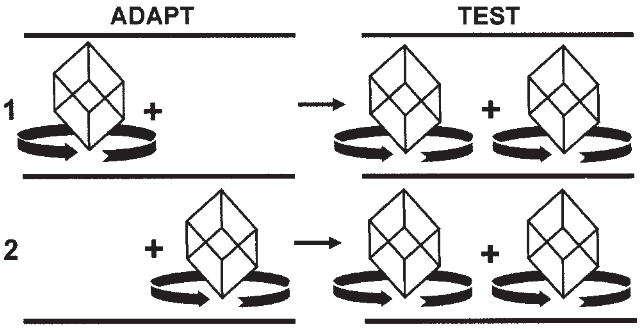

Figure 7. Depiction of research paradigm used by Toppino and Long (1987). The observer viewed an ambiguous rotating Necker cube that was presented to either the left (1) or right (2) of a fixation point. After this adaptation period, the observer then viewed two side-by-side rotating Necker cubes, one of which was in the same retinal position as the preceding adaptation cube.

Gillette, 1933) while a control group of observers are given "neutral" instructions. In other studies, observers are instructed to either "hold" the current percept or "switch" the figure as rapidly as possible (e.g., Pelton & Solley, 1968; Struber & Stadler, 1999). The results have been consistent across the variety of studies: Both types of instructions significantly affect figural reversal, either varying the duration for which a given percept is reported or altering reversal rate in the direction of the instructional set.

At times, it may be difficult to separate the argument for volitional control from that of the focal-feature hypothesis because, as noted above, the observer can indeed facilitate reversals by changing the points on the figure which he or she selects to receive primary processing (i.e., to be fixated and/or to be the focus of attention). However, Toppino (2003) recently obtained evidence that voluntary control can be independent of selectively processing particular focal features. Observers were instructed to view a Necker cube passively or to intentionally maintain a designated orientation of the cube. Simultaneously, fixation location was varied so as to bias processing of focal features that favored a particular perceived orientation. Depending on the combination of conditions, the demands of intentional instructions and fixation location were either compatible or incompatible. Toppino argued that if both factors depended on selecting certain focal features for primary processing, they should have produced interactive effects. However, both variables produced strong effects that were additive (independent). Furthermore, when a very small cube was used to reduce the likelihood of selectively processing different sets of focal features, the effect of fixation location was eliminated whereas the effect of intentional instructions was undiminished. He concluded that these findings were strongly supportive of the argument for an important role served by cognitive control in figural reversal. Why would a possible sensory-based process that is dependent on neural adaptation of cortical structures exhibit such sensitivity to top-down influences?

Knowledge of reversibility. The second set of effects routinely cited in the literature as supportive of cognitive processes is that of *familiarity,* or more precisely, knowledge of reversibility. Without a doubt, this work is most closely associated with Rock and his colleagues (Girgus, Rock, & Egatz, 1977; Rock, Hall, & Davis, 1994; Rock & Mitchener, 1992), who have demonstrated that observers' knowledge of the reversible character of the figure is critical to that figure's reported reversibility. If the observer does not know that the figure being presented is potentially bistable, few if any reversals are typically reported. In fact, this finding is so robust in Rock's work that he argues that in much of the reversible-figure literature experimenters may have unintentionally biased their results by familiarizing observers to the reversible character of the figures under study during the practice phase of their work. The basic conclusion from this line of work is that observers' "intention to reverse the figure" (Rock et al., 1994, p. 33) and their prior experience with the figure are critical. If a passive neural process were solely responsible for figural reversal, it is not clear why knowledge of reversibility and practice should play such a powerful role.

Learning effects on figural reversal. A closely related line of work has demonstrated that observers exhibit clear learning effects with reversible figures. For example, it has been argued that the negatively accelerating rate of reversals discussed above reflects a standard learning curve (e.g., Ammons, Ulrich, & Ammons, 1959). That is, the negatively accelerating response pattern, which was originally interpreted to reveal the joint activity of neural adaptation and recovery in competing neural networks, has been reconceptualized to reflect an active cognitive process. By this argument, its former presumed support for a bottom-up model is potentially neutralized. Moreover, this reinterpretation is given further support in those studies that use conditions that eliminate the role of transient adaptation effects. For example, observers report more reversals over successive sessions spaced by weekly intervals (e.g., Donahue & Griffitts, 1931; Long et al., 1983). Although transient adaptation effects would appear to be excluded by the long intersession periods, an increase in reversals is found. Similarly, Solley and Santos (1958) found that successive 2-s presentations of biased figures accompanied by verbal reinforcement produced a progressively stronger likelihood that the standard Necker cube would be seen in the biased version. In general, studies in this category of Table 2 demonstrate progressive changes in the observer's reported reversals over successive viewing periods under conditions in which transient adaptation effects are excluded.

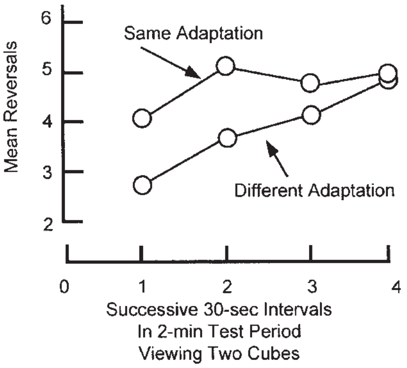

Figure 8. Results from Toppino and Long (1987) showing the number of reversals reported for the test cube that was either in the same or different position as the adaptation cube. From "Selective Adaptation With Reversible Figures: Don't Change That Channel," by T. C. Toppino and G. M. Long, 1987, *Perception & Psychophysics, 42,* p. 43. Copyright 1987 by the Psychonomic Society. Reprinted with permission.

Table 2
Classes of Results and Representative Studies That Are Typically Cited to Support a Cognitive, or Top-Down, Model of Figural Reversal

Class of result	Representative studies
Volitional effects on figural reversal	Gomez et al. (1995), Hochberg & Peterson (1987), Liebert & Burk (1985), Mull et al. (1952), Pelton & Solley (1968), Rock et al. (1994), Struber & Stadler (1999), Toppino (2003), Washburn & Gillete (1933)
Familiarity effects on figural reversal (observer's knowledge of reversibility)	Girgus et al. (1977), Horlitz & O'Leary (1993), Lindauer (1989), Rock et al. (1994), Rock & Mitchener (1992)
Learning effects on figural reversal (practice effects)	Beer (1989), Bills (1931), Donahue & Griffitts (1931), Horlitz & O'Leary (1993), Lindauer (1989), Long et al. (1983), Mefferd et al. (1968), Smith et al. (1968), Solley & Santos (1958)
Positive-bias ("set") effects on figural reversal	Botha (1963), Botwinick (1961), Bugelski & Alampay (1961), Epstein & Rock (1960), Fisher (1967, 1968), Goolkasian (1991), Leeper (1935), Long et al. (1992), Long & Olszweski (1999), Peterson et al. (1991), Solley & Santos (1958)
Cognitive-load effects on figural reversal	Reisberg (1983), Reisberg & O'Shaughnessy (1984)

Note. Some studies are cited in multiple categories because their results have implications for more than a single category of top-down processes in figural reversals.

Expectancy effects on figural reversal. The *effects of expectancy,* or *set effects,* make up the fourth class of results with reversible figures that favors a top-down model of reversibility and probably constitutes the best known line of work with such figures. In fact, reversible figures have frequently been chosen as one of the strongest research tools for investigating this cognitive process. (This is a favorite demonstration in many textbooks.) If perception is an active process in which the largely automatic processing of the retinal information is "filtered" or moderated by top-down effects that depend on contextual information and other experientially based biases, reversible figures provide a convenient experimental tool for researchers. For example, the work by Botwinick (1961), Leeper (1935), and Fisher (1967) demonstrated that showing an observer an unambiguous version of the reversible figure prior to the traditional ambiguous version clearly reduced the ambiguity of that figure. That is, the observer was much more likely to report the normally ambiguous figure in the biased interpretation. Leeper reported generally similar results if prior verbal information (i.e., a verbal description of one of the alternatives) was used to bias one or the other interpretation of the ambiguous figure.

In Bruner and Minturn's (1955) famous study, they demonstrated that an observer's perception of an ambiguous figure could be altered by the context in which it was presented (i.e., the figure *13* seen as the letter *B* or the numbers *1* and *3,* depending on whether it was embedded within other letters or other numbers). Bugelski and Alampay (1961) reported that the prior presentation of pictures in the same category as one or the other interpretation of the ambiguous figure (e.g., drawings of people vs. drawings of animals presented prior to viewing the rat–man ambiguous figure; see Figure 1h) similarly biased the observer to report the primed interpretation of the ambiguous figure. From this work, the critical role of top-down processes in the analysis of retinal stimulation for pattern perception would appear to be evident. Collectively, these studies and others have convincingly demonstrated that the presentation of visually or categorically or contextually relevant information can bias the observer to perceive one or the other interpretation of the ambiguous stimulus. Such factors reflect the top-down influence of higher order cognitive processes.

In this regard, reversible figures are conceptually similar to other classes of ambiguous figures that have been used in the study of form perception. For example, in the first half of the 20th century, there was considerable interest in so-called *overlapping* or hidden figures (see examples from Gottschaldt, 1926, as cited in Coren, Ward, & Enns, 1994) and in various versions of the relatively well-known incomplete or "closure" figures (e.g., Dallenbach, 1951; Mooney & Fergusen, 1951; Street, 1931); and the powerful role of cognitive factors such as observer's set was well established with these figures.[8] But perhaps most similar in this regard are the famous demonstrations by the so-called *transactionalists* whose unusual creations such as the Ames chair, the distorted room, and the rotating trapezoid were cleverly designed to assess the visual system's ability to process retinally ambiguous patterns in especially dramatic fashion (see Allport, 1955). The fact that observers resolve the ambiguity in these unusual three-dimensional targets by perceiving them as familiar objects (i.e., a chair, a normal room, an oscillating rectangular window) that would cast similar retinal images is thought to reveal the critical role of past experience in people's perception of a stable world

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[8] We are indebted to an anonymous reviewer who suggested the general similarity of reversible figures with these other classes of ambiguous stimuli. In this context, we find it interesting to note the frequent use of perceptual ambiguity, achieved through a variety of formats, that has been a common tool in the study of form perception. In addition to the reversible figures of explicit interest in the present article, there are also the transactionalist figures, hidden figures, incomplete figures, impossible figures (Penrose & Penrose, 1958), and even Navon's (1977) hierarchical figures.

from retinally incomplete and ambiguous information (see Ames, 1951; Ittelson & Kilpatrick, 1951).[9]

Effects of a secondary task on figural reversal. The final category of studies cited to support the role of top-down processes in figural reversals involves those studies in which a secondary task is incorporated into the viewing task with the reversible figure. The argument is made that the introduction of a mental load through counting backward or remembering a string of digits should have little impact on automatic sensory processes. That is, if figural reversal does not involve cognitive processes, then the introduction of a secondary task that requires cognitive processes should prove inconsequential. The results have not favored the automaticity of figural reversal. Reisberg (1983) and Reisberg and O'Shaughnessy (1984) found the introduction of a secondary task to increase the time until the first reversal of a reversible figure is reported as well as to decrease the rate with which subsequent reversals occur. They concluded that figural reversals required "perceptual judgments" that competed with the secondary task for working memory. This places their work clearly in the camp that views perception as a resource-limited, problem-solving process.

Evidence From Electrophysiological Research for Levels of Processing

Before proceeding to a discussion of a new theoretical framework for reversible figures, we think it is both appropriate and valuable to consider the status of electrophysiological research into the nature of cortical activity exhibited by observers viewing a reversible figure. Fortunately, much of this work has been reviewed recently by Leopold and Logothetis (1999), but we summarize this literature here especially with regard to its relevance for bottom-up or top-down models of figural reversals.

Electrophysiological study of brain activity during figural reversals has used a number of methodologies, including single-cell recording in monkeys (e.g., Dodd, Krug, Cumming, & Parker, 2001) and electroencephalography (EEG) and functional magnetic resonance imaging (fMRI) with humans (e.g., Basar-Eroglu, Struber, Stadler, Kruse, & Greitschus, 1995; Kleinschmidt, Buchel, Zeki, & Frackowiak, 1998; Klemm, Li, & Hernandez, 2000).[10] With this variety of methods, researchers have been able to address whether (and in what areas) cortical activity exhibits changes corresponding to the reported perceptual changes or whether the cortical activity exhibits a constant level of activity, mimicking the unchanging physical character of the stimulus.

The results across many studies seem to indicate that cells in the earliest areas of the visual cortex (areas V1 and V2), just as in precortical cells of the lateral geniculate nucleus, exhibit little or no variation in activity that corresponds to changing perceptions of the retinal pattern. These first synapses in the visual cortex behave "as if the unchanging pattern falling on the retina were the only factor determining their firing" (Leopold & Logothetis, 1999, p. 257). However, as one proceeds to later stages in the system such as V4 (and even beyond the occipital cortex in the middle temporal [MT; V5] and inferotemporal [IT] areas), the proportion of neurons exhibiting cyclic patterns of activity that correspond to perceptual changes increases markedly. Furthermore, Logothetis and his colleagues (Leopold & Logothetis, 1999; Logothetis & Schall, 1989; Sheinberg & Logothetis, 1997) have reported that results from the monkey single-cell research indicate two different types of percept-related neural activity. Many cells in the monkey cortex exhibit transient changes that precede the point of phenomenal change rather than corresponding to steady-state activity for one percept or the other. A smaller subset of cells, specifically in IT and the superior temporal sulcus (STS), exhibits firing patterns that appear yoked in both onset and duration to either Percept A or Percept B (e.g., Dodd et al., 2001; Logothetis & Schall, 1989). On a related note, Andrews et al. (2002) have reported findings with fMRI and human observers implicating other poststriate areas (e.g., fusiform gyrus) in which neural activity matches the bistable experience of the observer with the vase–faces figure. These two classes of percept-related neural activity have been suggested to reveal the neural substrate for processes initiating the reversal as well as those processes matching the observer's phenomenal experience. We return below to this apparent division of neural activity exhibited during figural reversal.

One final aspect of the electrophysiological work with reversible figures is of particular note. In their review of this work, Leopold and Logothetis (1999), as well as later investigators (e.g., Klemm et al., 2000), were especially impressed with the broad cortical areas that are involved during multistable perception. This allowed them to speculate that neural activity in those areas of the cortex that underlie the different perceptions of a reversible figure are essentially "steered and modified by central brain structures in higher non-visual cortical areas that play a critical role in planning and generating behavioral actions" (Leopold & Logothetis, 1999, p. 254). In the terminology we have adopted here, this conceptualization offers a physiological basis to a clear top-down model of figural reversals. Such a top-down model is consistent with the well-documented finding that frontal lobe damage, particularly right frontal lesions, produces much lower reversal rates with ambiguous figures (Cohen, 1959a; Meenan & Miller, 1994; Ricci & Blundo, 1990). Moreover, this model is readily able to accommodate empirical findings regarding a host of other variables that can influence reversals such as mood, intelligence, and pharmacological agents (e.g., caffeine) through the conceptually simple proposal that these factors affect those high-level, nonsensory cortical structures underlying the active modulation of passive sensory processing.

Returning to the present discussion of top-down versus bottom-up classes of theories of figural reversal, Leopold and Logothetis's (1999) model is clearly in the former camp. It is their

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[9] There is more than just a conceptual similarity between reversible figures and the ambiguous stimuli of the transactionalists. Long and Toppino (1994), borrowing a procedure they had previously used with reversible figures, demonstrated powerful fatiguelike effects with the rotating trapezoid illusion that overrode any immediate set effects. They argued that, even this class of figures, which historically has been treated within the cognitive or top-down models of form perception, can—like the reversible figures—be shown to reveal obvious bottom-up effects under the appropriate conditions.

[10] It must be emphasized that much of the electrophysiological research into multistable perception, especially the work involving monkeys, has used binocular rivalry as the perceptual paradigm. Its inclusion here is theoretically justified by the strong argument made by Leopold and Logothetis (1999) for the comparability of binocular rivalry and reversible figures on both phenomenological and physiological grounds. However, some caution should be exercised in extrapolating from one paradigm to the other because the limits of their similarities and differences have yet to be fully determined (see Andrews, 2001; Andrews et al., 2002).

proposal that the processing of sensory information is continually modified by systematic "interventions" that arise from frontal cortical areas. This top-down control serves to regularly interrupt continued, automatic sensory processing in an evolutionarily beneficial effort "to reorganize or 'refresh'" perceptions (Leopold & Logothetis, 1999, p. 261). Theoretically, such modulation allows an organism to experience other perceptual solutions as the likely distal cause of the proximal retinal stimulation. It is the unusual character of reversible figures that renders transparent this important property of the cortex.

While the model outlined in Leopold and Logothetis's (1999) review article is clearly a top-down model, later work from the same lab has suggested the need for a modification of this unidirectional influence on reversals. Leopold, Wilke, Maier, and Logothetis (2002) reported that the simple manipulation of removing the reversible figure from view after a brief 3-s presentation significantly slowed reversal rates. In fact, if the duration of the blank interval was increased to 40 s, perceptual stability was produced in which reversals were essentially eliminated. Several studies in the older reversible-figure literature had found similar results (e.g., Orbach et al., 1963; Thetford, 1963). Concerning their original model, this finding indicates that the frontoparietal areas that have been implicated as the locus of the hypothesized switching mechanism do not function autonomously or automatically. Leopold et al. (2002) concluded that because figural reversals are highly sensitive to stimulus manipulations—such as interrupted viewing (see Table 1 for other strong stimulus effects such as figure luminance)—the higher order mechanism must also monitor activity from lower levels. That is, significant bottom-up effects cannot be ignored.

Implications for Current Theory: A Hybrid Perspective

The studies listed in Tables 1 and 2 are not intended to provide an exhaustive review of the literature but to impress upon the reader the convincing bulk of evidence favoring important roles for both bottom-up and top-down processes in figural reversal. Although observers can voluntarily maintain or hold a particular interpretation of a figure to a significant degree, they cannot eliminate reversals. Hence, an observer's intent clearly influences reversals but seems neither necessary nor sufficient for complete control of reversals. Although continuous inspection of a typical reversible figure produces a relatively transient increase in reversal rate over time that is restricted to a circumscribed retinal region, the increasing familiarity with the figure also engendered by such inspection produces savings that extend over a week's interval. Hence, both localized, transient sensory processes and global, long-lasting cognitive processes are evident. Whereas prolonged adaptation to unambiguous versions of the reversible figure prior to the inspection of the standard reversible figure appears to produce localized fatiguelike effects, briefer presentations of the same unambiguous versions produce obvious setlike or priming effects. Our argument, then, is that impressive (in both a qualitative and quantitative sense) evidence exists for both bottom-up and top-down processes. No single process is likely to be the determining process in figural reversal.

Similarly, we also believe that it is important not to underestimate the powerful theoretical implications of the simple multiple-figure presentation of Flugel (1913) described above, which has been replicated and extended by many subsequent investigators (see Table 1). Flugel argued that an observer's ability to see side-by-side cubes in different interpretations essentially eliminates peripheral interpretations dependent on either eye movement or refraction as well as central interpretations dependent on a single global process as the sole determiners of figural reversal. That is, a critical role for centralized processing of specific, localized retinal regions is strongly implicated.

Another especially important class of work involves the demonstration of the moderating influence of variables that favor either cognitive- or sensory-level effects in figural reversal, depending on the particular viewing conditions. By establishing functional dissociations, this research provides strong evidence for the involvement of multiple processes in the perception of reversible figures. A good example of this work is the study by Long et al. (1992) involving the effect of prior presentation of an unambiguous version of the typical reversible figure prior to the viewing of the ambiguous figure. They demonstrated that brief presentation (e.g., less than 5 s) of the unambiguous version produced a positive-bias, or set, effect favoring the same perceptual response to the subsequently viewed ambiguous figure. However, as the duration of the adaptation period was systematically increased to levels more typical of the psychophysical literature investigating the adaptation of neural channels (e.g., 2–3 min), a reverse-bias effect was found (see Figure 9). Thus, the effect of prior exposure to an unambiguous version of a figure depends on its duration, with short and long exposure periods seeming to affect perception via top-down processes (i.e., set or expectancy) and bottom-up processes (i.e., neural adaptation), respectively. By revealing how sensory or cognitive processes may be more or less evident depending on viewing conditions, this demonstration of time dependency served to reconcile a previously contradictory literature dealing with prior exposure effects on reversible figures

The claim for multilevel effects with reversible figures is not new. For example, Hochberg and Peterson (1987) demonstrated that the very powerful manipulation of a subject's intentions through instructions to hold one or the other percept, though revealing a clear top-down influence on figural reversal, cannot eliminate reversals altogether. This led them to the conclusion that (a) there is at least one largely passive, stimulus-driven, automatic process underlying reversals, which they referred to as figural *instability* and (b) there is a second component of reversibility dependent on more cognitive factors (such as instructions), which they referred to as figural *malleability*. Other researchers (e.g., Garcia-Perez, 1989; Gomez, Argandona, Solier, Angulo, & Vazquez, 1995; Long et al., 1983, 1992; Palmer & Bucher, 1981; Toppino & Long, 1987) have also argued for the conjoint role of both top-down and bottom-up processes on the basis of both their own findings with cognitive and sensory manipulations and the wealth of supporting evidence in the literature for the two classes of processes. It is this hybrid conceptualization of reversible figures, which explicitly recognizes the powerful role of both sensory and cognitive process, that is the specific focus of this article. As Garcia-Perez (1989) noted well over a decade ago, "It is difficult to trace the boundary between what perceptual multistability owes to early visual processing, and what cognitive processing adds to it" (p. 397). We hope to clarify the interface of these sensory and cognitive processes as they are revealed, perhaps uniquely, through reversible figures.

Proposed Theoretical Framework for Reversible Figures

Given the current status of the literature on reversible figures just reviewed, we offer two conceptual proposals that we believe

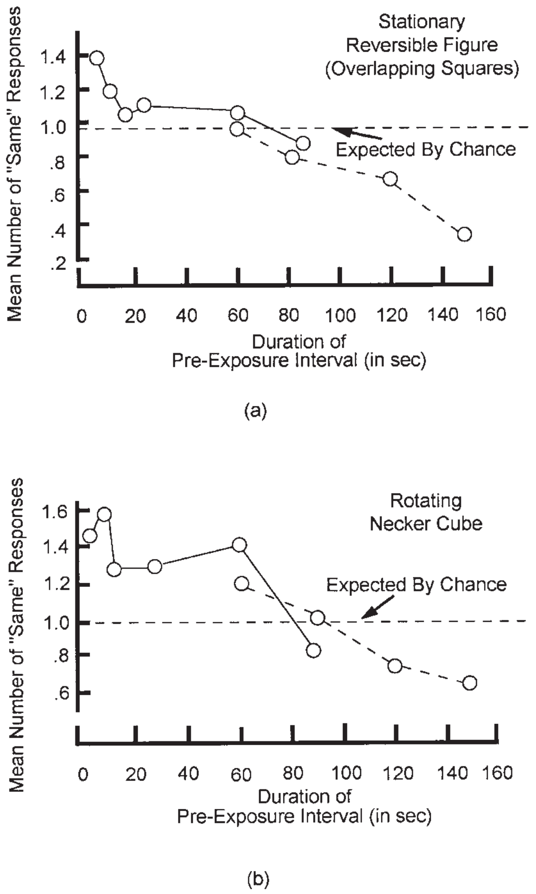

Figure 9. Results from Long et al. (1992) for the overlapping squares figure (a) and the rotating Necker cube (b). For both panels, the mean number of times that an observer reported the test figure to be in the "same" orientation as the preceding adaptation figure is presented as a function of the duration of the adaptation period. The solid and dashed lines in each panel represent the results from two separate groups of observers who experienced different but overlapping ranges of adaptation durations. From "Prime Time: Fatigue and Set Effects in the Perception of Reversible Figures," by G. M. Long, T. C. Toppino, and G. W. Mondin, 1992, *Perception & Psychophysics, 52,* p. 612. Copyright 1992 by the Psychonomic Society. Reprinted with permission.

afford a useful reorganization and integration of the extensive literature. The first proposal involves a practical distinction between the kinds of questions addressed by researchers with reversible figures. We argue that in choosing different methodologies, various investigators have in fact accessed different processes and that failure to recognize this fact has frequently led to conclusions that were incorrectly viewed as being incompatible. The second proposal involves a consideration of a hybrid model of figural reversal that incorporates both bottom-up and top-down processes contributing to reported reversals. Such a model seeks to integrate the extensive and convincing evidence for sensory and cognitive components to perceptual instability.

Proposal 1: Ambiguity Versus Reversibility

We argue that the extensive (and long-standing) psychophysical work reviewed above as well as the relatively recent electrophysiological work necessitates an appreciation of the complexity of processes underlying figural reversals. We suggest that the first step in bringing some order to this a 170-year-old field of research is to formalize a useful distinction that has been alluded to in some previous work (e.g., Rock, 1975; Rock et al., 1994; Vickers, 1972). That is, we would like to separate two aspects of the observer's experience with reversible figures, namely, ambiguity and reversibility.

By *ambiguity,* we are referring to the basic fact that with reversible figures the same physical stimulus can produce more than a single cognitive interpretation or percept, that is, stimulus → Percept A, and stimulus → Percept B. Stated differently, multiple mutually exclusive pattern perceptions are capable of being accessed by a single stimulus, thereby establishing competing perceptual responses for the same retinal stimulation. In a previous section, we noted that research with reversible figures has been especially revealing of the likely cognitive processes that are involved in the system's processing of ambiguous retinal stimulation. The famous work on observers' set with reversible figures by Leeper (1935) and Bugelski and Alampay (1961) and Fisher (1967, 1968) and many others provides powerful demonstrations of this role for reversible figures. In a similar vein, the extensive work by Rock and his colleagues reviewed above (e.g., Girgus et al., 1977; Rock et al., 1994; Rock & Mitchener, 1992) has demonstrated that past experience with the reversible figure is critical to the perceptual ambiguity. Observers unfamiliar with the figures and provided no leading instructions by the experimenter about the unusual nature of these figures may experience little or no ambiguity. This entire line of work strongly implicates a critical role for past experience (perceptual learning) in establishing the competing internal representations. And reversible figures have proven to be a useful research tool in the identification of this top-down process underlying pattern perception in a manner that is rendered transparent by the atypical ambiguous character of these figures.

The point we wish to emphasize is that the matching process between, on the one hand, the results of the complex feature analysis of the retinal information at the relatively early cortical levels and, on the other hand, the internal stored representations of objects is clearly dependent on both top-down and bottom-up processes. These two classes of processes can vary the likelihood that the observer will access one or the other perceptual interpretations (Percept A or Percept B). The involvement of top-down processes is required from the well-known work involving set effects with ambiguous figures mentioned above. Furthermore, to incorporate the work included in Table 2 revealing both the powerful familiarity effects as well as the several demonstrations of practice effects on figural reversal, a viable model must also be able to accommodate the impact of expectation and learning in establishing those competing internal representations. At the same time, however, bottom-up processes also appear to affect access to one or the other perceptual interpretations as revealed by the fact that localized adaptation to one unambiguous version of a reversible figure results in the opposite interpretation being accessed when the ambiguous version of the stimulus is presented subsequently to the same retinal region.

The benefit of disentangling the ambiguity component of one's experience from that of the reversibility component (discussed below) is that it permits a useful segregation of the extensive reversible-figure literature. Many reversible-figure studies have been concerned primarily (even solely) with ambiguity. As noted above, the types of questions addressed in these studies have been, for example, "What determines the initial perceptual organization of such figures for a given observer?" (Rock, 1975, p. 264). Or, more specifically, researchers have sought to identify those factors that determine whether a figure is ambiguous (e.g., the role of learning or the effect of varying eye position) or whether an observer can be primed to see one interpretation or another and, if so, what the nature of the priming is (e.g., set effects). The answers determined from research to address these important questions need not apply to the second perceptual experience, that of reversibility. The literatures are not in conflict, nor are the hypothesized processes either identical or mutually exclusive; they are engaging separate aspects of perceptual processing that are made apparent by this intriguing class of figures.

Distinct from the ambiguity aspect of reversible figures just described is the second routinely recognized aspect of these figures: reversibility. We contend that many researchers, rather than seeking an understanding of the system's ability to resolve retinal ambiguity, are clearly addressing this second component of experience that involves the observer's changing perceptions of the same retinal pattern over time. The basic question of interest to these researchers is why the system essentially "abandons" the perceptual interpretation (either Percept A or Percept B) first reached after it has solved the ambiguity problem discussed above and then subsequently alternates between the interpretations (Percept A ↔ Percept B). In Rock's (1975) words, "The more interesting question . . . is what determines the change in organization after the observer has been perceiving the figure in a particular way" (p. 265).

We believe that the value of treating the two perceptual experiences of ambiguity and reversibility separately is that the identification of a certain process as critical to perceptual ambiguity (or defeating that ambiguity) does not necessarily indicate that the same process is involved in the reversibility of the figure or, alternatively, that the process is involved in the same manner. To oversimplify the argument to be developed below, consider the plausible scenario in which initially the alternate perceptual interpretations (Percept A and Percept B) for a stimulus depend on active learning with that figure to establish competing internal neural representations or networks for that single stimulus pattern. Moreover, within a Hebbian conceptualization (Hebb, 1949) of this type, we propose further that, once established, these neural representations might function subsequently in a relatively passive manner such that the perceptual fluctuations that occur during extended viewing may be due to very different, even noncognitive factors.

Proposal 2: Toward a Hybrid Model of Figural Reversal

Basic characteristics of the model. In this section, we offer a theoretical framework presented in Figure 10 that we believe will be useful in constraining and guiding both future theory and

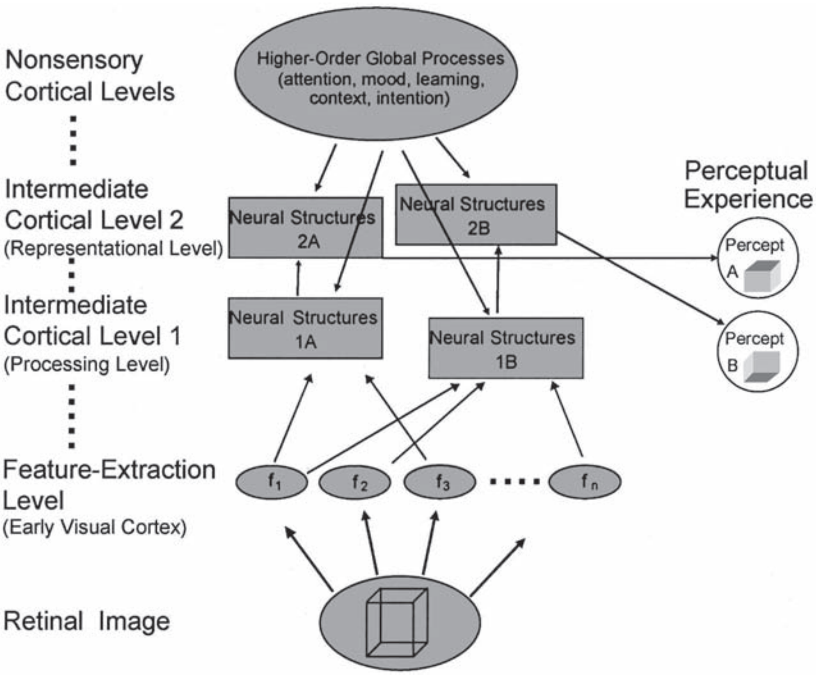

Figure 10. A tentative hybrid model of reversible figures that incorporates both bottom-up and top-down processes in a conceptual framework that can accommodate the myriad empirical results reviewed in this article. In the model, an early feature-extraction level encompasses (largely) automatic parallel channels ($f_1 \ldots f_n$) that are selectively tuned to stimulus features (e.g., orientation, depth, motion, size, and more) localized to specific retinal areas. Intermediate levels (1A, 1B, 2A, and 2B) receive input from the early feature-extraction level as well as from higher levels in the system that can differentially affect these neural structures and, thus, the alternate percepts of a reversible figure. In this conceptualization, descending signals from higher levels are responsible both for anticipatory effects that are established prior to viewing the reversible figure (e.g., context effects, volitional effects, familiarity effects) and for critical recurrent neural processes during target viewing by which the system seeks to reduce the impact of incomplete retinal information. See text for details.

research. We argue that certain characteristics of the model we propose are demanded by the multiple empirical considerations reviewed above. In particular, the model must include several levels of information processing that accommodate both bottom-up and top-down processes. The former are necessary because of the evidence that the physical characteristics of the stimulus are important and exhibit localized (i.e., retinal-specific) functioning (see Table 1). The latter are necessary to account for the effect of central, global processes such as attention, set, volition, and learning (see Table 2). This multilevel conceptualization is also consistent with the electrophysiological evidence reviewed above, which favors a highly distributed neural network with likely distinctive types of functioning underlying the phenomenal characteristics of reversible figures.

The available evidence also suggests that intermediate levels in the system may serve as the locus for the resolution of the competing interpretations of the reversible figures, although the exact location remains to be specified. Some theorists, particularly those favoring the critical role of top-down processes in figural reversal, are uncomfortable with any depiction of the perceived instability that relies on very early neural processing in the visual system. These researchers have argued that the competition between the multiple interpretations of the reversible figure occur at a representational level in the system. For example, the demonstration that learning effects can be quite pronounced with reversible figures has led some to suggest that, with practice, observers become increasingly facile at accessing the different internal representations of the figure (e.g., Rock et al., 1994). Similarly, explanations of figural reversal based on other cognitive factors, such as the visual system's proposed "preference for novelty" (e.g., Horlitz & O'Leary, 1993) would also seem to demand a late locus to the perceptual switching that involves a postrecognition level of analysis. Such internal representations of the multiple percepts of a reversible figure are presumably occurring beyond the primary and secondary visual cortex.

Another reason for suggesting an intermediate level for the antagonistic relationship between competing neural networks is the finding by Leopold et al. (2002) that the phenomenal disappearance of a figure produced through the motion-induced-blindness (MIB) paradigm (e.g., Bonneh, Cooperman, & Sagi, 2001) has the same effect on figural reversal as the physical removal of the stimulus. That is, even though the physical stimulus and the retinal image remain unchanged, the phenomenal disappearance of the stimulus disrupts the usual pattern of figural reversal in the same manner that physical removal of the stimulus does. Leopold et al. argued that this simple demonstration provides powerful evidence against those models of figural reversal that invoke passive (i.e., automatic) neural adaptation because the sensory input to the system has remained unchanged. However, as other investigators have argued after demonstrating attentional modulation of motion and figural aftereffects (e.g., Chaudhuri, 1990; Shulman, 1991; Yeh, Chen, DeValois, & DeValois, 1996), such findings do not rule out the role of neural adaptation effects but suggest an earlier locus to attentional modulation than previously ascribed. In the Leopold et al. finding with MIB, perhaps at least some of the "normal" neural adaptation effects from prolonged viewing of a reversible figure occurred beyond the early sites at which the mechanisms of MIB are engaged.

The relatively recent electrophysiological work reviewed previously also provides support for a multilevel processing model such as that shown in Figure 10. The neural activity in cortical areas such as the fusiform gyrus, IT, and STS tends to be yoked quite clearly to the organism's subjective experience (see Andrews et al., 2002, and the review by Leopold & Logothetis, 1999). This is not true of earlier levels in the visual system that exhibit either constant activity (V1 and V2), regardless of how the figure is seen, or transient activity (V4 and MT) that appears to be associated with the point of transition from one perceptual alternative to the other. Thus, although only the later temporal regions appear to exhibit percept-related activity that closely mimics the timing and durations of the observer's bistable phenomenal experience and may be the basis for the observer's conscious perception of the figure, both earlier and later levels may be involved in producing perceptual reversals.[11] This is depicted in the figure by a multiprocess model that allows for competition at multiple levels in the system.[12]

With regard to multilevel processing, converging anatomical, physiological, and psychophysical evidence suggests that the visual system is characterized by reentrant processes that permit "iterative exchanges of neural signals among levels" (DiLollo, Enns, & Rensink, 2000, p. 481). Although this conceptualization would require many more interconnections among levels than we have depicted in Figure 10, it nevertheless seems quite compatible with our model. The presumed role of reentrant visual processes provided by interacting ascending and descending neural pathways is to reduce inevitable noise and thereby to allow the visual system to determine the most plausible distal stimulus producing the given retinal pattern. In the case of reversible figures, more than a single

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[11] It is tempting to try to match the levels depicted in Figure 10 to specific cortical loci identified by electrophysiological work to be involved when the observer experiences perceptual ambiguity (see Leopold & Logothetis, 1999). For example, the feature-extraction level may correspond to early cortical levels in the V1–V2 complex that show steady neural activity unrelated to any phenomenal changes. The processing level may correspond to transient percept-related neural activity in V4 and V5 that may signal the time of phenomenal changes. The representational level may be realized by the stable percept-related neural activity in IT and STS that mimics the observer's bistable experience. And the nonsensory cortical levels may reflect the influence of extensive neural activity in the frontoparietal cortex.

Although such an analysis may seem attractive, the bulk of the electrophysiological work with perceptual ambiguity has chosen binocular rivalry as the stimulus model (see Footnote 10), and some questions have been raised recently regarding the degree of correspondence between the mechanisms underlying figural reversals and binocular rivalry (Andrews, 2001; Andrews et al., 2002). Consequently, we have opted to depict the model for figural reversals without specifying precise cortical locations for the separate processing and representational levels.

[12] Very recently, Kornmeier and Bach (2004) reached similar conclusions to those presented in the present article concerning the critical interplay of low-level and high-level cortical processes in figural reversals. By comparing EEG records exhibited during physical (exogenous) changes between unambiguous versions of a Necker cube figure to EEG records exhibited during subjective (endogenous) changes in the ambiguous Necker cube figure, they argued for a critical role of early, low-level (e.g., occipital) mechanisms in perceptual reversal. At the same time, they proposed that although perceptual reversal between percepts of the figure depends on alternating activity in these low-level mechanisms, modulation of these passive early structures through "recurrent activity from higher levels in the hierarchy of perceptual processing" is likely (Kornmeier & Bach, 2004, p. 7).

cognitive representation is activated by the initial bottom-up processes. Consequently, and unlike in most visual situations, the resulting top-down (reentrant) processes are not sufficient to confirm a single solution to the neural input. Perceptual ambiguity and reversal result—and these phenomena are affected by both the low-level and the high-level manipulations reviewed in this article.

Finally, we should also note that there are some known characteristics of reversible figures that are not specifically addressed by the theoretical framework shown in Figure 10. Perhaps most notable is the well-known phenomenon that observers report being able to see only one perceptual alternative of the reversible figure at any given moment and that each reversal cycle involves “characteristic sudden complete reorganizations of percepts” (Vickers, 1972, p. 32). This striking all-or-none character of figural reversal clearly implies some kind of mechanism that limits the number of perceptual organizations that can be consciously experienced at any given time. As noted previously, this characteristic has been referred to as the *property of exclusivity* and is apparently shared by all reversible figures (see Leopold & Logothetis, 1999). It is interesting—but perhaps not surprising—that various explanations for perceptual exclusivity have favored either low-level or high-level processes, and it may be instructive to briefly consider some of the alternatives that have been suggested.

More than 30 years ago, Attneave (1971) proposed an influential neural-adaptation account of reversible-figure perception. He conceptualized a “multivibrator flip-flop circuit” (Attneave, 1971, p. 70) in which the neural structures underlying the alternate percepts reciprocally inhibit one another in a rather passive fashion, such that only one set of structures can dominate or enter consciousness at any time. An interesting characteristic of this approach is that the limitation on what enters consciousness can be viewed as being localized to a particular pattern or object. That is, a single stimulus pattern at a single retinal/spatial location cannot be seen simultaneously as two different objects. This seems to make good sense from an adaptive, evolutionary perspective. How could an organism respond effectively if it perceived a single pattern to be two different things simultaneously?

Researchers favoring the role of top-down processes have generally been less specific about the mechanisms underlying the property of exclusivity. Prominent top-down theories that attribute reversals to fluctuations of attention (e.g., Kawabata & Mori, 1992), alternating decision processes (e.g., Rock, 1975; Vickers, 1972), or successive testing of perceptual hypotheses (e.g., Gregory, 1974) seem, at least implicitly, to attribute the property of exclusivity to the limited attentional character of higher order cognitive processes. Thus, one presumably can attend to, decide on, or test only one possible perceptual organization at a time. However, Leopold and Logothetis (1999) have pointed out several important dissimilarities between attentional processes and multistable perception. Figural reversals occur more slowly than shifts of attention, are less subject to voluntary control, and have a qualitatively different effect on experience. That is, whereas visual attention enhances processing of a selected object or spatial location, figural reversal changes one’s perceptual experience completely. The plausibility of the attentional–decisional account of perceptual exclusivity is further weakened by the fact that multiple simultaneously presented figures (to different retinal regions) are perceived to reverse independently (e.g., Flugel, 1913; Long et al., 1983; Toppino & Long, 1987). As we noted earlier, this finding creates serious conceptual difficulties for attentional–decisional theories.

The recent top-down model proposed by Leopold and Logothetis (1999) envisions the perceptual alternations of a reversible figure as reflections of a neural refresh process that allows a potential reevaluation and reorganization of the information in the visual array. This is thought to be an evolutionarily beneficial process analogous to a behavioral search process that theoretically supports the organism’s acquisition of new environmental information. This process, which is assumed to originate in nonvisual areas of the cortex such as the frontal lobes, is envisioned as a type of cyclical neural process that sends descending signals to the lower structures that determine the observer’s global perceptual interpretation of the figure. It is interesting that although Leopold and Logothetis (1999) proposed that reversals are initiated by higher order processes, they hypothesized that the property of exclusivity has “its origins in the structure of the sensory machinery itself” (p. 260). Unfortunately, they did not propose an actual mechanism underlying exclusivity and merely suggested that exclusivity reflects a fundamental (unspecified) operational principle of neurons in the visual cortex.

At present, the property of perceptual exclusivity seems to reflect constraints that originate in the visual cortex. Although higher order cognitive processes clearly make important contributions to the perception of reversible figures, they have not yet provided an adequate account of perceptual exclusivity. To date, the only clearly articulated hypothesis that does offer an explanation of exclusivity and integrates it with the phenomenon of reversibility is based on the older concept of reciprocal inhibition (e.g., Attneave, 1971). If this kind of mechanism were to be incorporated into the framework presented in Figure 10, the role of reciprocal inhibition could be represented, in part, by the inclusion of inhibitory connections between the neural intermediate structures underlying the alternate percepts.

Implications of a hybrid model. One of the fundamental characteristics of our theoretical framework is that it explicitly recognizes that both sensory and cognitive processes contribute significantly to figural reversals. This has the advantage of sensitizing researchers to the moderating effects of these processes on one another. For example, if observers are permitted to scan a reversible figure, then the role of sensory processes that are localized to specific retinal regions will be predictably reduced. Hence, clear adaptation effects (e.g., from extended viewing of a figure or from exposure to an unambiguous version prior to viewing the standard reversible figure) that are so evident when a fixation point is used (e.g., Carlson, 1953; Harris, 1980; Howard, 1961; Toppino & Long, 1987; Virsu, 1975; von Grunau et al., 1984) may be greatly attenuated when free viewing is permitted and even encouraged (e.g., Horlitz & O’Leary, 1993; Howard, 1961; Long & Olszweski, 1999; Long & Toppino, 1994; Taylor & Aldridge, 1974; Woodson & Tromater, 1979). Hence, often unintended stimulus or procedural differences across studies can produce marked—but ultimately predictable—differences in results.

Consider a second practical example. Research has shown that increasing the size of a reversible figure has a generally detrimental effect on reversal rate (e.g., Borsellino et al., 1982; Dugger & Courson, 1968; Toppino, 2003; Toppino & Long, 1987; Washburn et al., 1931). This could easily result from the consequent increase in the likelihood of eye movements during the viewing period with the large figure, which produces less stimulation of particular retinal regions and therein less neural adaptation in the cortical structures receiving input from those areas. If this plausible argument is correct, then the choice of stimulus size, which varies markedly across studies, could be a critical—though unintended—decision by an investigator. A manipulation with a central effect (e.g., instructions) could produce different scanning strategies among observers, which might have a proportionally greater effect on reversals for large targets rather than small targets (e.g., Goolkasian, 1991).

In this same vein, consider the recent study by Toppino (2003) cited above in which clear instructional effects to hold one or the other version of the Necker cube were obtained. Whereas this effect was obtained with both a small and a large Necker cube, the effect of a second variable, namely the location of the fixation point that favored one or the other interpretations of the ambiguous figure, was evident only with a large figure. Toppino favored the interpretation of these results that the smaller figure reduced the observer's ability to differentially process different regions within the figure, thereby rendering the effect of fixation less critical than with a large figure. In the present discussion, this finding is important because it demonstrates that stimulus selection in reversible-figure research, which has been noted to vary widely from study to study (Price, 1969b), can differentially access the hypothesized processes.

Although this work suggests that different viewing conditions can differentially engage top-down and bottom-up processes, another distinct possibility must be considered when interpreting the results of individual studies. Researchers must be willing to entertain alternative explanations for a given manipulation. Remaining with the powerful instruction effects just described, how should the locus of the effects be interpreted? As Washburn and Gillette suggested in 1933, these effects could be mediated by different scanning strategies or by influencing the cognitive accessibility of the different perceptual representations. In fact, it is possible that either the motor-mediated process or the dual-accessibility processes (or both) may contribute, depending on the particular viewing conditions involved. Without a fixation point, observers may differentially fixate portions of an ambiguous figure when instructed to control reversals. With a fixation point, observers may rely on solely cognitive processes that affect the accessibility of the two versions of the figure.

Finally, a likely focus of interest suggested by the hybrid model of figural reversal is the effect of the particular reversible figure selected for investigation by researchers. It is unlikely that the myriad reversible figures favored by investigators over the years engage the bottom-up and top-down processes in identical fashions. The relative simplicity of reversals of perspective with the Necker cube compared with the apparently more complex reversals of meaning with Boring's (1930) wife/mother-in-law figure is a good example. Perhaps it is not surprising that the former class of figures is less susceptible to instructional manipulations to hold or to reverse than are the latter class of figures (Struber & Stadler, 1999). Figures that reverse in meaning may engage critically different cognitive processes or engage those processes to a different degree than figures that reverse in perspective. That would appear to be a reasonable hypothesis.

We argue that the value of this multilevel conceptualization of figural reversal is at least twofold. First, when an empirical finding indicates the involvement of a particular process (e.g., when prior exposure produces long-term learning effects), this does not preclude the possibility that very different processes (e.g., transient set effects) may also be involved, but affecting other levels in the processing network. The "either-or" character of (too) much of the reversible-figure literature is rendered unnecessary. Second, this multilevel model attempts to provide a useful theoretical framework that elucidates how the many different experimental manipulations identified by researchers over the past 170 years may logically produce their marked effects on the perception of reversible figures by impacting the process of ambiguity, the process of reversibility, or both. And it is our further contention that one practical consequence of this theoretical conceptualization will be greater attention to critical methodological and procedural conditions that may inadvertently impact experimental results through the influence of unanticipated processes.

More than 30 years ago, Price (1969b), in a review of the extensive reversible-figures literature at that time, concluded that there had been few attempts to control systematically stimulus and viewing conditions, and he offered the opinion that "until this is done, the proliferation of noncomparable results is likely to continue" (p. 105). He has been proven correct. The point that we would like to add to Price's (1969b) warning is that the differences obtained across studies because of different selections of conditions need not be viewed simply as experimental noise reflecting flawed or incompatible designs.[13] Rather, we believe that in many cases these empirical differences reflect the differential involvement of either bottom-up, stimulus-driven, sensory processes or top-down, resource-limited, cognitive processes that collectively contribute to perceptual reversals in ultimately specifiable ways. Reflecting this complexity, the multiprocess model presented in Figure 10 incorporates the bulk of the existing reversible-figure literature in an internally consistent framework requiring few assumptions. Moreover, the model fosters an approach to future work in which experimental conditions are chosen to elucidate the relative sensory or cognitive locus of various manipulations and to specify the critical conditions favoring each.

Summary

Reversible figures have been a topic of recurring interest to researchers and theorists for well over a century-and-a-half. Myriad theoretical explanations of these figures' curious perceptual instability, involving both peripheral and central and both sensory

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[13] Another cautionary note sounded by Price (1969a, 1969b) involved the choice of dependent variable in this line of work. Most reversible-figure research has required observers either to report which interpretation of the figure they see or to indicate each reversal of the figure (i.e., number of reversals) over some specified viewing interval. However, in even some of the earliest work (see Price, 1969a), researchers recorded the duration for the two percepts (A and B) of the reversible figure. Price (1969b) argued that this could be of theoretical interest if the durations for Percept A and Percept B did not exhibit systematic changes over time as predicted by the satiation or fatigue model of figural reversal (see also Sadler & Mefferd, 1970). More recent versions of this approach seek to determine the statistical characteristics of these duration measures (e.g., Aks & Sprott, 2003; Gomez et al., 1995). Several investigators have reported that these distributions are easily modeled as a two-parameter gamma distribution (e.g., Borsellino et al., 1982), which has led to the conclusion that the perceived reversals are stochastically independent events. As "memory-less" events, reversals are more easily conceptualized as reflecting relatively automatic central switching processes (see Leopold et al., 2002, p. 607).

and cognitive processes, have been proposed. Furthermore, reversible figures have proven to be a popular research tool by investigators who have used the figures to render more transparent the processes underlying individuals' normal perceptual experience. In an effort to bring some order to this extensive and often seemingly contradictory literature, we have proposed two theoretical considerations. First, we have argued that perceptual experience with reversible figures involves two related but distinguishable components: ambiguity and reversibility. It is our contention that this distinction results in a useful segregation of the reversible-figure literature in terms of the type of questions addressed by researchers, and it allows for a possible separation of hypothesized processes underlying the two aspects of experience. The first component (ambiguity), which has been the focus of perhaps the best known reversible-figure work, refers to the basic fact that a reversible figure can elicit more than one interpretation by an observer on different presentations. This property of reversible figures is proposed to depend critically on (a) past experience in the establishment of competing neural representations of the figure and (b) the current sensitivity of these neural representations that may vary depending on immediate excitation levels (e.g., adaptation history) or cognitive variables (e.g., observers' set). The second component of figural reversal (reversibility) deals with the alternating perceptual experience while an observer inspects a reversible figure and may reflect the operation of somewhat different processes than those revealed through perceptual ambiguity alone. In particular, available evidence suggests strongly that largely passive adaptation and recovery among reciprocally inhibited neural mechanisms may be implicated.

Our second proposal, which has been alluded to by previous researchers, is that both ambiguity and reversibility are influenced in varying degrees both by relatively low-level sensory processes that affect perception in a bottom-up manner and by higher order cognitive processes that affect experience in a top-down fashion. We have proposed a framework within which the relationship among these processes can be conceptualized, and the wide array of evidence supporting the critical role of both types of processes in figural reversal is reviewed. Finally, we emphasize the value of this hybrid model not only in integrating the often contentious literature within a single conceptual framework but also in reframing the kinds of useful questions to be raised by future investigators.

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