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Gestalt theory reconfigured: Max Wertheimer's anticipation of recent developments in visual neuroscience†

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Abstract. In the 1920s Max Wertheimer enunciated a credo of Gestalt theory: the properties of any of the parts are governed by the structural laws of the whole. Intense efforts at the time to discover these laws had only very limited success. Psychology was in the grips of the Fechnerian tradition to seek exact relationships between the material and the mental and, because the Gestalt movement could not deliver these, it never attained a major standing among students of perception. However, as neurophysiological research into cortical processing of visual stimuli progresses the need for organizing principles is increasingly making itself felt. Concepts like contour salience and figure segregation, once the province of Gestalt psychology, are now taking on renewed significance as investigators combine neural modeling and psychophysical approaches with electrophysiological ones to characterize neural mechanisms of cognition. But it would be perilous not to take heed of some of the lessons that the history of the Gestalt movement teaches.

Gestalt, a German word variously translated as shape, form, figure, and configuration, has played an important role in discussions of perception ever since it was used by Ernst Mach in his *Analysis of Sensation*, first published in 1886. Mach made quite clear what he had in mind. He identified the two parts of figure 1 as two equal Gestalten but of different colors. Cutting to the heart of the matter, Mach contrasted the immediacy of the perception of what is shared by the two parts of figure 1 with the 'mechanical and intellectual operations' that are necessary to recognize the commonality of the two parts of figure 2, regarded by him as geometrically congruent but physiologically quite different. According to Felix Klein's (1872) Erlanger Program—the most influential layout of the mission of geometry—a geometrical structure is defined as something that remains invariant under the displacements of the principal group, ie translation, rotation, zooming, and mirror reflection. The square can be made into the diamond in figure 2 by simple rotation and hence the two have the same geometrical structure. Yet this is not immediately and compellingly evident on inspection and it follows that one cannot expect to look to geometry as a firm guide in ordering perception.

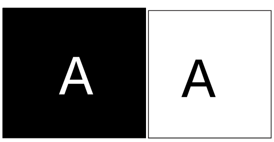

Figure 1. Example cited by Mach (1886) of how the similarity between the two parts of the figure can be recognized at first glance (or in current parlance, pops out) in spite of a difference in what Mach called 'color' and we would term contrast polarity. Mach used the word 'Gestalt' here.

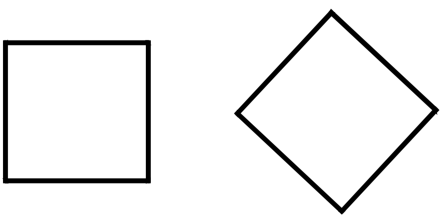

Figure 2. Example of two forms which, in spite of their geometrical identity, are not recognized as being the same without 'mechanical and intellectual operations' which Mach (1886) counterpointed to the immediate and compelling nature of a Gestalt.

† The Max Wertheimer Lecture delivered at the University of Frankfurt am Main, May 1998.

Just a few years later, Ehrenfels (1890), in an influential essay, tried to enumerate the properties that endowed a percept with immediacy and unity. He called them Gestaltqualitäten and, as interpreted later by his disciples and admirers, there were two of them: lack of overt concatenation of the parts making up the whole ('keine Und-Verbindungen') and capacity of being transposed (Katz 1948). Specifically, there is something to a melody that is more than just the tones composing it, and its essence remains unaffected by transposition to another key. In the heyday of Gestalt psychology, Wolfgang Köhler, one of its principals, assigned to the word Gestalt the meaning of a "concrete individual and characteristic entity, existing as something detached and having shape or form as one of its attributes" (Köhler 1929, page 192).

In perhaps the most concentrated expression of the credo of the Gestalt movement, Max Wertheimer, widely credited with being its guiding spirit, went even further. Not only is there more to the whole than merely the sum of its parts, but the properties of the parts are conditioned by those of the whole: "There are entities where the behavior of the whole cannot be derived from its individual elements nor from the way these elements fit together; rather the opposite is true: the properties of any of the parts are determined by the intrinsic structural laws of the whole" (Wertheimer 1924, page 7).

Such utterances by themselves would not have made a powerful scientific trend. Far from being armchair philosophers, the early Gestaltists were as active in the laboratory as any student of human behavior. The quintessential experiment was that on movement perception, published by Wertheimer in 1912 in which Köhler and Koffka participated as subjects. It involved presentation of two separated features with asynchrony and the associated perception of stroboscopic movement. Movies were, of course, well known by that time, and that sensation of movement results from asynchronous presentation of two closely-spaced points had been explicitly stated by Exner 30 years earlier. But Wertheimer went further. He said that when a line *a* was shown followed by a line *b*, the conjunction $a \phi b$ yields an experience that is beyond the sensations of a spatial separation of *a* and *b* and the time difference between them. Thus phi is a phenomenal experience. (Hence the universal use of the term phi phenomenon.) The experiment then went on to analyze the best conditions for this unique sensory experience that is not derived directly from its constituent components in space and time, for the sensation of an actually moving target cannot be distinguished from that of a stroboscopic stimulation. Wertheimer might have added the waterfall illusion, where at times a sensation of motion occurs without anything moving in the visual field, or indeed without anything at all in the visual world. In his assessment of Wertheimer's monograph, Sekuler (1996) has admirably shown how seminal these ideas proved to be in subsequent research.

Phi motion was, however, only the beginning of Gestalt psychology. When Wertheimer made his pronouncements of the early 1920s that the properties of the parts are determined by the laws of structure of the whole, he was well aware that this is not a viable research program unless the laws were actually discovered. During the decade of the 1920s there were many attempts to do just that. The single best example is Wertheimer's 1923 contribution. In it he presented a variety of visual patterns and was able to demonstrate some situations in which it was easy to recognize configurations and others where even with the best of intentions the opposite was the case. Wertheimer was successful in enunciating a few rules. For example, components that were closer to each other (factor of proximity) or that were similar to each other (factor of similarity) tended to be grouped together into a configuration. Wertheimer's article contains many compelling examples of such groupings or Gestalten. But just a few pages later the rules invoke factors of 'common fate' (page 316) and of "changes that do and don't fit in with a structure ('strukturgerecht' and 'strukturwidrig', page 330)". Without pausing, he goes on to talk about 'inner connection' of parts to give 'good Gestalten' and a factor of closure. Thus, in this early stage of study, two impressions are inescapable: the difficulty of arriving at rules that have even a semblance of generality, let alone the force of a law in physics; and the need to appeal to the observer's perceptual judgment, evidenced on every page of Wertheimer's text. Not that a viewer of his figures could disagree with the demonstrations that some groupings of components instantly 'pop out' while others cannot, or can only with great difficulty, be perceived even though there are good geometrical or intellectual reasons for their existence.

Psychology was in the grips of Fechnerian tradition ("Psychophysics is an exact discipline of the functional dependence and relationship between the mental and the physical"—Fechner 1860) or had followed Watson into behaviorism; physics had not yet emerged from its 19th century mechanistic successes—and here were scientists whose only research tool was to appeal to an observer's subjective judgment whether in an array of dots they are perceived to be grouped in one way or another! No wonder that they encountered opposition from the positivists, who demanded operational definitions in science, and from dialectical and other materialists who perceived hopelessly mentalist and idealist tendencies for which they saw no room in a rationalist world view. Köhler, the academically most successful Gestalt psychologist, tried another tack. He felt that the central nervous system, which was an acceptable site as the substrate for perception, would have properties that inevitably lead to these perceptual forms, much as the properties of a string or drum membrane naturally allow the generation of some tones and not others. A connection was thus made to physics. The concept of isomorphism was born, according to which there is a match between brain states and perception. Köhler's original formulation, using brain analogues of electromagnetic and thermodynamic theories (field theories), obviously was premature given the state of knowledge about cortical anatomy and physiology of those days, but the idea of isomorphism, albeit in much more sophisticated forms, lives on.

That Gestalt psychology did not take root in America, to which its main practitioners emigrated just before World War II, is only peripherally related to the lack of welcome of European émigrés in some prominent academic institutions. After all, as Mitchell Ash (1995) recounts in loving detail, the Gestalt movement did not by any means inhabit a bed of roses in Weimar Germany. Psychological laboratories in America were populated by people who yearned for rigor. Courses in visual perception started with Hecht's photochemical theory and ended with psychophysical observations on brightness, flicker, color, and depth thresholds (see for example Graham 1951, 1965); illusions almost to this day are taught as a warning about the difficulties of veridicality in perception rather than pointers to the rules of perceptual organization.

The failure of Gestalt psychology to become a viable force in post-World War II psychology was a consequence of an inability to deliver on a promise to provide the kind of workable rules that are taken for granted in the sciences elsewhere. When the psychophysicists and behaviorists, who did aspire to at least a semblance of such rules, were done, the void was filled by writers such as Gibson (1950) and Hochberg (1971) who laid out in attractive and thoughtful terms a sampling of phenomena where what is seen is so much richer than a collection of the kind of abstract stimuli resorted to by psychophysicists. Their expositions were no more, in fact often less, compelling than those of the earlier Gestaltist, but served well as reminders of what needed doing if perception was to become a rigorous discipline.

But the enigma of perception persists. In the middle of the 20th century, two paths to it were reopened, predicated on advances, on the one hand, in computation, and on the other, in the brain sciences. Neither is new, but technologies developed during World War II encouraged hope of insights that had eluded Köhler in his earlier vision of isomorphism and Wertheimer in his quest for Gestalt laws.

Fresh tools have become available in the study of the brain; anatomical pathways and physiological states are being discovered that make the match with perceptual states, conjectured by Köhler, seem less than just a mirage. Starting with electrical recording from single brain cells, this development continues to gather momentum, now that the armamentarium of medical imaging, molecular biology, and genetics is being progressively more utilized.

As an example of how the old Gestalt theory has remained relevant even as contemporary research methodology allows broad inroads into the working of the brain, I here examine in some detail one rather typical area of perception, that of contour salience.

From the earliest days of perception research the preeminence of borders has been commented on. When there is a uniform field before one eye, any pattern of contours before the other predominates. The processing of borders was proposed as a visual mechanism early on (Blachowski 1913), but this view was held in abeyance for more than half a century while the attention of researchers was riveted on the retinal apparatus for highlighting light differences, implemented by the center/surround receptive fields of ganglion cells. A variety of contrast phenomena fitted well into that, and the association of Kuffler's (1953) ganglion cell responses with human observations on Mach bands for example (Ratliff 1965), constituted a highlight of psychophysical – neurophysiological reductionism of the 1960s. But retinal ganglion cell activity is a strictly local apparatus which, though it is effective at the interface of larger areas, cannot really be extended to account for contour salience. Hubel and Wiesel's (1968) classical demonstration of orientation-selective receptive fields in the primary visual cortex of the monkey changed the emphasis of discussion back to contours. There is, however, still quite a gap between elongated receptive fields of cortical neurons and an observer's seeing of lines and edges. Attempts at bridging it were not helped by the detour imposed on the subject by the obsession with sinusoidal grating targets which have little standing in either the theory or the practice of visual perception. There was need, at the outset, to examine the tiling of the visual field with these orientation-selective units: how highly tuned and densely spaced are they in the orientation domain, how big a patch of visual space do they cover with how much overlap? How would they have to behave to account for such perceptual capabilities as line-orientation sensitivity and orientation contrast (the tilt illusion—Gilbert and Wiesel 1990)? As this kind of correlation work progressed, it became apparent, from both psychophysical and neurophysiological research, that the world of these neurons—though they are just at the beginning of cortical events—has some added dimensions: far from acting as linear filters which sift the sensory stimulus and then simply hand on the processed signals to a next stage, they are heavily interconnected, their behavior can vary depending on previous and concurrent stimuli, and, even more importantly, they are subject to lateral and top – down influences from other parts of the brain. Researchers are now disabused from holding the simplistic view that cortical operations can be compartmentalized into cascaded, albeit perhaps parallel, processing modules, the properties of each capable of independent characterization.

One of the problems that Wertheimer examined in 1923 concerned the situation when an observer was shown intertwining or touching contours. According to what rules did observers prefer one interpretation over competing ones? In some of Wertheimer's patterns there is no doubt about which contour components belong together, yet it turned out to be not at all easy to set out applicable rules. The problem, in a somewhat different form, was not new. Helmholtz had enquired how one made the decision, even in monocular vision, which of two objects was the nearer. He pointed out that when the contours meet, the object whose contour retains continuity is judged the nearer. This was given a mathematical form, continuity of the first derivative of the contour, by Ratoosh (1949). But, as is typical in such situations, once expressed rigorously, the formulation became immediately open to challenge (Chapanis and McCleary 1953)—see figure 3.

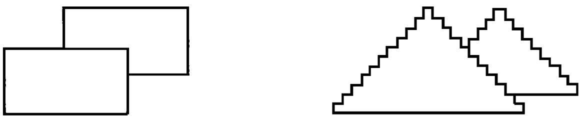

Figure 3. A simplified example of interposition as a monocular clue to distance, based on an earlier argument by Helmholtz, was given by Ratoosh (1949). Where the contours meet, the one belonging to the nearer feature has a continuous first derivative. But a few years later, Chapanis and McCleary (1953) subverted this formulation by the example on the right, where at the junction points the first derivative of the boundary of the apparently farther of the two patterns is continuous and that of the nearer discontinuous.

But the problem raised by Wertheimer was at once simpler and more searching. There is no doubt that figure 4 contains two contours, BC is a straight line, AD a sinusoid. Why don't we see a sinusoid veering off into a straight line (AC) and a straight line turning into a sinusoid (BD)?

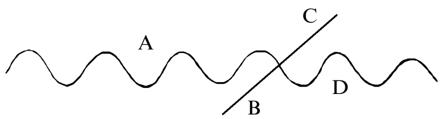

Figure 4. An example from Wertheimer (1923) of two intersecting contours. Wertheimer asked why all observers immediately see this pattern as composed of the sinusoid AD intersected by the straight line BC, rather than the contour AC joined to the contour BD.

A possible entry point into this question is suggested by the orientation-selective units of the visual cortex characterized by Hubel and Wiesel. Individual neurons have receptive fields which cover a small portion of the visual field, but it is now clear that there are connections between neurons which allow them to process information from much larger parts of the visual field. Ullman (1990) takes a computational approach in modeling how the neural connections might lead to contour salience (figure 5). Images are first broken down into edges, identifying contours. This step is followed by an attempt at segmentation, the selection of regions containing an object to be recognized. Structures need to have salience to attract attention, which may be local, such as a single green dot among many red ones—the pop-out effect highlighted in Treisman's work. But Ullman also posits a global salience, when a figure becomes conspicuous in the field owing to the arraying or arrangement of elements which by themselves are not individually salient. This is surely the same problem posed by Wertheimer in his 1923 study, and it is interesting to see what form it takes in the 1990s. Ullman postulates an algorithm for extracting global salience of a structure. It begins with the tiling of the visual field. Each small patch contains a full range of orientation-selective units whose output highlights the most prominent edge orientation in this patch. Salience is calculated by using a coupling factor between neighboring patches which decreases with the angle between their favored orientation.

Ullman's formulation is a contemporary incarnation of the 1920s Gestalt approach. Contemporary, because it replaces Mach and Wertheimer's appeal to immediacy of perception and 'bevorzugte Formen', with a mathematical algorithm that can be implemented on a computer (Ullman, not accidentally, was a student of David Marr at MIT) and also because a neural realization of the model is almost at hand. As is befitting, the link between computational modeling and neurophysiological analysis was provided by psychophysics. A series of studies (Uttal 1975; Beck et al 1989; Field et al 1993) provided experimental evidence that in a field of randomly scattered tokens, if a series of them are laid out in a row, they stand out as forming a path (figure 6). In particular, if the elements are elongated, with a sequence of them that form a 'snake', ie have

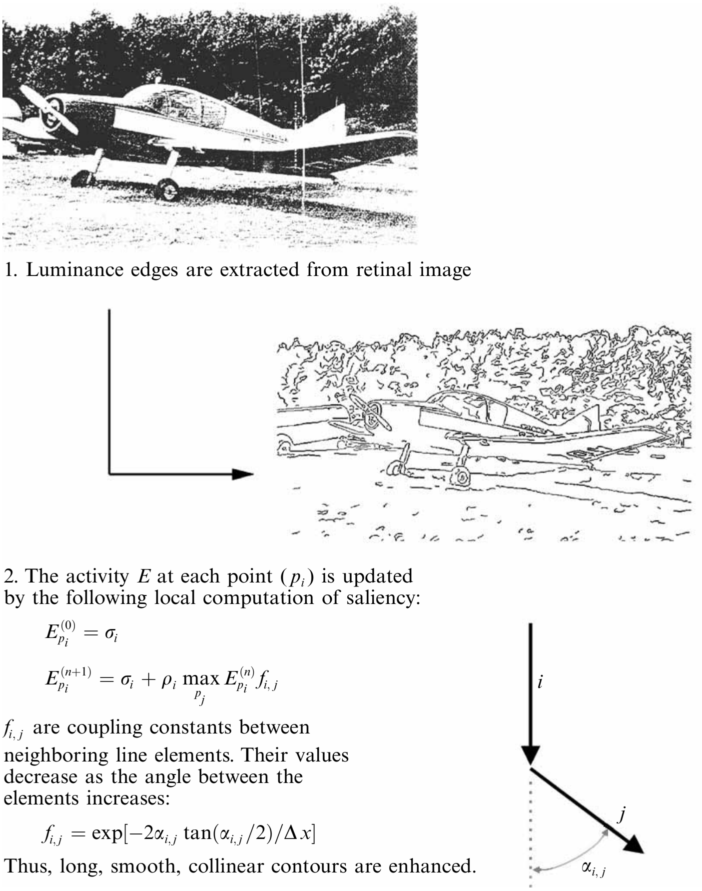

Figure 5. Steps in the model of contour salience of Ullman (1990). Luminance boundary lines of a picture are subjected to multi-step processing, including (a) patch-wise selection of edge orientation and (b) an algorithm in which the best single orientation of each contour element is elaborated from the ensemble of local orientation-selective units, and global salience is determined by potentiation according to relative position and orientation.

constraints as to their orientation and position with respect to each other, the observer would report that they could detect it. This kind of formulation allowed numerical evaluation of the range of orientation differences and distances between elements that most favored the emergence of a form. As it happens, the neurophysiologists were ready for these results: Hubel and Wiesel had discovered orientation-selective neurons, and anatomical and physiological studies have since demonstrated that they are interconnected (Gilbert 1992). In a series of researches, it was shown that the oriented elements are more easily seen when flanked in the right manner by other elements, suitably positioned and oriented (Polat and Sagi 1993). Moreover, in paired psychophysical and neurophysiological experiments Kapadia et al (1995) succeeded to show facilitation of single-cell neural responses in the alert monkey by flanks which also improve a human observer's detection of a target line (figure 7). We have here a fulfillment of Köhler's premonition of isomorphism between perception and brain state—perceptually preferred forms contain elements that potentiate each other in psychophysical experiments and, when used as stimuli for single units in the visual cortex of the awake monkey, they facilitate such units' responses. And it is precisely the kind of mechanism that is needed to implement Ullman's model of how long, smooth contours become salient and how global percepts may be built from local features.

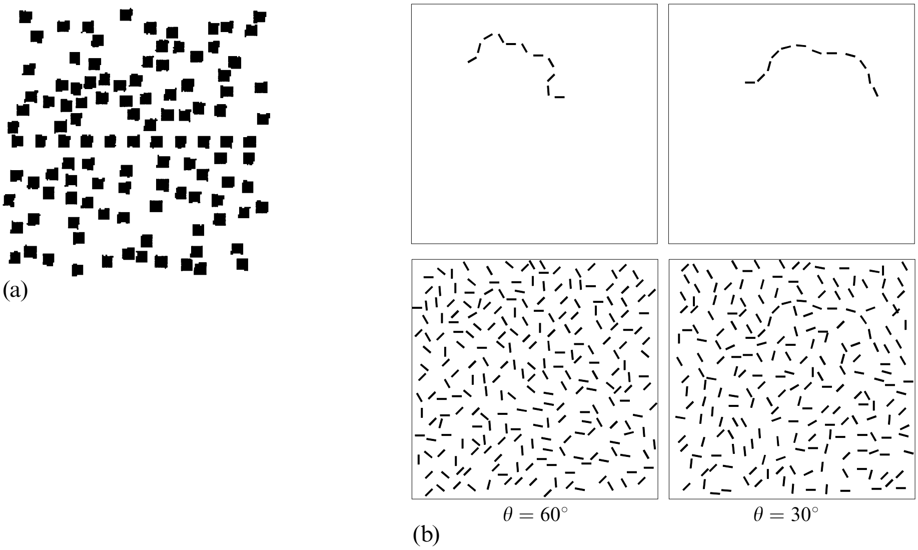

Figure 6. (a) A sequence of elements restricted in their relative position can form salient contours that emerge among random elements (after Beck et al 1989). (b) If the elements are elongated, relative orientation is a significant factor because the 'snake' on the right, whose components differ in orientation by 30° is easily detected, whereas it does not stand out on the left, where the orientation differences are 60° (after Field et al 1993).

The actual state of knowledge is both more complicated and even more exciting than is apparent from this minimalist description. It had been traditional for a while to rest one's case once the responses of single nerve units had been found to match an animal's behavior. Now we are more aware that we need information about neuronal population and circuits even more than about single cells. In particular, the pertinent question at the present state of knowledge is the extent to which any change in firing of single neurons early on in the stream of visual processing in the brain is an expression of influences on those neurons of higher neural centers feeding back signals to the earlier ones—top–down influences, as they are called. And this raises the associated question of ad hoc changes in neural connection depending on the imperatives of a particular perceptual or cognitive situation. We are here faced not only with the major problems of 'neural plasticity', which obviously underlies learning, but also with the possibility of processing modules and pathways whose properties—unlike those of the retina—change from one situation to the next and whose future study, hence, will need a vast amount of information about and control of the stimulus state. Is there a better example of Wertheimer's vision of a whole determining the behavior of its constituent parts than an experimental verification of the fact that what a visual cortical neuron responds to best depends more on the properties of the overall configuration in the visual field than on the parameters of the stimulus in its receptive field?

Yet we must not lose sight of the fact that the more we have closed the circle between Wertheimer and the neurophysiological/psychophysical enterprise of the 1990s the more urgent the need to examine the roots of the failure of Gestalt psychology in the intervening era. Certainly, an impressive nexus has been established between three independent, modern, and technically highly proficient methodological approaches to that textbook case of Gestalt theory, contour salience, an almost verbatim translation of one of Wertheimer's favorite terms 'bevorzugte Formen'. An algorithm, implementable on computers, was put forward by Ullman and translated into a set of visual patterns allowing first perceptual (Field et al 1993), then rigorous psychophysical experiments (Polat and Sagi 1993; Kapadia et al 1995), and finally, based on previous

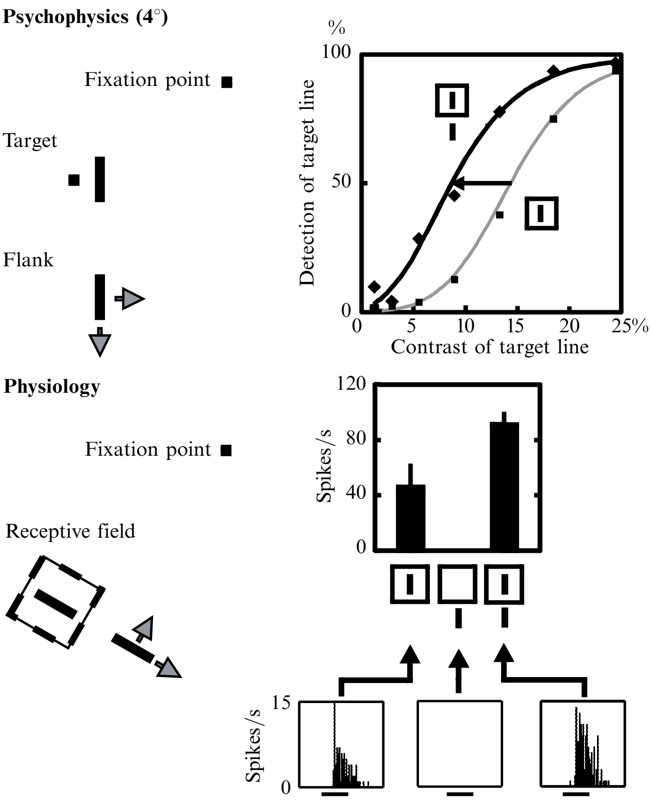

Figure 7. An example of what Köhler called isomorphism. Identical patterns were used in a human psychophysical experiment with peripheral viewing and in measurements of the responses of neurons in the primary visual cortex of the alert monkey in a similar part of the visual field. A collinear flank makes a line segment more easily visible to the human observer, as determined by the psychometric curve of 'seen' responses to test stimulus presentation at various levels of contrast. For a similar stimulus, the response of a neuron in the primary visual cortex of the alert monkey is facilitated in the presence of a similar flank. Note that the flank does not stimulate the cell if shown by itself. From Kapadia et al (1995).

anatomical and neurophysiological knowledge (Gilbert 1992), single-unit responses in the cortex of alert monkeys (Kapadia et al 1995) showed isomorphism in a modern form. And in conformity with the vision of the early Gestalt theorists, the very idea of dynamic, top–down and context-driven brain states invites the consideration of global structure that, in turn, conditions the properties of its parts rather than the reverse.

There have been related attempts to bring some other original Gestalt rules into this context. One of them relates to closure, wherein a closed curve has more salience than an open one. Kovacs and Julesz (1993) demonstrated that when, amongst many randomly located and orientated Gabor elements, one set outlines a closed contour, it is more easily detectable than when it forms a somewhat similar but open contour (figure 8). But, as much as this formulation tended to support the Gestalt rule of closure, it is insufficient: a simple closed contour such as a circle is detected more easily than one shaped like a crescent moon, and for such a shape the advantage of closure has already been lost (Pettet et al 1998).

It seems that we have difficulty escaping a dilemma so well articulated by Wertheimer when he pointed to the many kinds of stimulus layouts, in which some pattern components segregate themselves into perceptual wholes or figures whereas others appear separate, and then asked: "Are there principles for the kinds of resulting arrangements? What are they?"

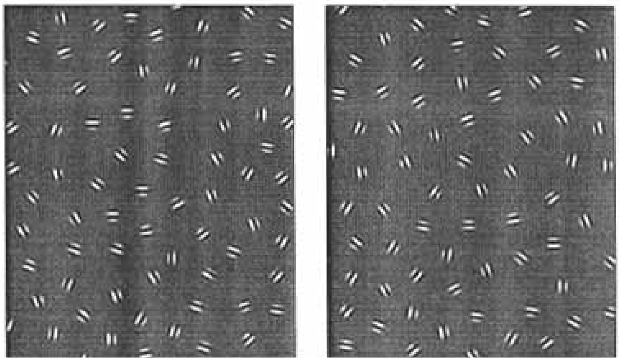

Figure 8. Closure was put forward early as a principle for a good Gestalt. Here Kovacs and Julesz (1993) demonstrate that a closed contour (right) has an advantage when used in a contour salience demonstration.

Actually, Wertheimer had considered—and rejected—the idea that the relationship between the angles which two borders make at a point of intersection determined the segregation of the two contours (figure 9). There are further reasons for concern that consigning these perceptual imperatives solely to neural operations in the primary visual cortex may not be the whole story. In particular, the latter are fairly well localized to small patches of the visual field with quite prominent changes in grain with retinal eccentricity, whereas perceptual grouping and contour salience remain substantially invariant with changes in position, though not necessarily orientation (see figure 2) or size. The dialogue between Ratoosh and Chapanis and McCleary (figure 3) is actually paradigmatic of a more generic problem. There are Gestalt phenomena, contour salience, pop-outs, etc. But as soon as expression is given them in reasonably rigorous form—not even yet in mathematical notation—counter-examples present themselves. Wertheimer in 1923 was fully aware of this dilemma. Should his explanation, opaque to the eyes of reductionists, be interpreted that perception itself is the ultimate arbiter of what is perceived? "Es kommt auf die 'gute' Fortsetzung an, auf die '*kurvengerechte*', auf das '*innere Zusamengehören*', auf das *Resultieren in 'guter Gestalt'*, die *ihre* bestimten 'inneren Notwendigkeit' zeigt." [It depends on 'good' continuation, the one *appropriate to the curve*, on the '*inner connectivity*', on the '*resulting in a good Gestalt*', which has *its* own specific 'inner necessity'. Quotation marks and italics in the original (Wertheimer 1923, page 324).]

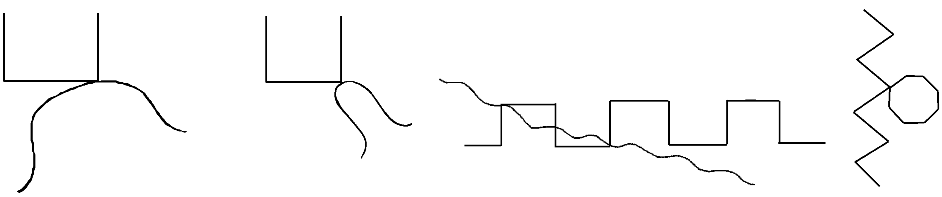

Figure 9. In a search for laws of structure of 'wholes', Wertheimer, anticipating theories and experiments of the 1990s, considered the possibility that continuity of direction determines how contours segregate themselves. However, as these illustrations from his 1923 paper show, this is by no means a universal rule. In each figure there are two easily segregated components, yet at the junction points continuity of the contours is between components rather than within them.

The dissonance that accompanied the original Gestalt theory in its ups and downs during most of the 20th century remains. Attempts to synthesize our perceptual experiences through knowledge of the structure and function of our physical and physiological sensory apparatus invariably reach a point so well articulated by Hering (1906). In response to a Helmholtz remark on the need to take the visual system apart like a watch to look at its cogs and gears, Hering urged that when we want to figure out what a watch does and are prevented from inspecting its inside, we should look at its hands. So every generation of visual scientists, as their reductionist program strikes an impasse, looks for guidance to the actuality of perception. Modest starts yield modest successes. We are comfortable with matches between retinal photochemistry and dark adaptation, between the eye's optics and cone spacing and visual acuity, between cone pigments and color matching and mixing. Spectacular progress in the neural apparatus as the visual stream enters the brain now makes us wish to match that knowledge of neurobiology with the recognition of spatial forms and the assignment of position, depth, and movement attributes of simple visual features. For knowledge of the latter we find the Fechnerian psychophysics limiting and hence naturally turn to what Gestalt theorists kept dwelling on in the 1920s. But imbued as we are with the rigor of physics and physiology, and demanding that rigor also for the laws of perception, we do not yet find an equivalent match. The program ahead then needs flexibility and tenacity—flexibility by doing the best with what is given and not trying to place perceptual laws into impossible straightjackets, and tenacity by persevering, by incremental steps if necessary, and keeping in mind just how immense and ultimately rewarding the task ahead.

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