Perceptual Processes that Create Objects from Fragments

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Abstract-**Perception of objects depends on a number of interacting information processing tasks. This paper gives a brief overview of processes of contour and object perception that overcome fragmentary input and produce representations of objects. A simple geometry accounting for contour interpolation is described, and its applications to 2-D, 3-D, and spatiotemporal object interpolation processes is considered. Some aspects of the model -- especially the unified treatment of illusory and occluded objects -- raise questions about the nature of seeing. Although it is often believed that illusory objects are *perceived*, while occluded objects are *inferred*, I suggest that both the representational theory of mind and the results of research converge in supporting the unified account. Illusory and occluded contours and surfaces do not divide into the real, the perceived, and the inferred, but are all *represented*, and in key respects, derive from identical perceptual processes.**

I. Introduction

How does the visual system create representations of objects from partial information? When it does so, is it creating illusions? In this paper, I both describe some current directions in research on object perception and consider a couple of larger philosophical issues involving the creation of perceptual representations.

The focus will be on processes of perceptual organization, particularly those processes that build representations of complete contours, objects, and surfaces from fragmentary input. To keep the discussion brief, I provide only the gist of research findings, giving references to other published work with more details.

Perceptual systems provide the information that humans and other organisms use to guide thought and action. Vision is special among these systems, in that it gives detailed knowledge of objects and the spatial layout, and it works at a distance. Understanding vision requires us to determine how visual information leads to descriptions of objects, spatial arrangements, and events.

Our descriptions of perceived reality are heavily based in a vocabulary of *objects* -- bounded volumes of matter that function as units in our interactions with the world. Objects are both physical and psychological units; in fact, they may be best described as ecological units [1]. In physical reality, we believe that there exist coherent entities, such as pebbles, books, and cars. They separate from other things and cohere over movement. At the same time, our psychological notions of objects are restricted in terms of size, duration, and degree of cohesion. Neither the planet earth nor a sub-atomic particle is an object for ordinary cognition and behavior. So, objects are physical units at scales relevant to our thought and behavior.

How do we perceive objects? Although the operation of object perception is ordinarily quick and effortless, the scientific explanation of object perception is extremely challenging. Many of the problems are commonly considered together as issues of *visual segmentation and grouping*. Whether the problem is segmentation or grouping depends on the description with which you start. If the starting point is an image of a scene, either on your retina or on a CRT screen, the issue is how to segment this entity into parts that correspond to different objects in the world. If instead you start with the well-known coding of visual inputs in mammalian vision into small, local patches of oriented contrast in early cortical areas, the problem is how to group together the outputs of thousands of units that might all be registering parts of a single object. Grouping is also the issue if one starts with an image description in terms of many pixels. Likewise, if we start with visible regions, parts of a single object must be grouped, as often they project to several different retinal locations, as we will consider.

A pervasive and fundamental difficulty in achieving descriptions of objects from information in reflected light may be labeled the *fragmentation problem*. Whereas the world and our representations of it contain coherent objects and continuous surfaces, the input from the world to our eyes is fragmentary. Most objects are partly occluded; their projections to the eyes are interrupted by parts of other objects. Viewing a scene through foliage, the observer's retina receives many separate patches of each object in the scene. How do we obtain representations of complete objects -- a building, a car, a person -- under these circumstances? The answers are important, as these circumstances are more the rule than the exception in ordinary perception. The problems become all the more complicated when observers or objects move, as patterns of occlusion continuously change.

II. Visual Interpolation Phenomena

Fortunately the visual system has processes that overcome fragmentation in the input and produce representations of complete objects. Shown in Fig. 1 are examples of several phenomena in which the visual system overcomes gaps in the input in perceiving objects. Fig. 1a shows a case of partial occlusion; the three black regions all appear as part of a complete object, whose shape is apparent. Fig. 1b shows an example of the phenomenon of *illusory contours* or illusory objects. Here, contours are

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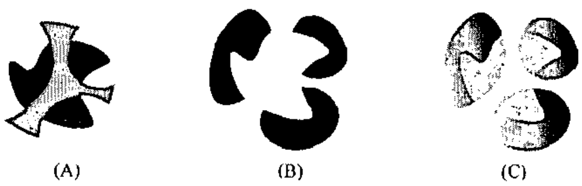

Fig. 1. Visual Interpolation Phenomena. A) Partial occlusion. B) Illusory contours. C) Transparency.

connected across gaps such that these interpolated parts appear in front of other surfaces. In Fig. 1c, an additional effect, one of transparency, can be observed in the figure that is created across the gaps.

These phenomena are formally similar in that equivalent or similar visible contours and surface fragments become linked to form objects, despite intervening gaps. Research suggests that the similarity is more than formal: these phenomena share a common underlying interpolation process.

III. Visual Interpolation Processes

How do visual processes overcome fragmentation to achieve accurate object perception? The visual system uses relationships among visible *contour* segments to guide segmentation and derive shape. It also uses relationships of *surface* properties to establish surface continuity. Most of our focus will be on contour processes, but we will describe surface processes briefly in a later section. After giving a sketch of these processes, I will consider their implications for the nature of seeing: Do these processes create illusions or give us windows into reality?

A. Contour Extraction Processes

Object perception involves a number of conceptually distinct information processing tasks and representations. (These may or may not be realized as separate processes or mechanisms in the brain.) Fig. 2 provides a schematic model of these processes, representations and their interactions. Some components and their connections reflect established findings whereas others represent newer conjectures. Considerable differences exist in how much is known about precise computations and neural implementations in the specific boxes. Rectangles indicate functions or processes, and octagons indicate representations. The model has few representations: output representations of shape and unity (labeling regions belonging to a single object) and one intermediate representation: the *visible regions representation.* Among other things, this representation marks connected visual areas, derived from depth, velocity, and luminance maps, and labels their contours as bounding or belonging to other (occluding) objects. (For details, see [2].)

Our immediate concern is the contour stream, which locates discontinuities in luminance, color, texture, depth, and motion, uses these to find edges and junctions, and *ultimately leads to meaningful contours and object shape.* The importance of contours derives from the fact that objects will tend to be relatively homogenous in their composition (and thus in their lightness, color, texture, depth, etc.) and will often differ from nearby objects and surfaces. Visible contours often, but not always, mark the locations of object boundaries.

Computations leading to perception of contours and edges appear to begin in the early cortical areas V1 and V2. Cells in these areas respond to oriented luminance contrast at particular spatial frequencies in particular retinal locations [3,4]. By area V2, and perhaps earlier, many cells respond selectively to particular binocular disparities, providing the basis for stereoscopic depth perception [5]. Some cells in the early cortical areas also respond preferentially to motion, although areas upstream, particularly area V5 (the human homologue to macaque area MT), appear to be specialized for motion processing. Numerous proposals in both biological and computational vision have been made about how early cortical responses can be utilized to detect luminance edges in the optical

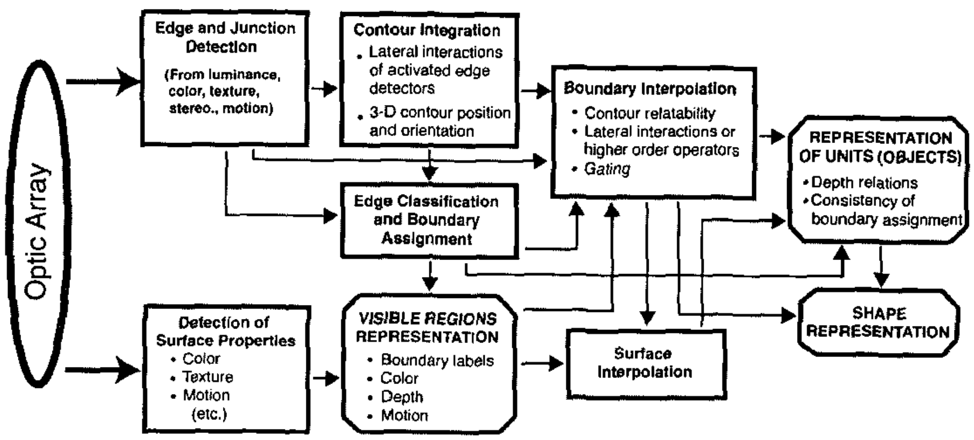

Figure 2. A Framework for Object Perception. Rectangles are functions; octagons are representations. (See text.)

projection. The modeling of object perception based on other types of edge inputs, such as discontinuities in stereoscopic depth and motion is less advanced. Likewise, how the visual system integrates edge information arising from various sources remains relatively unknown.

Additional tasks that we will not discuss here include the classification of edges, as arising from illumination or reflectance differences, and boundary assignment of those edges determined to be occluding edges.

B. Contour Interpolation

Although the tasks of contour finding, classification, and boundary assignment are challenging in themselves, even their complete solution does not provide reasonable representations of objects. Because of occlusion, in normal scenes, most objects are partly occluded by others. *Contour interpolation* processes connect visible contours across gaps caused by occlusion to produce perceptual units that correspond more accurately to the actual objects in a scene.

In recent years, we have learned a great deal about how interpolation processes proceed (e.g, [2,6]). These computations begin with contour intersections or *junctions*. Junctions are points of *tangent discontinuity* -- places where contours have no unique orientation. Most often there are two orientations at image junctions. As can be seen in Fig. 1, interpolated contours begin and end at these tangent discontinuities in the image. These points include all of the places where edges go out of sight and need to be interpolated. It has been proposed that "end-stopped" cells in visual cortex (cells sensitive to the contours that end or abruptly change direction within their receptive fields) underlie junction detection (e.g., [7]).

Interpolated contours not only begin at tangent discontinuities, but they agree with the slopes of visible contours that terminate at these connection points (see examples of Fig. 1). Contour interpolation can be summarized by saying that visual system interpolates according to a smoothness principle, called *contour relatability*, such that interpolated contours are smooth (differentiable at least once) and monotonic (singly inflected), and at their endpoints, they match the slopes of real contours. Fig. 3 shows a geometric construction defining relatability [6]. The notion of relatability in perceptual grouping is not the same as but is related to the principle of *good continuation*, proposed as one of several principles of perceptual organization in the early 20th century by the Gestalt psychologists [8]. Relatability appears to tap into important regularities about the smoothness and predictability of objects (e.g., [9]).

1) *Implementation of the Relatability Geometry*: How are the relationships captured by the geometry of relatability implemented in neural mechanisms of vision? This is an active area of research. Several neural-style models of contour interpolation have been proposed [e.g., 10,11]. There are two basic ideas about the mechanisms used by the visual system to surmount gaps. One is the use of higher-order operators, often called bipole cells. Real edge inputs on either side of a gap feed into these nonlinear, higher-order grouping operators (e.g., [11]). The activation of these operators, centered over a discontinuity in edge input, may be used to construct a contour that spans the gap (Fig. 3B).

Interpolation may also be carried out by an interactive network of orientation-signaling units (e.g., [12]). (See Fig. 3C). According to this idea, luminance-defined edges activate some units, leading to facilitative interactions with other units that do not receive direct stimulus input. Interpolation occurs when a path of units, defined on either end by directly-stimulated units, becomes active as the result of these interactions. Some models combine aspects of both bipole and network schemes [10].

Current models do not fully implement all that is known about the geometry of relatability and other determinants of contour strength, such as support ratio [13; but see 14]. Yet, the basic concepts of cooperative units and network interactions seem likely to be the building blocks of future advances. Both use outputs of orientation-sensitive cells in early cortical areas. (For further discussion of the relation of geometric and neural models in object formation, see [2]).

A controversial argument about the process as described above is the *identity hypothesis* -- the claim that the same interpolation process applies to several different-looking contour interpolation phenomena. These include the phenomena in Fig. 1. Occluded objects, illusory objects, and

(A)

(B)

(C)

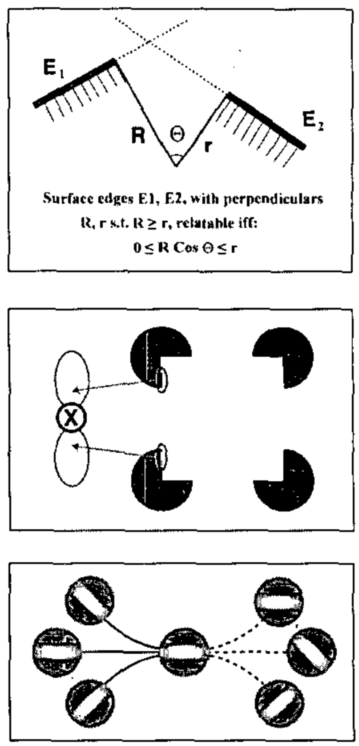

Fig. 3. A) Relatability geometry (Kellman & Shipley, 1991).
B) Bipole implementation of interpolation (e.g., Grossberg & Mingolla, 1985; Heitger et al, 1998). C) Network implementation (Field, et al., 1993)

other cases of interpolation differ in appearance and involve differing assignments of depth and boundary ownership relative to adjacent surfaces. Despite these differences, in appearance, research indicates that an identical interpolation process operates in all of these cases [15-17]. Some models (e.g., [10]) and recent evidence [18,2] suggest a *promiscuous* early interpolation process that makes more connections than are realized in the final scene representation Later stages delete some interpolations and determine the final depth arrangements of interpolated and other contours and surfaces.

Fig. 4 illustrates two phenomena that implicate a common interpolation process. Fig. 4a presents a stereo pair that may be free-fused by crossing the eyes to obtain a 3-D display. (The effects to be described are also visible in each image alone, although less vividly due to all parts lying in a single depth plane.) The central white figure has 4 interpolated contours. Each one is an illusory contour for part of its length and an occluded contour along another part. That these *join* to form a single contour (or perhaps more to the point, that interpolation *occurs* between these two different kinds of endpoints) is significant and unexpected. It indicates that the interpolation process accepts either type of input, including combinations. This would be strictly prohibited, by the way, in some current models (e.g., [11]), because of constraints on the inputs allowed to a given bipole operator. Fig. 4B (after [19]) shows a display having entirely homogeneous surface characteristics. This kind of display is an excellent demonstration and test of the basic segmentation and grouping concepts described above. Although one might expect a homogeneous region to be perceived as a single unified object, it splits into two perceived objects. The reason is the presence of the four tangent discontinuities in the concavities of the display, and the relatable edges leading into them. Once interpolation occurs, closed contours formed by real and interpolated edges define each of the two objects, the triangle and the quadrilateral.

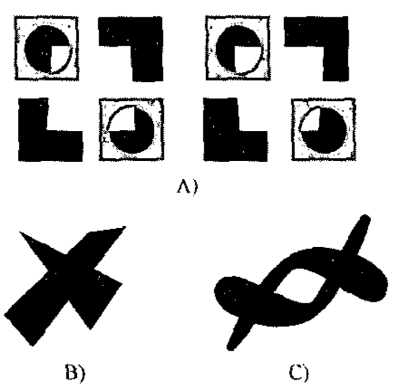

Fig. 4. A) Illusory and occluded contours join. Display is a stereo pair; free-fuse by crossing the eyes. B) and C) Examples of homogeneous areas that split into two perceived objects. (See text.)

This kind of display also has some interesting properties relevant to the identity hypothesis. Where the two objects cross in the image, one appears in front, having illusory contours, and the other appears to pass behind, having occluded contours. With prolonged viewing of Fig. 4B, the depth order appears to switch, so that illusory contours become occluded ones and vice versa. There is an interesting regularity in such displays [19]. Where interpolated boundaries cross, those crossing the smaller gap appear in front, as illusory contours, whereas the boundaries crossing the larger gap are seen behind, as occluded contours (Fig. 4C). The depth order ambiguity in 4B derives from the approximately equal lengths of interpolated edges. This claim about relative extent of interpolation, sometimes called Petter's Effect, has substantial experimental support and has been around for a long time. What has only recently been realized is that the effect provides a strong argument for an interpolation mechanism common to illusory and occluded contours. The reason is that in these displays, the determination of illusory vs. occluded appearance depends on a *comparison* of interpolated contours. Which appears in front depends on the relative lengths of crossing contours. If the illusory or occluded appearance of an interpolated contour depends on its length relative to a crossing interpolated contour, there must be, implicitly or explicitly, a length comparison process. This implies, in turn, that the locations and extents of contour interpolation are determined prior to their final appearance as illusory or occluded, at least in this case.

Several logical arguments of the kind given above and substantial experimental evidence combine to support the notion of a common underlying interpolation process, one that produces very precise and essentially identical representations of boundary locations in both illusory and occluded interpolation cases (e.g., [16, 20]). Of course, different looking interpolation phenomena do involve differences in other aspects of scene representation, such as their depth relations with (projectively) adjacent surfaces.

The idea of a common perceptual process underlying illusory objects and occluded ones cuts against deep-seated assumptions in sensory and perceptual research. We will take up some of these issues in the last section. First, we comment briefly on the scope of interpolation processes.

2) Three-Dimensional and Spatiotemporal Interpolation

Most interpolation research has addressed static, two-dimensional displays. Recent research in our laboratory has focused on three-dimensional and moving contours. It is clear that interpolation processes utilize three-dimensional and motion-carried information and produce representations of three-dimensional objects.

Fig. 5 illustrates 3-D interpolation. Both rows show stereo pairs that should be free-fused by crossing the eyes. In Fig. 5A (and Fig. 4A above), illusory surfaces are visible. These utilize as inputs 3-D orientations and positions of edges, and produce as outputs contours and surfaces traversing all three spatial dimensions. Fig. 5A and 5B

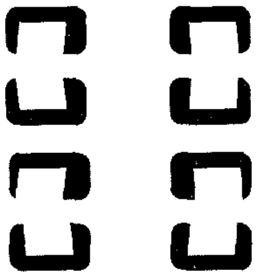

Fig. 5. 3-D Interpolation Displays. (See text.)

illustrate one of the findings of our research [21], namely that an expanded 3-D principle of relatability appears to govern 3-D interpolation. In 5A but not 5B, contours can be connected by a smooth, monotonic curve; an interpolated surface is seen in the former case, but not the latter. Also important for our perception of complete objects is dynamic information. Moving observers and moving objects produce changing patterns of occlusion. Our recent research [22] indicates that a notion of spatiotemporal relatability appears to govern which successively visible fragments get perceptually connected. It appears that briefly visible regions are encoded in a buffer, along with information about their velocity relative to the observer. The velocity information is used to extrapolate over time the positions of these stored fragments. As new contours and regions become visible, they are connected to the previously viewed regions following the geometry of spatial relatability, here applied to currently visible and previously stored regions in updated positions.

Neural style models have most often grappled with interpolation in static, 2-D situations. More comprehensive treatment of 3-D and dynamic aspects of object formation from partial information are research tasks of high priority.

C. *Surface Interpolation*

Contour interpolation is not the only visual process that links visible areas; surface relations also play a role. Fig. 6 illustrates. Note that the black circles in the display have no tangent discontinuities and therefore cannot participate in contour interpolation. Those circles that appear within interpolated edges of the surrounding black figure appear as holes. This is a manifestation of surface interpolation. In

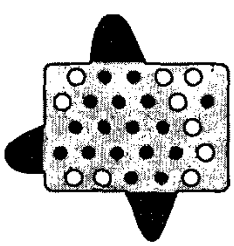

Fig. 6. Example of surface interpolation process that complements contour interpolation. (See text.)

contrast, the black spot outside the figure appears as a spot on a surface. Likewise the white circles appear as holes through which the background is seen. Surface spreading behind occlusion links visible areas but provides little shape information; it is confined by real and interpolated contours. Visible regions are connected across gaps in the input based on the similarity of surface qualities (e.g., lightness, color and texture). (For details and experiments, see [23, 24]).

IV. Objects from Interpolation: Illusions, Realities or Representations?

What does it mean to say we *perceive* occluded regions of contours, surfaces, and objects? Do we really see them, or are they inferred? The issues are interesting, and they raise important questions about illusion, reality, and what it means to see.

The identity hypothesis, arguing for a common process in illusory and occluded contour completion, raises these issues directly, as these phenomena have traditionally been considered very different. Michotte [25] labeled them as *modal* and *amodal* varieties of completion. Modal referred to the presence of sensory attributes, or modes, in the completed object, whereas amodal meant that the completed parts exist perceptually but without sensory attributes.

This distinction in phenomenology has most often led to a common sense conclusion. Illusory contours and surfaces are clearly *perceptual* phenomena, because we *see* them, i.e., they produce sensory experiences. Occluded contours and surfaces are out of sight, so in what sense can we be said to see them? They are *cognitive* phenomena; occluded parts are somehow known or inferred, not perceived.

Obviously, the account we sketched above clashes with this view of seeing vs. knowing. Where does the problem lie, in our unified account or in implicit conceptions of what it means to see?

The source of the problem, I believe, is confining the meaning of *seeing* to local sensory responses based on local physical data. Perceptual descriptions are functions of incoming information, but they need not be restricted to some narrow class of functions, such as a one-to-one correspondence between represented properties of objects and local sensations or stimuli.

This point has been made convincingly about once a generation in visual science, but it remains a source of abrasion between sensory and physiological approaches on one hand, and approaches to higher-order perception on the other. The Gestalt psychologists (e.g., [8, 26]) presented a compelling case that perception is not a summation of local sensory responses. Gibson (e.g., [27]) argued that sensations are actually quite incidental to perception. Rather than reviewing their arguments, perhaps the best way to sweep away the cobwebs here is to remind ourselves of the arguments for computation and representation in perception and information processing generally (e.g., [28]). On the computational/representational theory of mind, what is the principled difference between representing some contour as going behind another surface and representing some contour in front of another surface? Nothing. One is not more privileged or "real" than the other. Characterizing one as a "sensory" effect and the other a "cognitive" effect reflects an epistemology that did not work out. Occluded contours are no more and no less "inferred" than are illusory ones.

Given that there is no theoretical barrier separating represented contours and surfaces that are occluded or illusory, why do they *look* so different? What causes the robust difference in phenomenology? An answer is that this aspect of our phenomenology -- the modal/amodal appearance -- may simply code whether some surface or contour is nearest to the observer in some visual direction. This piece of information is important and, unlike the connectivity of objects, depends on the vantage point of the observer. Parts of an object that are nearest in a visual direction may be reached or grasped, whereas those equally real edges and surfaces behind some other object may not be reached without going around or through something.

The point is that all seeing is representational. So-called "real" contours must be represented to be seen just as much as illusory or occluded ones. As we have seen, there is no basis for designating representations derived solely from local sensations as being the only "real" ones. There are, however, multiple aspects of scenes that we need to represent. The connectivity of objects is one, best served by processes that are relatively indifferent to whether part of a contour goes behind or in front of something else. On the other hand, the reachability of a surface is a different aspect; it depends on the vantage point of the observer, and it is related to the phenomenology of modal/amodal. In the mind, there are not real contours, perceived contours, and inferred contours, only represented ones.

So, are interpolated parts of objects illusory or real? Our analysis brings us to a useful answer. For the representations needed for effective thought and action, encoding visible fragments alone would never do. Although faithful to local stimulation, such fragments are not the objects of the physical world. Interpolation processes pick up on basic regularities in the physical environment, probably as a result of evolutionary processes. As a result, they supply missing parts that lead to less faithful representations of the momentary image, but more accurate representations of the physical environment. In this sense they are produce not illusions, but representations that bring us closer to reality.

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