Psychological Review
2007, Vol. 114, No. 2, 488–508

0033-295X/07/$12.00 DOI: 10.1037/0033-295X.114.2.488

Interpolation Processes in Object Perception: Reply to Anderson (2007)

Philip J. Kellman
University of California, Los Angeles

Patrick Garrigan
University of Pennsylvania

Thomas F. Shipley
Temple University

Brian P. Keane
University of California, Los Angeles

P. J. Kellman, P. Garrigan, & T. F. Shipley (2005) presented a theory of 3-D interpolation in object perception. Along with results from many researchers, this work supports an emerging picture of how the visual system connects separate visible fragments to form objects. In his commentary, B. L. Anderson (2007) challenges parts of that view, especially the idea of a common underlying interpolation component in modal and amodal completion (the *identity hypothesis*). Here the authors analyze Anderson's evidence and argue that he neither provides any reason to abandon the identity hypothesis nor offers a viable alternative theory. The authors offer demonstrations and analyses indicating that interpolated contours can appear modally despite absence of the luminance relations, occlusion geometry, and surface attachment that Anderson claims to be necessary. The authors elaborate crossing interpolations as key cases in which modal and amodal appearance must be consequences of interpolation. Finally, the authors dispute Anderson's assertion that vision researchers are misguided in using objective performance methods, and they argue that his challenges to relatability fail because contour and surface processes, as well as local and global influences, have been distinguished experimentally.

Keywords: object perception, modal completion, amodal completion, interpolation, unit formation

Kellman, Garrigan, and Shipley (2005) proposed a theory of 3-D interpolation in object perception. Building on earlier work by many investigators and recent experimental results, this research supports an emerging picture of how the visual system uses separate visible fragments to form objects. Certain image features trigger early contour interactions, and these interactions, constrained by certain 3-D geometric relations, allow interpolation of contours across gaps. Surface qualities can also link visible regions in the absence of contour completion or within regions confined by it. Not all constraints on final scene representations are present when interpolations occur. Additional constraints operate to determine which early interpolated contours appear in final scene representations. These constraints ensure consistency of segmentation and border ownership, resolve certain issues of relative depth, and ultimately determine the modal or amodal appearance of interpolated contours and surfaces. This view fits with a great deal of data.

In his commentary, Anderson (2007) challenges parts of our theory. Although he does not dispute our formal account of contour interactions that comprise 3-D relatability or the data that support it, he does take issue with our unified treatment of interpolation in modal and amodal completion. In particular, he claims that experiments reported by Anderson, Singh, and Fleming (2002) and Singh (2004) offer evidence against the view that modal and amodal completion are subserved by common mechanisms. He also challenges our arguments that in at least some cases, interpolation logically precedes assignment of modal or amodal appearance. Finally, Anderson claims that because both surface and contour processes and global and local processes are indistinguishable, relatability is neither necessary nor sufficient for contour interpolation.

In this reply, we argue that the only evidence Anderson presents that uses objective performance methods (Anderson et al., 2002) involves a misunderstanding of the key experimental display. We present new demonstrations showing that—contrary to Anderson's claim—transparency or "camouflage" constraints do not govern modal completion. We contend that the claims used to attack logical arguments for the identity hypothesis are either unsubstantiated or lead to contradictions with what Anderson claims elsewhere. Moreover, we provide new demonstrations that counter Anderson's claims that amodal contours in Petter displays are stronger than modal ones and that quasimodal contours do not join. We argue that Anderson's conjectures vary by phenomenon, offering no viable alternative model of interpolation that can account for object formation phenomena in a unified manner.

Philip J. Kellman and Brian P. Keane, Department of Psychology, University of California, Los Angeles; Patrick Garrigan, Department of Physics and Astronomy, University of Pennsylvania; Thomas F. Shipley, Department of Psychology, Temple University.

This work was supported by National Eye Institute Grant R01-EY13518 to Philip J. Kellman and Thomas F. Shipley, National Science Foundation ROLE Grant 0231826 to Philip J. Kellman, and National Science Foundation IBN Grant 0344678 supporting Patrick Garrigan. We thank Marc Albert, James Hilger, Don Kalar, and Dario Ringach for helpful discussions.

Correspondence concerning this article should be addressed to Philip J. Kellman, Department of Psychology, University of California, Los Angeles, 405 Hilgard Avenue, Los Angeles, CA 90095-1563. E-mail: Kellman@cognet.ucla.edu

Finally, we argue that Anderson's challenges to relatability as a description of the geometry of contour interactions fail because they depend on conflating separable processes. Contour and surface processes, as well as local and global influences, can be distinguished experimentally. These distinctions are notably straightforward and viable, in contrast with the claim of separate modal and amodal interpolation processes.[1]

Object Formation: An Illustration

Figure 1—a new variant of what has been called a self-splitting object—provides a useful example of the operation of our model. Although the black area in the figure is homogeneous, visual processing splits it into three objects. How can we understand this phenomenon?

Our theory accounts for object formation in this display as follows. The segmentation process begins with the sharp corners (*tangent discontinuities*) in the display. These locations (some labeled in Figure 1B) where contours have no unique slope are image features that enable interpolation. Contours leading into tangent discontinuities are candidates for interpolation. Whether such contours are interpolated across gaps depends on geometric constraints, known as *contour relatability*. Contour relatability is a 3-D notion; it depends on the 3-D positions, orientations, and relations of input edges (Kellman, Garrigan, & Shipley, 2005). In the figure, there are three pairs of collinear contours. With stereoscopic depths, each contour has one 3-D-relatable partner; interpolating these produces closed contours defining three separate perceived objects. Tangent discontinuities and relatability explain the breakup of these homogeneous black displays into objects, as well as a large variety of other object-formation phenomena.

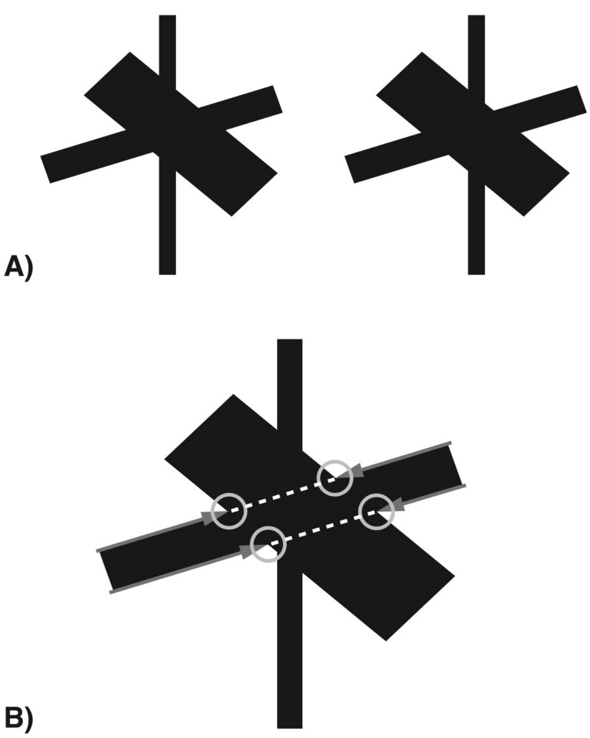


Figure 1. An illustration of object formation. (A) The display is a stereopair (free-fuse by crossing the eyes, or view in a stereoscope). Three distinct objects are seen completed across a central gap, in determinate depth order. The thin vertical rod has a modal (in front) appearance, whereas parts of the other interpolated objects are partly modal and amodal where they pass behind another object. (B) One eye's view of the display in Panel A, with tangent discontinuities (marked by circles) and relatable contours leading into them (marked by gray lines) shown for one object formed by interpolation.

When early contour interactions occur, the system has information about 3-D positions and orientations of input edges and often about depth ordering at junctions, but certain aspects of final scene appearance are not yet determined. These include the modal or amodal appearance of certain edges. One reason for adopting this view is evident in the display of Figure 1. The vertical rod has a *modal* appearance: Its contours and surfaces are seen in front of other objects. The other two objects, where they cross, appear *amodal*: They pass behind something. It is important to note that the thing that the two objects pass behind is not physically specified in the original stimulus. This covering object was formed by interpolation. The fact that in crossing interpolations, the modal or amodal appearance depends on the positions of other, crossing interpolations suggests a unified interpolation process, rather than separate processes of modal and amodal completion. At least in some cases, whether an interpolation appears modal or amodal depends on another interpolation going in front of or behind it. This is one reason why "modal" and "amodal" should be considered labels of final appearances of interpolated contours, rather than designators of separate interpolation processes.

The strongest reasons to believe an account along these lines are that (a) it predicts and explains a large range of data, and (b) some phenomena imply that interpolation can occur prior to the determination of modal or amodal status and resolution of certain other scene constraints. For example, interpolation itself sometimes influences border ownership: In a Kanizsa triangle, border ownership for some contours is reversed from what it would be if inducing elements were presented alone or in nonrelatable positions. This view—of early interpolation processes whose output is modulated by higher level scene constraints—is consistent with recent neuropsychological findings (Giersch, Humphreys, Boucart, & Kovacs, 2000; Humphreys, 2001). In what follows, we address issues related to Anderson's commentary and present arguments and novel demonstrations to further substantiate our theory.

The Identity Hypothesis: Empirical Evidence

Is there, as we have proposed, a common underlying contour interpolation process in amodal and modal completion? We have described the rationale and evidence that there is indeed a common process (Kellman, 2003b; Kellman, Garrigan, & Shipley, 2005; Kellman, Yin, & Shipley, 1998). Anderson, by contrast, claims

[1] Because of space limitations, we do not address every claim of Anderson's. (A rough count indicates that his commentary contains approximately 113 separate arguments.) However, the ones we address suffice, we believe, to show that Anderson has not provided any reasonable way around the arguments about identity, nor has he suggested anything resembling a comprehensive, workable theory that could engage a range of object formation phenomena.

that there must be two separate processes of modal and amodal completion, because certain constraints apply to modal, but not amodal, completion (Anderson et al., 2002) and because observers sometimes report slight shape differences between modally and amodally completed figures (Singh, 2004). In the following, we examine and respond to Anderson's arguments for rejecting the identity hypothesis.

The Experiments of Anderson et al. (2002)

A result considered important by Anderson, and the only one involving objective performance data, was reported by Anderson et al. (2002; see Anderson, 2007, Figure 1). Participants judged on each trial which of two intervals contained a slight misalignment of circular patches of adjacent black and white stripes. With reversed stereo depth information, these patches were shown behind apertures or floating in front of the background. Luminance relations were varied, so that when in front, the patches were either consistent with "camouflage" or not. Anderson et al. claimed that phenomenologically, there was clear modal completion in the camouflage case, but not otherwise. Discrimination of misalignment was better in the camouflage case. Anderson (2007) argues that these results demonstrate two distinct—modal and amodal—completion processes. He asserts that "modal completion involves the camouflage of nearer surfaces by more distant surfaces and, hence, depends critically on the luminance relationships in the image" (p. 472).

Below we argue that this claim is false. What of the paradigm and data claimed to support it? Parts of the logic make sense. In our view, if tangent discontinuities (junctions) and contour relatability are equally intact in modal and amodal versions of a display, there should be early contour linking in both. Whether this linking results in clear phenomenal contours is subject, however, to other scene constraints. When interpolation requirements are met but phenomenal contours are weak, one might still expect to find evidence of early contour linking on an objective task, if that task is sensitive to contour interpolation (Field, Hayes, & Hess, 1993; Guttman & Kellman, 2001; 2005).

Beyond the initial logic, however, lie fatal problems of design and data. To preview, the manipulation Anderson et al. (2002) used to create the displays, which they claimed had luminance relations that blocked modal completion, introduced a cue conflict in crucial contour junctions. The data show that this variable drove the experimental effects, effects misattributed to constraints on modal completion. Moreover, the paradigm was never validated as being sensitive to interpolation, a problem that included omission of the most important control group, specifically one that could have indicated when interpolation was eliminated, rather than merely weakened.

Although Anderson et al. (2002) introduced a new task for studying interpolation, they said "This task . . . has been the main kind of method used to assess the similarity of modal and amodal completion" (p. 175), and "interpolated contours account for . . . performance in contour alignment tasks just like those in our study" (Anderson, 2007, p. 472). These are puzzling statements, as their method did not match that of *any* previous interpolation study. They appear to equate all tasks involving positions or relations of contours. But tasks differ; theirs was novel, lacked validation, included display confounds, and omitted a needed control group. Their data provide little evidence that the task is sensitive to contour formation and considerable evidence against this idea. This contrasts with other tasks that Anderson rejects, such as the fat–thin task, a task subjected to multiple, successful validation efforts in several laboratories.

The display confound involved contour junction characteristics that covaried with differences in the luminance relations said to permit or block modal completion. To construct modal displays, Anderson et al. (2002) took amodal displays, in which stereodisparity and pictorial cues placed stripes behind circular windows, and swapped the left and right views. This reversed stereo depth, placing circular patches of stripes in front of a background. When the stripes in this display matched the surround, Anderson et al. claimed that modal completion occurred, but when black or white stripes were given with a gray surround, modal completion was prevented from occurring.

The difficulty is that the key manipulation changes more than the luminance relations claimed to be relevant for modal completion. When displays with stripes that do not match the surround are stereo reversed, they create a *conflict* at contour junctions. Binocular disparity indicates the stripes in front, but T-junctions indicate the circular boundary in front (as this remains unchanged from the amodal case). The junction conflict does not occur when one set of stripes matches the surround, because such displays have L-, rather than T-, junctions. The junction conflict has multiple consequences. One is that the cue conflict makes the display hard to look at and hard to fuse stereoscopically. This could easily account for the somewhat worse performance participants showed in judging alignment of display parts. Second, at least one appearance of the display, possibly the dominant one, is of the stripes curving backward in depth to go just under the aperture boundary. Because stereo information is strongly present along the vertical edges, this curving back occurs only at the top and bottom of the display, and the apparent curvature is extreme. This curvature may well make the edge pairs exceed the limits of relatability. Whether strictly nonrelatable or simply bent backward, this anomaly gives a different specification of 3-D position in that condition. Because the inputs into interpolation processes are changed, this anomaly flatly removes the predictions that Anderson et al. (2002) claimed to test.

Anderson et al. (2002) explicitly acknowledged the junction confound. They wrote:

> One possible explanation of the pattern of results . . . is the difference in junction structure of the two kinds of displays. When the surround luminance is light, it matches the luminance of the gratings' maxima. This causes the intersections of the grating with the background to form L-junctions. In contrast, when the surround luminance is gray, the intersections of the grating and the background form T-junctions. Thus it is possible that the different effects of the light and intermediate surround luminances may be due to the difference in junction structure present in these images rather than a difference in the completion processes *per se*. (pp. 177–178)

They attempted to address this problem in their Experiment 4, in which they used sinusoidal stripes rather than square-wave patterns in the discrimination task. They claimed that sinusoidal stripes equated the junction structure between their two conditions. This is incorrect on the stimuli (there was still luminance contrast that created T-junctions). It is also incorrect with regard to the literature on junctions, which suggests junctions can be processed at different spatial scales (e.g., Würtz & Lourens, 2000). Finally, it is incorrect on the phenomenology: T-junctions could still obviously be seen in their Figure 16c. The blurred stripe manipulation did not eliminate the confound, so we are left unable to attribute their results to interpolation effects.

Let us imagine, however, that this manipulation did, in fact, make the two conditions equivalent in terms of junction structure. If this were the case, we would expect the control condition (with luminances allowing both modal and amodal completion) to remain the same as in the first experiment. We would also expect the difference between the experimental condition ("bad" luminance relations for modal completion) to differ just as strongly from the control condition ("good" luminance relations). That is, the purpose of Anderson et al.'s (2002) Experiment 4 was to show that junction structure was *not* the cause of their effects. In fact, the data provided actually *supported* the confound interpretation. They predicted:

> If the difference in junction structure present in the square-wave displays was responsible for the observed effects of surround luminance, then this effect should be weakened or abolished by using sine-wave grating patterns that do not contain these large differences in junction structure. (p. 179)

But this is exactly what happened. The effect was weakened. The data show that the results of the experiment Anderson uses as a centerpiece of his attack on the identity hypothesis were due to a simple confound.

Anderson (2007) claims that the junction manipulation did not change the data. He writes:

> Of importance, the average difference in these two functions [modal vs. amodal cases] in the square-wave and sine-wave conditions were essentially identical (12% and 13%, respectively), implying that the difference in junction structure in these two experiments cannot account for the differences in performance in these displays. (pp. 472–473)

Unfortunately, the comparison of interest is not the one Anderson mentions. The crucial inference in the experiments requires in each a comparison of a group claimed to have a modal/amodal difference with a control group claimed *not* to have such a difference.

For some reason, the blurring of the stripes in the control condition led to a 7% accuracy advantage for the amodal case relative to the modal case. If performance on this task depended, as predicted, on interpolation effects, no such effect should have occurred. This result alone shows that junction characteristics affected performance in this task in a way that confounded the effort to assess interpolation effects. In Anderson et al.'s (2002) Experiment 2 (with junction confound present), there was a 12% difference between modal and amodal displays that had "bad" luminance relations and about a 0% modal/amodal difference between modal and amodal displays that had "good" luminance relations. Experiment 4 (in which Anderson et al. attempted to reduce the junction confound) produced a 13% difference between modal and amodal displays for the "bad" luminance relations, compared with a 7% difference between modal and amodal displays for the "good" luminance relations. That is, the original effect (12% vs. 0%) was approximately *halved* in magnitude (12% vs. 7%). Moreover, for the two lowest stimulus values (including the smallest, which showed the strongest effect in Experiment 2), the difference between the experimental and control groups completely vanished. No statistics were provided, but the crucial experimental versus control group difference in Experiment 4 was markedly and reliably smaller than in Experiment 2.

Anderson incorrectly appraises the data. The crucial effect—the difference between the experimental and control groups—was cut in half by a manipulation that aimed to reduce an acknowledged junction confound. Moreover, the junction manipulation produced a completely unexpected modal versus amodal difference in a control group. Surely these data confirm that junction issues drove the effects, in whole or in part.

There is an equally fundamental design problem. The argument of Anderson et al. (2002) requires knowing what task performance should look like when, uncontroversially, no interpolation occurs. This step was omitted. As a result, the superiority of one condition over another cannot indicate whether interpolation in the lower performing condition was merely weakened or, as Anderson et al. suggested, prevented. Assuming junction confounds could be removed, what would our theory predict if varying luminance relations weakened or removed the phenomenal appearance of interpolated contours? Consistent with other data in which evidence supports early interpolation but little phenomenal connection (e.g., Guttman & Kellman, 2001; 2005), we would expect worse performance than in good interpolation cases but better performance than in a zero interpolation control condition. To see this pattern, we would have to know what a zero interpolation case looked like in the data. Others have expended considerable effort to construct and validate control groups that eliminate interpolation (e.g., Kellman, Garrigan, Yin, Shipley, & Machado, 2005; Palmer, Kellman, & Shipley, 2006; Ringach & Shapley, 1996). Anderson et al. omitted this step and could therefore make no valid inferences that required knowing a zero point.[2]

[2] This issue of needing to know a baseline of what zero interpolation effects look like in the data is something about which Guttman and Kellman (2005) were careful, and their series of experiments contains persuasive data. Control stimuli that disrupted relatability included misalignment beyond 20° of visual angle, outward facing partial circles, and similarly oriented, grouped partial circles to control for general grouping effects on processing. Tangent discontinuities were removed by rounding in other control stimuli. Performance advantages for relatable outline displays, filled plus signs, and L-shaped inducers always exceeded the misalignment, grouping, and outward-facing control groups. In other words, cases in which no theory would predict contour interpolation produced effects consistently worse than cases in which early interpolation effects (plus weak perceived contours) would be predicted to occur on the basis of our model. Further, consistent with other research, the rounding of tangent discontinuities reduced performance advantages. These results support the hypothesis that early contour interpolation occurs on the basis of tangent discontinuities and relatable edges. In discussing these results, Anderson (2007) asserts, incorrectly, that distance between edges was not equated between our experimental and control groups. In at least two of our control groups, it was equated exactly. He says that misalignment as the standard for zero interpolation blocks observers from imposing a "mental template of a vertical contour" (p. 482). Leaving aside that a mental vertical contour template is a speculative, unelaborated, and unsupported idea, the claim is simply not true. Guttman and Kellman tested two control groups that preserved vertical contour alignment. Finally, Anderson says it could just be "grouping." This is a perennially vague notion, used in all kinds of ways, and worthy of a separate discussion. But we tested a grouping control, which equated vertical alignment and distance, in which all inducers faced the same way. The display made a fine perceptual group, but it did not help discrimination performance.

Elusive Constraints on Interpolation

The point of the displays and studies by Anderson et al. (2002) was to argue that modal, but not amodal, completion depends on certain rules about surface luminance relations and that, therefore, modal and amodal completion are subserved by separate mechanisms. Specifically, they argued that modal interpolation of contours cannot occur when the contours are induced by black or white inducers and must cross a gray gap.

To cross the gap, there must be a surface accompanying the contours, and that surface must be consistent with camouflage, as in the case in which gray stripes cross the gray gap. Anderson et al. (2002) could not be more explicit about this:

> However, there are differences in the ecological conditions that will support modal and amodal completion: Amodal completion arises when objects or surfaces are partially obscured by an occluding surface, whereas modal completion will only be initiated when a nearer surface is camouflaged by a more distant surface. (pp. 168–169)

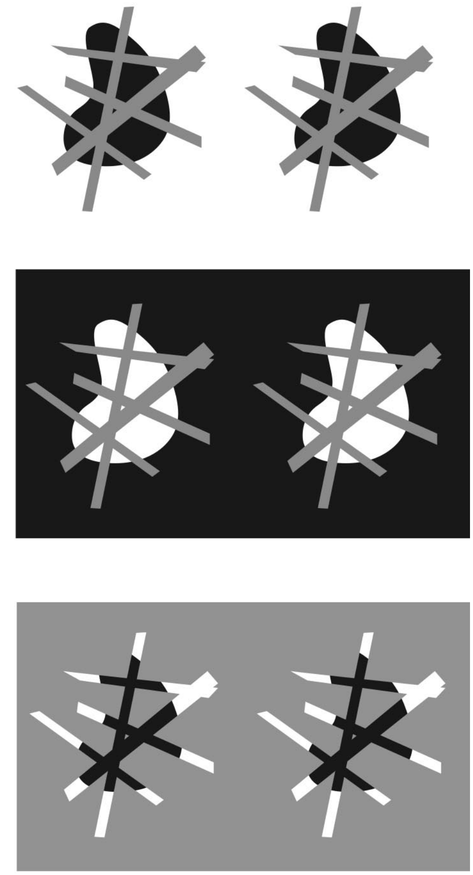
Regarding their black and white stripes, they say "When the background is an intermediate luminance, neither the contours nor the surface structure are seen to complete across the gap, in contrast to the claim of Kellman and colleagues that the contour completion process is 'color-blind'" (p. 169). Anderson's argument against our identity hypothesis rests on the idea that there is a general constraint about these luminance relations reflected in this display. We believe this general claim about constraints required for modal interpolation is false.

Figure 2 shows contours vividly completing across gaps, even though the inducing fragment surfaces are different from the background. Thus, if Anderson wishes to draw a distinction between modal and amodal completion, he cannot do so on the basis of his camouflage constraints.

Figure 3 takes these arguments further. Camouflage constraints are not the only stimulus variable that Anderson has argued can prevent completion from occurring. He has made the same claims about border ownership. Figure 3 shows a type of display that indicates that interpolation occurs despite purported constraints regarding border ownership and camouflage. Clear illusory contours and forms are seen, despite the fact that no surface of an object or surrounding aperture is consistent with the occlusion geometry in the scene. Shipley and Kellman (1994) reported this appearance in their studies of bidirectional transformations in spatiotemporal boundary formation. We call these *crystalline interpolations* because the appearance is like looking through a piece of glass with thin, visible edges, with the edges here created by interpolation. Crystalline interpolations are of considerable theoretical interest, because (a) they counter the notion that separate amodal and modal completion processes are implicated on the basis of luminance relationships; (b) they appear to be pure cases of contour interpolation, apart from an extended surface; and (c) they illustrate that agreement of border ownership of adjacent inducing forms is not required for interpolation.

It is worth noting that Anderson and Julesz (1995) discussed a case of such glasslike appearance, saying that because "there is no way for the intermediate luminance to perceptually 'split' into the appearance of two surfaces and generate illusory contours . . . observers find these stereograms very unstable" (p. 727). This observation and our examples of very stable crystalline interpolations contradict the key assertions in Anderson's current commentary and in Anderson et al. (2002), namely, that certain luminance relations are required for modal completion and that contour interpolation cannot occur without bringing with it an attached surface. If crystalline interpolations do attach to a surface, it is a completely transparent one; if so, interpolation need not be constrained by surface luminances seen through such a surface.

The fact that the luminance constraints described by Anderson do not prevent interpolation does not mean that they are unimportant. In our view, such scene constraints affect the presence and salience of phenomenal contours in final scene representations. In the striped display, besides the junction and luminance issues, there is likely a border ownership conflict when neither stripe matches the surround. Likewise, other displays that Anderson has claimed as counterexamples to the identity hypothesis involve border ownership issues that may be worked out after interpolation (Albert, 2007; Kellman et al., 2001). This effect is part of a



(A) (B) (C)

Figure 2. Luminance constraints do not block modal completion. All displays are stereopairs (free-fuse by crossing the eyes). Ten black (A) or white (B) patches are separated from each other in the image by gray regions. Displays with these luminance relations should prohibit modal completion, according to Anderson et al., 2002. Vivid, modally completed objects are seen. (C) An alternate assignment of luminances also involving completion across gray gaps induced by white and black patterns. In this display, completion in the upper leftmost part of the display is indefinite, as relatability is not satisfied in that region.

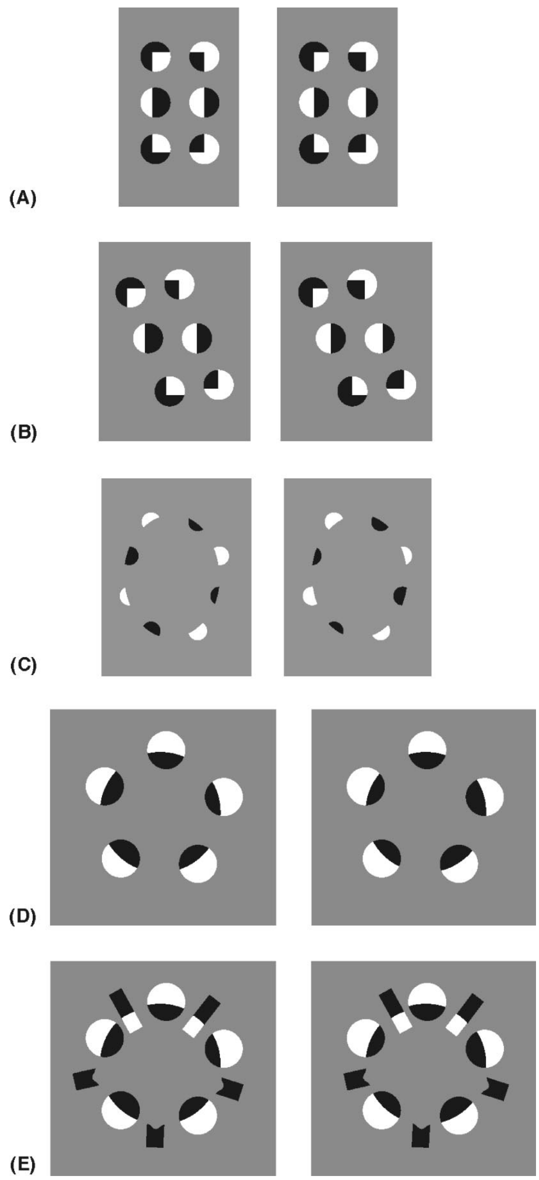


Figure 3. Examples of crystalline interpolation. All displays are stereopairs (free-fuse by crossing the eyes). (A) Contour interpolation in Kanizsa-style display occurs despite violation of luminance relations claimed to be required for modal completion. A glasslike object is seen. (B) A shifted version of Panel A shows that interpolation depends on relatability; disrupting relatability results in no connected object being seen. (C) Crystalline interpolation in which all adjacent inducers have opposite border ownership. Clear contour completion shows that inconsistency of border ownership does not block interpolation. (D) A vivid interpolated illusory circle is seen, despite having unusual surface properties (e.g., it is transparent but makes segments of circles seen through it look black). (E) Display in Panel D with added elements shown to illustrate the presence of interpolated contours. Elements at 4 and 6 o'clock show contour interaction via relatability as these elements "pull" the contour outward. The element at 8 to 9 o'clock does not undergo this interaction because of depth misalignment sufficient to disrupt 3-D relatability.

sorting-out process that seeks to impose consistency of objects and arrangements in scenes (Williams & Jacobs, 1997). This view and associated data, help to resolve a number of puzzles in the illusory contour literature, such as why illusory squares appear so weak between + signs made from solid surfaces (Guttman & Kellman, 2005; Kellman et al., 2001).

If correct, this idea would predict that interpolation effects can change outcomes involving border ownership from what they would be otherwise. Figure 4 provides a novel example, illustrating that interpolation can cause rearrangements of border ownership and depth relations in a scene. If border ownership in various parts of the display were fixed at the outset, we might expect that interpolation would be blocked. Instead, interpolation occurs and rearranges border ownership and depth relations for several contours in the display.

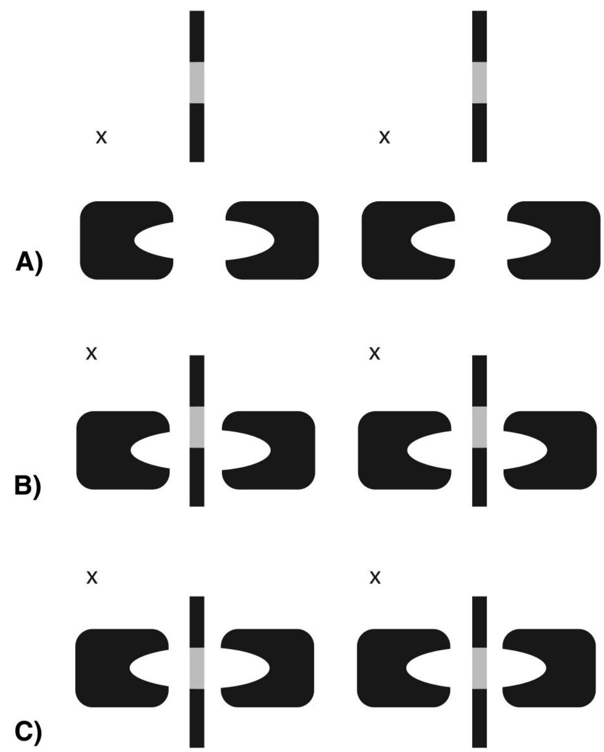


Figure 4. Contour interactions: A play in one act. All displays are stereopairs (free-fuse by crossing the eyes). (A) Scene 1: A pole having three sections is seen as an object in front of the white background. Below it are two windows through which is seen an amodally completed white ellipse. (B) Scene 2: The pole has moved in front of the area where the ellipse is seen. Horizontal contour segments on the pole are not relatable to those of the ellipse, so no change is seen in the appearance of the objects. (C) Scene 3: The same pole, with the same disparity and other characteristics is moved so its contours are relatable with those of the ellipse. Two profound changes in the scene occur. First, the border ownership of the pole switches, so it is now a rectangular aperture in the white surface. Second, the middle portion of the pole is now seen as part of the ellipse. Because all depth relations and border ownership were stable in Scene 1, Scene 3 shows that contour interactions via relatability can provoke changes in stable scene organization, leading to adjustments in contour appearance and border ownership. If constraints of border ownership and contour appearance are determined in advance of interpolation, such phenomena should not occur.

Claims About Shape Differences in Modal and Amodal Completion

Anderson argues that any form of the identity hypothesis must predict identical shapes for modally and amodally interpolated contours. He then argues that evidence suggests that they are sometimes not identical. In the following, we first focus on an experimental result reported by Singh (2004), which Anderson claims to be "compelling." We then comment on Anderson's serrated-edge display.

Singh (2004) reported that observers' shape judgments showed small but consistent differences for displays whose appearance was changed from modal to amodal using binocular disparity. He used an indirect "smoothing" measure to express these shape differences. From this nonstandard measure, it is hard to assess the magnitude of the effect in visual angle or other familiar terms. Our calculations suggest that the largest reported shape difference was about 8 min of visual angle for the vertical extent of a diamond-shaped figure 4.7° (282 min) wide. More intuitively, if the nail of your thumb has a width of 1.7 cm, the reported amodal–modal difference would correspond to a change in position of the outer contour of your finger nail of just under 0.5 mm. Although small, this is a carefully obtained and interesting effect.

Contrary to Anderson, we and Singh (2004) see no reason to abandon the identity hypothesis on the basis of these results. Singh interpreted his data this way:

> It does not logically follow, however, that modal and amodal completion cannot share a common mechanism. Indeed, a natural hypothesis suggested by the current results is that the two forms of completion share a common interpolation mechanism, but this mechanism involves a free parameter (responsible for generating the parametric variation in the smoothing level) that can take on different values for modal and amodal completion. (p. 458)

Singh's position resembles our own. Guttman and Kellman (2004) also reported minor shape differences obtained with their dot-localization paradigm. This paradigm allows objective measurement of precision of interpolated contours. Unlike Singh, their data showed small (about 3 arc min) differences in the direction of flatter interpolations for amodal completion relative to modal. They attributed the difference to other contours and surfaces in the scene that differed between modal and amodal displays, notably the presence of an occluding contour. Similar influences of context are found with real contours in illusions of visual space (e.g., the Poggendorf and twisted-cord illusions): The presence of nearby contours can cause slight alterations in perceived contour position and orientation.

Because Singh's (2004) data came from subjective reports, another important question is to what extent the observed differences were due to interpolation. Although a local interpolation process is common to illusory and occluded displays, we have argued that occlusion allows another influence: what we have called "recognition from partial information" (Kellman, Garrigan, & Shipley, 2005). Observers can notice and report that the visible regions in a display are consistent with some familiar or symmetric object. For example, seeing the tail of your cat protruding from under the bed allows recognition of the presence of the cat. The same tendency operates when observers in experiments report that straight edges that could meet behind an occluder (e.g., to form the vertex of a triangle) actually do meet (Kellman et al., 2000). This tendency can be distinguished from local contour interpolation.

Evidence from a dot-localization paradigm indicates that recognition from partial information does not produce the accurate and precise localization characteristic of local-edge interpolation (Kellman et al., 2000). The tendency to recognize an occluded "corner" by some participants, or on some trials, could account for the slightly more "cornerlike" appearance Singh (2004) reported for his amodal display; this is surely a concern, given his subjective method and the averaging of data across participants.

Another shape difference alleged by Anderson involves his "serrated edge" display. Albert (2007) has analyzed Anderson's display and arguments thoroughly, concluding that they do not indicate different processes of modal and amodal completion. We add only brief observations. First, virtually all interpolated contours in this demonstration are noticeable in both depth versions. Bringing different parts to the front and enforcing border ownership for parts by stereo disparity produces salience differences. In our view, border ownership can be given unambiguously for some inputs to interpolation (e.g., by disparity), but interpolation itself can change border ownership (as in the border ownership reversals caused by interpolation in ordinary Kanizsa triangles). These issues interact in Anderson's display with the ways certain black areas can connect via surface spreading under occlusion (Yin, Kellman, & Shipley, 1997; 2000), a factor not considered. In terms of data, the most consistent result involved Figure 2B in Anderson's current commentary. Anderson et al. (2002) reported that in the amodal version, all observers perceived all six visible black areas along the right side of the display as complete circles. In these displays, 75% to 90% of each circle was occluded, with only 10% to 25% physically specified. We invite the reader to examine Anderson's Figure 2B and see how compelling these "complete circles" appear. We are not told what instructions were given to participants, but such reports are unlikely to derive from edges interpolated by the participants' visual systems. Other research (e.g., Rauschenberger & Yantis, 2001; Shore & Enns, 1997) shows that amodal completion for circles decreases rapidly when gap size exceeds 25% of the circle (i.e., beyond the 90° limit suggested by relatability). Recent research suggests that this limit can be slightly exceeded, but not by much; Guttman, Sekuler, and Kellman (2003) found evidence of completion for 32.5% gaps, but only with longer temporal exposures. Anderson's claim of complete "circles" under 75% to 90% occlusion is inconsistent with all of these studies and is likely an example of recognition from partial information.

The preceding arguments have examined the best cases put forth by Anderson to claim two distinct interpolation processes. More detailed analysis reveals that they can be readily accommodated by our theory.

Logical Arguments From Empirical Phenomena

Since 1998, we have discussed logical arguments for a common interpolation step in modal and amodal completion. These arguments are important because, as we have pointed out (Kellman, Guttman, & Wickens, 2001), the identity hypothesis cannot be conclusively proven by finding similar data patterns in cases that have equivalent physically given edges but differing modal or amodal appearance. Likewise, if these phenomena depend on a common underlying interpolation step, there will still be differing relations of interpolated contours to other surfaces (namely, they will be in front or behind), and these factors produce perceptual differences (Kellman, 2003b). Such factors can be studied and understood, but it is an ongoing effort.

More illuminating are indications that some interpolations, when they occur, are neither modal nor amodal. Their appearance is determined subsequently. If interpolation can be shown to precede determination of modal or amodal appearance, the idea of distinct modal and amodal processes (as opposed to final appearances) cannot be sustained. Such phenomena are the basis of our logical arguments, which have empirical premises. They have the following form: "If certain phenomena occur and certain facts about perception are true, then it can be shown that interpolation must at least sometimes occur prior to the determination of modal or amodal appearance." These arguments were originally advanced by Kellman, Yin, and Shipley (1998), and a current, detailed treatment of our logical arguments for identity—extended to 3-D—may be found in Kellman, Garrigan, and Shipley (2005, pp. 596–600). Here we consider Anderson's comments on our logical arguments.

Physiology

As part of his attack on our logical arguments, Anderson alleges that we have used them to "discount physiological data . . . inconsistent with our views." We have noted that the logical arguments, if true, suggest skepticism about some results, but we have also been attentive to physiological issues. In recent years, findings have offered conflicting suggestions about the cortical loci of interpolation and related issues. Some of the most recent physiological results, with arguably improved methods, strongly support the identity hypothesis (e.g., M. M. Murray, Foxe, Javitt, & Foxe, 2004). In any case, using psychophysics and logic to reason about these results seems prudent. Kellman, Garrigan, and Shipley (2005), for example, considered the possible loci of 3-D interpolation, arguing from psychophysical data that, despite common claims, it is unlikely to be computed in the earliest visual cortical areas.

As we noted, our logical arguments have empirical premises. In his treatment, Anderson suggests a number of new explanations, saying that they must be shown to be "illogical." That is not quite correct. They may be illogical, or they may be ruled out by accepted facts, or both, as we consider below.

Self-Splitting Objects and Petter's Effect

Anderson concurs that for two crossing interpolations in a 2-D self-splitting object display, the interpolation spanning the shorter distance tends to appear in front (Petter's effect). He does not, however, appreciate the implications of this phenomenon, as he proceeds to claim that Petter's effect "explicitly expresses an asymmetry between modal completion and amodal completion" (Anderson, 2007, p. 476). In a nutshell, our point is that there is no modal or amodal contour completion in Petter's effect until a contour created by interpolation is placed in front of another contour created by interpolation. Which interpolation gets to be modal and which gets to be amodal depends on a comparison of the interpolated contours' lengths, which is why Petter's effect logically implies that interpolation must sometimes precede determination of modal or amodal appearance.

Anderson is correct that for a unified interpolation (identity) hypothesis, something more needs to be said about self-splitting objects and Petter's effect. But he is wrong in claiming it has never been said. What needs to be added is (a) the visual system seems to obey a constraint that two crossing objects formed by interpolation cannot simultaneously occupy the exact same space at the same time (Kellman & Loukides, 1987), and (b) in Petter's effect, this constraint is realized by having the *stronger* interpolation (usually the one crossing the shorter gap) appear in front (Albert, 1993; Kellman, 2003b; Singh, Hoffman, & Albert, 1999).

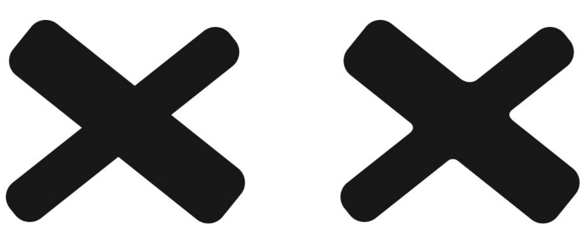
We have argued that if the modal or amodal appearance in Petter's effect is determined by which of the crossing interpolations is shorter, the visual system must register the sites and extents of interpolation prior to this determination. Anderson's reply is that the comparison of distances could occur before interpolated contours are formed. This is true, but that comparison already presumes that the visual system knows where interpolations are going to be. Those interpolations it "knows" about—prior to their comparison—are neither modal nor amodal, because that is what the comparison determines. Comparisons of distances of "possible" interpolations require starting points and endpoints; they are not computed willy-nilly between all points in the visual field. Moreover, in a given display, it is the two crossing interpolations that need to be compared. If modal and amodal appearances are determined according to such a comparison, however implicit, this supports the idea of a unified interpolation process.

This is the principal error Anderson makes when he asserts two distinct interpolation processes, one for modal and one for amodal completion. Take this example: "At each L-junction, two contour completion processes are initiated" (Anderson, 2007, p. 476). He does not appreciate that he has at this point already lost his argument. Remember the claim that there is an amodal process of interpolation and a modal process of interpolation? To have any meaning, an amodal completion process would be one sensitive to information that something is going behind other surfaces, and the reverse would be true for a modal process. Prior to interpolation, in a Petter display, there is no surface to be behind or in front of in the stimulus. Consider how Anderson et al. (2002) put it: "there is an inherent asymmetry in the depth information contained in relatively near and far image contrasts and . . . this causes an inherent asymmetry in the elements that participate in modal and amodal completion" (p. 166). There are no relative depth differences at the start in a self-splitting object display; all parts of the display are initially unoccluded. If a process goes to work in the absence of information that a boundary is going to appear in front of others, it cannot be a modal completion process. Likewise, if a process operates without information that a boundary will go behind another surface, it cannot be amodal completion at the outset. The idea of an initially neutral interpolation process whose products get to be modal or amodal depending on competition with each other or because of other scene constraints fits with our view and constitutes an abandonment of Anderson's view.

At the core of this phenomenon is a fascinating question: Why does a self-splitting display split into two (or more) objects in the first place? Our theory postulates contour interactions, enabled by tangent discontinuities, that can occur without surfaces initially being nearer, farther, or initially split. In our model, contour interpolation *is* what splits this kind of display, and it does so when there is nothing modal or amodal, because there is nothing in front or behind. We have shown that when the conditions required by our theory, specifically tangent discontinuities and/or relatability, are removed, these displays do not split (see Figure 5).

Splitting and Petter's effect are caused by an interpolation process that is triggered by tangent discontinuities and that connects relatable edges. In crossing interpolations, the shorter interpolated boundaries tend to appear modal. How can any of this be explained by a two-process theory, especially one which, for interpolation to ever occur, requires something nearer or farther initially? Interpolation processes go to work on stimuli that are not initially behind or in front of each other. Petter phenomena provide a compelling logical refutation of Anderson's view, because what Anderson et al. (2002) say is required—an "inherent asymmetry in the elements that participate in modal and amodal completion" (p. 166)—is simply missing at the start here.

Given the foregoing arguments, there is no need to delve deeply into the complex array of mechanisms and suppression processes suggested by Anderson to circumnavigate the simple logic of Petter's effect. Still, a few facts may be useful. Anderson says that two kinds of interpolation processes go to work on identical inputs, but then there are two types of suppression between mechanisms: suppression of modal and amodal processes within and between crossing edges. The problem, however, is still just as we posed it. A single edge in a Petter display of a certain length may appear modal or amodal; *it depends on the crossing interpolated edge*. In Anderson's account, both edges, after some distance, would generate stronger amodal than modal responses. What then determines their depth ordering? Notably, it is determined by relative "strength," which is a function of distance of interpolation. Put more simply, depth ordering is determined by a comparison of the interpolation lengths. In Anderson's account, amodal was initially the dominant effect for both contours, but in a final stage an additional suppressive mechanism engaged to make the shorter amodal boundary become a modal boundary. This model only posits a new, convoluted, and arbitrary process by which relative interpolation lengths can be estimated, and it gives the output a name, "strength." Its behavior is ultimately exactly in agreement with our view that interpolation sites and lengths must be known prior to determination of modal or amodal appearance. The shorter one ends up appearing modal, and the longer one appears amodal.



A) B)

Figure 5. Self-splitting object displays. Splitting in these displays, as well as modal and amodal appearance, depend on crossing interpolations and their interactions. The interpolations depend on tangent discontinuities and relatability. (A) Conditions for interpolation are satisfied. Relatable edges lead into tangent discontinuities for both objects. Interpolation processes produce a split into two objects, crossing interpolations, and Petter's effect (the object with shorter interpolated boundaries tends to appear modally completed). (B) Tangent discontinuities have been rounded slightly, reducing or blocking the split into two objects.

In his account, Anderson asserts that amodal completion has "greater extrapolation strength" (Anderson, 2007, p. 477) and cites Singh (2004) as having considered this possibility. We believe this interpretation is incorrect. Singh et al. (1999) examined this issue in detail. In their study, two variables known to affect the strength of interpolation were varied independently. One variable, which they called "distance ratio" (corresponding to the Petter rule), was found to have a greater effect on interpolation strength than did the other variable, "support ratio" (Banton & Levi, 1992; Shipley & Kellman, 1992b). It is important to note that Singh et al. (1999) found that increasing interpolation strength by manipulating either geometric property, distance ratio, or support ratio increased the proportion of trials on which subjects perceived the corresponding contours as modal. That is, increased interpolation strength correlated with modal completion, a relatively intuitive result. These data exactly contradict the mechanism by which Anderson's model attempts to account for Petter's effect. The results fit with our view that Petter displays involve crossing interpolations generated by a common interpolation process, in which the crossing interpolation of higher strength tends to appear in front.

Unlike Anderson's, our view applies naturally to more complex cases. Figure 6B presents the display of Figure 1, along with two related displays. These are not 2-D self-splitting object displays, as stereo depth has been added to the contours. However, they are relevant in terms of crossing interpolations. In Figure 6A, we see a modally completed object passing in front of an amodally completed object. In Figure 6B, a third object, the vertical rod, has been added in front. Because it is in front, it receives a modal appearance. As a consequence, the object that was modal now becomes amodal where it passes behind the rod. In this figure, the mutual suppression processes postulated by Anderson will not work, because two crossing interpolations can both appear amodal, as is the case for the two crossing objects behind the vertical rod. From our perspective, this outcome is straightforward. In 2-D self-splitting objects, where there is no relative depth information, strength of interpolation determines depth ordering. Where depth information is given (by disparity at contour ends in Figure 6B), modal is the appearance given to the object nearest to the observer. Where any interpolated contour passes behind another surface (including interpolated surfaces constructed by the visual system), the appearance, for that object, is amodal.

This display makes one other significant point; it concerns the object at the middle depth. As Figure 6C shows, none of the points where the perceived vertical rod crosses the middle object exists as a visible contour junction (in either eye's view). This has direct consequences for theories of interpolation. Interpolation of the middle object is triggered by tangent discontinuities further out; where this interpolation begins, it has, at both ends, a modal appearance. Yet this same interpolation—with no new inputs because of other tangent discontinuities—becomes amodal where it passes behind the vertical rod. The idea that a single interpolated edge can appear modal (in front of other things) along part of its length and amodal (behind other things) along other parts follows straightforwardly from our theory. We do not know any way to explain this phenomenon on the basis of the assumption of two distinct processes for modal and amodal completion. Modal and amodal appearances mark whether interpolated contours pass in front of or behind other opaque surfaces.

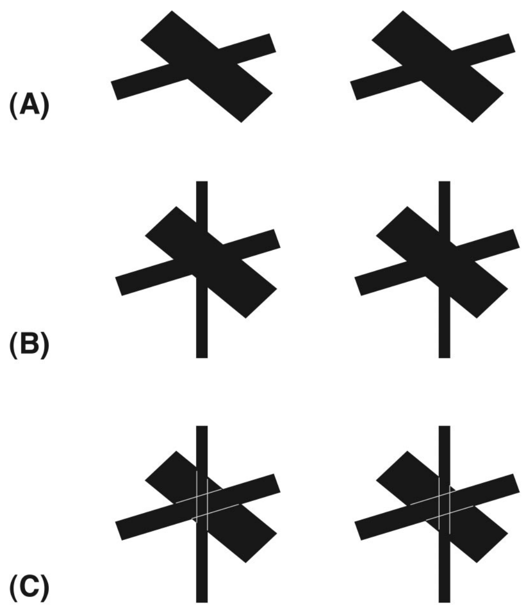


Figure 6. Understanding crossing interpolations and modal or amodal appearances. All displays are stereopairs (free-fuse by crossing the eyes). (A) The display resolves into two objects; because of stereoscopic depth information inherited from the physically specified contours, the thinner interpolated object passes in front of the thicker object. (B) The same display as in Panel A, with a vertical rod added. A modally completed vertical rod is seen, passing in front of two other objects. The thickest object is seen in back (amodally completed). The middle object is modally completed along part of its interpolated contours and amodally completed where it passes behind the vertical rod. (C) Lines added to the display in Panel B show that there are no visible junctions between the middle and front object; their interpolated contours have crossing points entirely within the black region, in both eyes' views. With regard to Panel C, the display in Panel B makes two important points about object-formation processes. First, the two-process account proposed by Anderson (2007) will not work, because that account relies on mutual suppression allowing only one object in a given direction to appear amodal (there are two here). Second, the middle object's interpolated contours leave both inducing points with modal appearance. If they are the product of a modal completion process, there should be no way for this interpolated boundary to be seen passing behind another object in the middle of its length (see text).

Quasimodal Contours

Quasimodal contours, which connect one inducer for an illusory contour with one for an occluded contour, also suggest a unified interpolation process. They were discovered on the basis of a prediction of the identity hypothesis, and Kellman et al. (1998) found that quasimodal interpolations exerted effects indistinguishable from illusory and occluded contours in an objective task.

Anderson claims that we "failed to consider data by Rubin (2001) who presented clear counterevidence to the claim that completion occurs in quasimodal displays" (Anderson, 2007a, p. 478). This is both misleading, because Rubin (2001) made no mention whatsoever of quasimodal displays, and confused, because Anderson's display (his Figure 7) is not quasimodal. (A quasimodal display has an amodal inducer at one end and an illusory contour inducer at the other. Anderson's display does not have the latter.) Rubin's article involved the disruptive effect of placing dots on tangent discontinuities. Her point that tangent discontinuities are important for triggering the interpolation process fits closely with our views (Shipley & Kellman, 1990), as Rubin noted. For the present discussion, a more relevant display from Rubin is shown in Figure 7A. When Rubin placed a dot in the path of an interpolated contour, but not on top of the contour junctions, all 20 participants reported that the contour appeared continuous. This result conflicts with Anderson's view, as the only stimulus-induced interpolated contour here is modal. As in our demonstration above, in a separate process view, how can a modally completed contour go behind another object?

Crossing Interpolations and Depth Spreading

Like our analysis of Petter's effect, our depth spreading example draws out the implications of crossing interpolations. Suppose a stimulus display presents no depth value at a point in a scene, but objects form by interpolation, and depth given at their edges spreads within those objects. If you now imagine that this happens for two interpolated objects that cross, you have our example (see

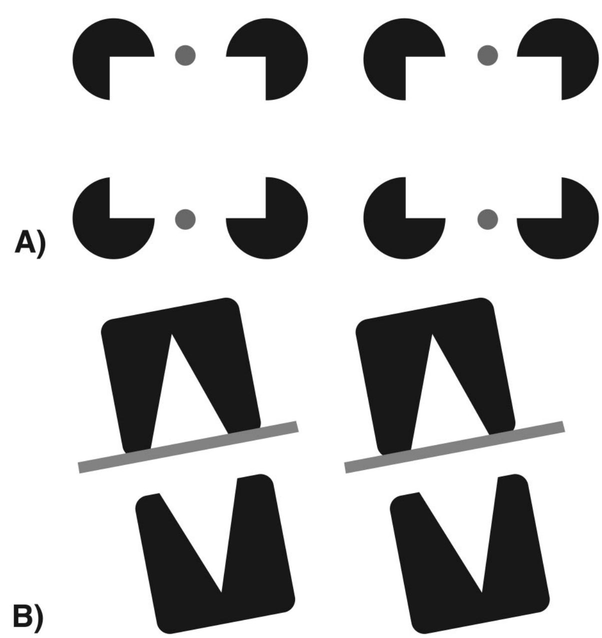


Figure 7. Displays showing interpolations can appear modal or amodal as they pass behind or in front of other surfaces. Both displays are stereopairs (free-fuse by crossing the eyes). (A) Display used by Rubin (2001). A modally completed contour with a dot placed in front is seen as continuous. This display excludes Anderson's (2007) "continuation" hypothesis, because a modal contour should not continue behind another surface (the dot). (B) Quasimodal display showing interpolation rather than continuation. The display is quasimodal in that it contains interpolation between an occluded figure at one end and a modal inducing element at the other. If modal and amodal contours continue (extrapolated) from a single inducer but do not *join*, the unified object with curved sides should not be seen here. Inducing edges contain straight edges only, but curved completions are observed. The display shows that quasimodal contours involve interpolation effects, as their spatial position is dependent on both inducers (one amodal, one modal) and deviates from paths that would be given by extrapolation alone.

discussion of Figure 14 in Kellman, Garrigan, & Shipley, 2005). In the figure, the central white rectangle is seen to slant in depth; its contours appear modal along part of its length and amodal along others, depending on its passage in front of other interpolated contours and surfaces. How are these appearances determined? In our view of a unified interpolation process, the answer is simple. The visual system assigns modal appearance to the surface with the nearest depth values at each point. As the figure shows, this assignment may vary from point to point for a single object or surface (see also Figure 15 in Kellman, Garrigan, & Shipley, 2005). When interpolation for one object occurs, it is neither modal nor amodal, nor can it be, because its status in that respect depends on a crossing interpolation. Modal or amodal appearances of interpolated areas in such a display depend on comparisons of the depth values for object parts that do not exist prior to interpolation.

Anderson's two-interpolation-process view of this phenomenon is unconvincing. He presents an irrelevant discussion of different cases of depth spreading. Depth spreading in our displays is not complicated, and we are not the originators of the idea that depth spreading is confined within objects or connected surfaces (e.g., Hakkinen, Liinasuo, Kojo, & Nyman, 1998). If relative depth is available at the start of 3-D interpolation, Anderson asks, why is there not information sufficient to determine depth relations in the final scene? Here is why. Prior to interpolation, all parts of this display are specified by depth information to lie in a single 2-D plane except the far left and far right vertical edges. There is no information about objects passing in front of each other. Specifically, the middle of the display contains two black rectangles indicated by stereodisparity to be frontoparallel. In this situation, nothing can be decided about how a contour passing along the bottom of the upper black rectangle or along the top of the lower rectangle will extend behind or in front of the vertical white strips adjacent to these middle rectangles. Interpolation captures these edges. It is only after interpolation and depth spreading that these relative depths can be decided (c.f. Albert, 1993). This is a point that Anderson confuses regarding the example and our theory. There is no contradiction in claiming that the interpolation process takes 3-D inputs and is sensitive to 3-D relations and also claiming that the relative depths of some contours and regions get worked out after interpolation, especially where depth order issues are consequences of interpolation, as in this example. To suggest that these relations exist prior to interpolation is to suggest a process that is entirely redundant with interpolation. Such a process does not exist, we believe, and would have no value.

Anderson argues that contour interpolation is not presupposed by depth spreading. If it is not, how does depth spreading stay out of the surround? Why does it not travel to the vertical edges of the middle black rectangles? Given that depth spreading does stay out of the surround, it is necessary that something constrains it. There are no ideas on the table other than contour interpolation for how depth spreading gets constrained here. Anderson can say that the constraint of interpolated contours on depth spreading happens simultaneously with the interpolation itself, but this is the problem: That middle area has no depth or slant until depth is inherited from the rectangle's endpoints. And it cannot inherit until it is linked to those endpoints. The linking cannot be done by depth spreading alone, as that would not give the observed selectivity in where depth spreads. The linking is done by contour interpolation of relatable edges. Appropriate depth spreading presupposes this linking; we are unaware of any other workable account.

As we have pointed out previously, the amodal or modal status of the vertical bars in this display are also determined by the position of the rectangle slanted in depth. Their modal or amodal appearance is a consequence of the depth that spreads within interpolated contours of the rectangle. One of the two bars ends up appearing modal and the other amodal. This is determined by the position of the interpolated rectangle as it slants in depth. Incidentally, because the two vertical bars are otherwise identical, Anderson's complex account of Petter's effect cannot work here.

The depth spreading displays provide strong support for the identity hypothesis. In such cases, modal versus amodal appearances depend on depth positions of crossing interpolations; those depth positions are derived from depth spreading, and depth spreading in these displays depends on interpolation. Modal versus amodal appearance is therefore a consequence of, not an input to, interpolation.

Methodological Issues

Anderson criticizes the community of vision researchers who study perceptual organization for increasingly relying on objective performance methods, that is, methods in which perceptual organization is inferred from performance on tasks that have objectively correct answers. This trend is not unique to work on object formation, so it is unclear why this issue is directly relevant to the present discussion, except that a considerable body of evidence from objective methods supports our theory (e.g., Field et al., 1993; Kellman, Garrigan, Yin, et al., 2005; Kellman et al., 1998; Yin et al., 2000).

Before turning to this interesting topic, however, we correct a series of misstatements. We did not say objective methods were of greater value; we said both objective performance and perceptual report methods are important. We have not questioned the concept of volume completion in Tse's (1999a; 1999b) work merely because of the lack of any objective data (see Kellman, Garrigan, & Shipley, 2005). Nor has Ringach and Shapley's (1996) "fat–thin" method been the main objective technique we have used. We have used a variety of methods. In particular, in neither the article on which Anderson is commenting nor in our related experimental work on 3-D interpolation did we use the fat–thin method.

Perceptual experience is a focus of research in perceptual organization, but Anderson is incorrect in saying "we must turn to phenomenology" (Anderson, 2007, p. 481) for the final answer to questions in perceptual organization. We should also be interested in perceptual computations and representations. Some of these may be available to conscious awareness, but some are not. The view in which we represent aspects of the scene nonphenomenally is not new. Breitmeyer, Ro, and Singhal (2004), for example, showed that a briefly flashed, colored disk can prime or inhibit the color identification of a later-appearing target, even when participants were unable to say what color the priming or inhibiting stimulus was. Blindsight phenomena (Weiskrantz, 1986), wherein participants report facts of which they are not consciously aware, are another example in which the absence of phenomenology does not entail the absence of representation. Anderson's ideas put nonphenomenal representations out of reach. Moreover, he conflates verbal report with perceptual experience. Perhaps he does not believe, as we do, that biases, demand characteristics, and cognitive influences are important concerns when one asks people what they see. For this reason and others, we believe that research in perceptual organization should take advantage of both objective and subjective methods.

Because it is not used in our 3-D interpolation research, we guess that Anderson brings up the fat–thin method developed by Ringach and Shapley (1996) because we have used it in studies of our "promiscuous interpolation" hypothesis (Guttman & Kellman, 2005; Kellman et al., 2001). Careful work in multiple laboratories suggests that this method is sensitive to interpolation effects. Ringach and Shapley (1996) validated the method using two to three control groups, and Kellman et al. (1998) used two others. The fat–thin paradigm, we believe, is one of the best-validated methods in our field. In an influential set of studies, Gold, Murray, Bennett, and Sekuler (2000) used a reverse correlation technique (classification imaging) to show that when participants repeatedly discriminated noise-corrupted fat–thin squares, participants were responsive to noise pixels along interpolated boundaries, both when the squares were illusory as well as when they were occluded. Anderson apparently does not find this sort of evidence convincing; he doubts that the classification image paradigm can say anything about interpolation, let alone the identity hypothesis.

Our results using the fat–thin task and other methods are consistent with the promiscuous interpolation hypothesis (Kellman et al., 2001), which posits that contour linking processes operate relatively early in processing, subject to later constraints that can weaken or remove connections in final scene representations (and perceptual experience). Guttman and Kellman (2001; 2005) carried out a series of tests using contours with relatable edges and tangent discontinuities that did not yield strong perceived contours. Their displays included outlines, L-shaped inducing elements, and elements shaped like plus signs. They found evidence of contour interpolation effects—advantages in sensitivity with a signal detection measure—in these displays when perceived contours were weak or absent. These effects tended to be weaker than interpolation effects reported for phenomenally clear interpolated contours. Our interpretation (Guttman & Kellman, 2001; 2005) was that that all of these stimuli with relatable contours induce early contour linking, but because of later constraints, such as border ownership, these interpolated contours are weakened or absent in final percepts. Anderson is incorrect in claiming that our recent data contradict earlier data about illusory contour displays with outlined inducers (Kellman et al., 1998). Both the earlier response-time data and more recent sensitivity data suggest that outlines show nonzero interpolation effects but weaker effects than do ordinary surface edges.

Anderson dislikes our interpretation of these data and (incorrectly) believes that our theory was made up to explain them. A competing scientific explanation, however, would be one that predicts the results. He mentions that R. F. Murray's (2002) unpublished dissertation contains classification image data from the fat–thin paradigm with L-shaped inducers. The data show effects similar to those previously claimed to reveal interpolation processes (Gold et al., 2000). Our model would predict this result, because the L figures involve relatable edges.

Anderson chooses a different interpretation, claiming that if they produce any data at variance with phenomenology, neither the classification image paradigm nor the fat–thin task are sensitive to interpolation. He dismisses a coherent set of results from these paradigms as being due to unspecified "grouping" or "strategy" effects. We ask how a grouping or strategy idea predicts that observers would use particular pixels in gaps between inducers in their discrimination choices. Such results, as well as those reported by Guttman and Kellman (2001; 2005), are highly consistent across observers. These outcomes require an explanation more specific than vague invocations of "grouping" and "task strategies." Recent data further confirm that the fat–thin and classification paradigms reveal interpolation effects and suggest that the methods can be used together to study the time course of visual interpolation (Gold & Shubel, 2006).

Finally, Anderson claims that our theory and results involving the promiscuous interpolation hypothesis indicate that we have discarded the role of tangent discontinuities in our model. This is in response to an article (Kellman, Garrigan, & Shipley, 2005) that contains an entire section on tangent discontinuities and elsewhere defines the promiscuous interpolation process by saying "On this hypothesis, contour interpolation happens among all relatable edges that lead into tangent discontinuities" (p. 15). We assume this speaks for itself (see also Kellman, Garrigan, Yin, et al., 2005, Experiment 4).

Relatability and Separating Processes in Object Formation

Relatability provides an account of the geometric relations of contours that support contour interpolation. Anderson's counterevidence to relatability ultimately rests on claims that local contour relations cannot be separated from global influences and that contour processes cannot be distinguished from surface processes. Assuming that global, local, contour, and surface issues cannot be disentangled in any way, Anderson suggests that relatability criteria are neither necessary nor sufficient for predicting completion.

Although object perception involves all of these factors, and they may have some important interactions, we believe Anderson's argument is unsustainable. There are clear ways to separate these determinants and study them. Take the global–local dichotomy. If a global influence can be specified, then it can be removed from displays to study local geometric contour relations. This is the purpose of experiments with unfamiliar, nonsymmetric displays (e.g., Field et al., 1993; Shipley & Kellman, 1992a; Palmer et al., 2006). Prior to the early 1990s, most studies of amodal completion and illusory contours involved triangles, squares, and circles. In our research, we have often used unfamiliar, asymmetric displays, sometimes randomly sampled under constraints (e.g., Shipley & Kellman, 1992a). In addition, we have almost always used visible areas separated by gaps, rather than partial covering of a single object. Such displays better address object-formation issues and provide more realistic tests for global accounts. A good scientific strategy, however, extends beyond display selection. Along with others, we have used experimental methods to define the properties of contour and surface processes, as well as global and local determinants. Each of these dichotomies can be distinguished by a strategy analogous to what neuropsychologists call "double dissociation."

Separating Local and Global Influences on Completion

In his claims about both identity and relatability, Anderson's arguments depend crucially on there being no way to separate global and local effects. But we are not alone in distinguishing these (e.g., van Lier, van der Helm, & Leeuwenberg, 1994). When interpolated contours are predicted by contour relatability, they are located with striking precision and accuracy (Guttman & Kellman, 2004; Kellman et al., 2000). In contrast, when completion is predicted by global factors, such as symmetry, our dot-localization data show worse precision and poorer accuracy by nearly an order of magnitude (Kellman, 2003a; Kellman et al., 2000). These data suggest that local and global completion influences have different properties with regard to providing precise local boundary information. In response, Anderson says that "data of this kind do not seem useful for distinguishing one theory of interpolation from any other" (Anderson, 2007, p. 475). The reason, he says, is that any theory would predict better precision and accuracy for less complex interpolations, interpolations that have a uniform sign of curvature, and so on. This reasoning inadvertently concedes the argument. Imagine that there is no local relatability but only global symmetry at work in object perception. Why would simple local contour interactions be more precise? Why would monotonic curvature be simpler? Anderson takes the predictions of our theory and writes them off as common knowledge. These phenomena may be common in perceptual experience, but they nevertheless require explanation. Conversely, a symmetry-based model that imposes precise symmetry on hidden parts in an occlusion display would be an imaginable theory: It would predict symmetry-based interpolations of high precision. Common sense does not exclude such a view; only the data do.

On the particulars, Anderson is wrong in stating that "the type of symmetric stimuli that they tested clearly involves more complicated geometric structures than the smooth, monotonic interpolations that would arise from relatable contour interpolations" (Anderson, 2007, p. 475). In fact, great care has been taken to address this issue. Kellman (2003a) reported data in which the distance and relative positions of interpolations were equated for a global and local completion. Precision and accuracy were superior (2–3 times better) for the completion predicted by relatability than for the matched global display. Kellman et al. (2000; discussed in Kellman et al., 2001) showed the same result for completion of an acute angle of a triangle. This case is arguably among the simplest cases of interpolation, requiring only linear extrapolation of two lines to the corner of the triangle. As predicted by its nonrelatability—and by the lack of illusory contour perception in a modal version of the display—dot localization in the amodal display showed consistently inaccurate placement of the triangle vertex and imprecision nearly an order of magnitude greater than that found in relatable displays. The data show that global influences can be experimentally distinguished from local relatability by the precision of local-edge representations that result.

Recent results (de Wit & van Lier, 2002) support the idea that interpolation by local-edge relatability differs from global completion. These investigators found that multiple global completions can be primed after exposure. This finding is highly consistent with the proposal of Kellman et al. (2001) that global influences represent recognition (memory access) from partial information, a process known to be sensitive to priming.

Anderson asserts that global and local influences can never be distinguished "without bringing additional assumptions to bear on how these putatively separate processes each contribute" (Anderson, 2007, p. 475). Here we have common ground. The problem is that Anderson believes that this goal cannot be achieved. He invokes poorly specified or untestable influences. Our view is that global influences can be experimentally manipulated and tested, *if* they can be specified. One who asserts, for example, that symmetry affects contour interpolation should be willing to say something about what comprises symmetry and whether it is present in a given display. Our experimental work on local and global effects does not, as Anderson claims, invoke a second, mysterious process whenever we wish. We have tested specifically stated descriptions of global influences. These include symmetry (e.g., Sekuler, Palmer, & Flynn, 1994) and, as applies directly to Singh's (2004) displays, perception of corners from continuing straight edges (e.g., Boselie & Wouterlood, 1992).

Separating Contour and Surface Processes

For some time, Anderson has argued that contour relatability is neither necessary nor sufficient for interpolation by invoking examples that confound contour and surface interpolation processes. We distinguish these on the basis of a number of findings that indicate that contour and surface processes depend on different variables. For example, surface interpolation depends on commonalities in lightness, color, or texture; its properties can be studied in the absence of contour interpolation by removing edge relatability (Yin et al., 1997, 2000). Likewise, contour interpolation can be studied by manipulating local contour relations with surface fragments that differ in surface properties (Kellman & Shipley, 1991). Some of these dissociations are illustrated in Figure 8. The top row shows that surface interpolation can be altered in the absence of any change in contour relationships. The bottom row shows that object formation from contour interpolation survives major changes in surface color of the visible regions, but it does not survive disruption of contour relatability. Anderson's criticisms of relatability are based on his claims of the inseparability of contour and surface processes and local and global ones. These have been doubly dissociated, and the theoretical value of distinguishing two object formation processes with different inputs, computations, and consequences is apparent.

There is a laundry list of other comments in Anderson's article (thin lines; He and Ooi displays; lack of phenomenal contours in Field et al., 1993, displays) that space does not permit our taking up here. We are flattered to be accused of having not yet solved all the problems in the field. In closing, we comment on the relation of several issues we have discussed. Regarding the identity hypothesis, we have maintained for some time that the logical arguments are of first importance. If these are sustainable, as we believe they are, they reflect on most of the other issues regarding that hypothesis. For example, the confounds and issues of interpretation in the experiments of Anderson et al. (2002) cohere with the logical arguments in suggesting that their data do not provide evidence of separate modal and amodal processes. Nevertheless, the study of scene constraints that work with early interpolations to determine final scene appearances is an important and unfinished task. We share with Anderson the belief that the field could profit from more methodological discussions, such as the relation between objective and subjective data. Finally, with regard to relatability and its adequacy in describing the geometry of contour interpolation, we see no reason to abandon a concept that has proven to be among the most useful and unifying in the field. The value of relatability in understanding object formation has been shown in two dimensions (Fulvio, Singh, & Maloney, 2006; Kellman & Shipley, 1991), three dimensions (Kellman, Garrigan, & Shipley, 2005), and spatiotemporally, where motion furnishes frag-

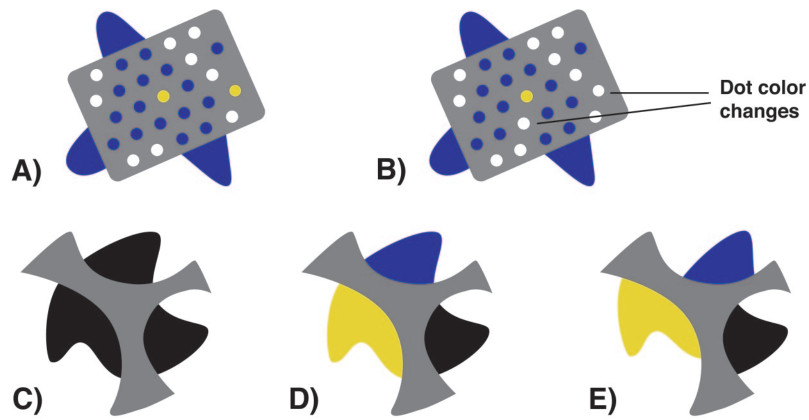


Figure 8. Double dissociation of contour and surface processes. (A) Display illustrates surface interpolation. Blue dots within relatable edges (or linear extensions of nonrelatable edges) become holes, joining other blue regions. Upper right blue dot is not seen as connected and appears as a spot on top of the gray surface. White dots appear as holes, because of surface interpolation with background. Yellow dots appear as spots. (B) Color changes in two dots indicated cause changes in surface interpolation. These interpolation changes occur despite no change in visible contours. (C) Display illustrates contour and surface interpolation. The three black regions appear as a unified object behind the gray occluder. (D) Contour interpolation, because of contour relatability, preserves the unity of the object despite the surface color changes. (E) Disrupting contour relatability results in perception of three separate objects behind the occluder.

ments (and gaps) across space and time (Palmer et al., 2006). Yet the importance of contour interpolation on the basis of relatability in object formation does not imply the absence of other determinants. We have found it useful to distinguish processes in object formation that have different properties. There is support for distinctions between global and local processes and between contour and surface processes. We have not encountered any arguments that suggest that our field should abandon these or fail to investigate them further.

Our understanding of object perception is advancing despite its humbling complexity, and many issues remain to be resolved. We hope this reply clarifies some matters and opens new pathways for exploring others.

References

Albert, M. K. (1993). Segmentation, grouping and nonlocal cooperativity in stereopsis. *Investigative Ophthalmology & Visual Science, 34,* 1438.

Albert, M. K. (2007). Mechanisms of modal and amodal interpolation. *Psychological Review, 114,* 455–469.

Anderson, B. L. (2007). The demise of the identity hypothesis and the insufficiency and nonnecessity of contour relatability in predicting object interpolation: Comment on Kellman, Garrigan, and Shipley (2005). *Psychological Review, 114,* 470–487.

Anderson, B. L., & Julesz, B. (1995). A theoretical analysis of illusory contour formation in stereopsis. *Psychological Review, 102,* 705–743.

Anderson, B. L., Singh, M., & Fleming, R. W. (2002). The interpolation of object and surface structure. *Cognitive Psychology, 44,* 148–190.

Banton, T., & Levi, D. M. (1992). The perceived strength of illusory contours. *Perception & Psychophysics, 52,* 676–684.

Boselie, F., & Wouterlood, D. (1992). A critical discussion of Kellman and Shipley's (1991) theory of occlusion phenomena. *Psychological Research, 54,* 278–285.

Breitmeyer, B., Ro, T., & Singhal, N. (2004). Unconscious color priming occurs at stimulus-dependent not percept-dependent levels of visual processing. *Psychological Science, 15,* 198–202.

de Wit, T. C. J., & van Lier, R. J. (2002). Global visual completion of quasi-regular shapes. *Perception, 31,* 969–984.

Field, D. J., Hayes, A., & Hess, R. F. (1993). Contour integration by the human visual system: Evidence for a local "association field." *Vision Research, 33,* 719–741.

Fulvio, J. M., Singh, M., & Maloney, L. T. (2006). Consistency of location and gradient judgments of visually-interpolated contours. *Proceedings of the 2006 Conference on Computer Vision and Pattern Recognition Workshop.*

Giersch, A., Humphreys, G. W., Boucart, M., & Kovacs, I. (2000). *Cognitive Neuropsychology, 17,* 731–759.

Gold, J. M., Murray, R. F., Bennett, P., & Sekuler, A. (2000). Deriving behavioral receptive fields for visually completed contours. *Current Biology, 10,* 663–666.

Gold, J. M., & Shubel, E. (2006). The spatiotemporal properties of visual completion measured by response classification. *Journal of Vision, 6,* 356–365.

Guttman, S. E., & Kellman, P. J. (2001). Contour interpolation: Necessary but not sufficient for the perception of interpolated contours [Abstract]. *Journal of Vision, 1,* 384a. Retrieved from http://journalofvision.org/1/3/384/

Guttman, S. E., & Kellman, P. J. (2004). Contour interpolation revealed by a dot localization paradigm. *Vision Research, 44,* 1799–1815.

Guttman, S. E., & Kellman, P. J. (2005). *Promiscuous interpolation: Contour completion without perception of completed contours*. Manuscript submitted for publication.

Guttman, S. E., Sekuler, A. B., & Kellman, P. J. (2003). Temporal variations in visual completion: A reflection of spatial limits? *Journal of Experimental Psychology: Human Perception and Performance, 29,* 1211–1227.

Hakkinen, J., Liinasuo, M., Kojo, I., Nyman, G. (1998). Three-dimensionally slanted illusory contours capture stereopsis. *Vision Research, 38,* 3109–3115.

Humphreys, G. W. (2001). A multi-stage account of binding in vision: Neuropsychological evidence. *Visual Cognition, 8,* 381–410.

Kellman, P. J. (2003a). Interpolation processes in the visual perception of objects. *Neural Networks, 16,* 915–923.

Kellman, P. J. (2003b). Segmentation and grouping in object perception: A 4-dimensional approach. In R. Kimchi, M. Behrmann, & C. R. Olson

(Eds.), *Perceptual organization in vision: Behavioral and neural perspectives* (pp. 155–201). Mahwah, NJ: Erlbaum.

Kellman, P. J., Garrigan, P., & Shipley, T. F. (2005). Object interpolation in three dimensions. *Psychological Review, 112,* 586–609.

Kellman, P. J., Garrigan, P., Yin, C., Shipley, T. F., & Machado, L. (2005). 3-D interpolation in object perception: Evidence from an objective performance paradigm. *Journal of Experimental Psychology: Human Perception and Performance, 31,* 558–583.

Kellman, P. J., Guttman, S., & Wickens, T. (2001). Geometric and neural models of contour and surface interpolation in visual object perception. In T. F. Shipley & P. J. Kellman (Eds.), *From fragments to objects: Segmentation and grouping in vision* (pp. 193–245). London: Elsevier.

Kellman, P. J., & Loukides, M. G. (1987). An object perception approach to static and kinetic subjective contours. In G. Meyer & G. Petry (Eds.), *The perception of illusory contours* (pp. 151–164). New York: Springer-Verlag.

Kellman, P. J., & Shipley, T. F. (1991). A theory of visual interpolation in object perception. *Cognitive Psychology, 23,* 141–221.

Kellman, P. J., Temesvary, A., Palmer, E. M., & Shipley, T. F. (2000). Separating local and global processes in object perception: Evidence from an edge localization paradigm. *Investigative Ophthalmology and Visual Science, 41,* 741.

Kellman, P. J., Yin, C., & Shipley, T. F. (1998). A common mechanism for illusory and occluded object completion. *Journal of Experimental Psychology: Human Perception and Performance, 24,* 859–869.

Murray, M. M., Foxe, D. M., Javitt, D. C., & Foxe, J. J. (2004, August 4). Setting boundaries: Brain dynamics of modal and amodal illusory shape completion in humans. *Journal of Neuroscience, 24,* 6898–6903.

Murray, R. F. (2002). *Perceptual organization and the efficiency of shape discrimination*. Unpublished doctoral dissertation, University of Toronto, Canada.

Palmer, E. M., Kellman, P. J., & Shipley, T. F. (2006). A theory of contour interpolation in the perception of dynamically occluded objects. *Journal of Experimental Psychology: General, 135,* 513–541.

Rauschenberger, R., & Yantis, S. (2001). Masking unveils pre-amodal completion representation in visual search. *Nature, 410,* 369–372.

Ringach, D. L., & Shapley, R. (1996). Spatial and temporal properties of illusory contours and amodal boundary completion. *Vision Research, 36,* 3037–3050.

Rubin, N. (2001). The role of junctions in surface completion and contour matching. *Perception, 30,* 339–366.

Sekuler, A. B., Palmer, S. E., & Flynn, C. (1994). Local and global processes in visual completion. *Psychological Science, 5,* 260–267.

Shipley, T. F., & Kellman, P. J. (1990). The role of discontinuities in the perception of subjective figures. *Perception & Psychophysics, 48,* 259–270.

Shipley, T. F., & Kellman, P. J. (1992a). Perception of partly occluded objects and illusory figures: Evidence for an identity hypothesis. *Journal of Experimental Psychology: Human Perception and Performance, 18,* 106–120.

Shipley, T. F., & Kellman, P. J. (1992b). Strength of visual interpolation depends on the ratio of physically specified to total edge length. *Perception & Psychophysics, 52,* 97–106.

Shipley, T. F., & Kellman, P. J. (1994). Spatiotemporal boundary formation. *Journal of Experimental Psychology: General, 123,* 3–20.

Shore, D. I., & Enns, J. T. (1997). Shape completion time depends on the size of the occluded region. *Journal of Experimental Psychology: Human Perception and Performance, 23,* 980–988.

Singh, M. (2004). Modal and amodal completion generate different shapes. *Psychological Science, 15,* 454–459.

Singh, M., Hoffman, D. D., & Albert, M. K. (1999). Contour completion and relative depth: Petter's rule and support ratio. *Psychological Science, 10,* 423–428.

Tse, P. U. (1999a). Complete mergeability and amodal completion. *Acta Psychologica, 102,* 165–201.

Tse, P. U. (1999b). Volume completion. *Cognitive Psychology, 39,* 37–68.

van Lier, R. J., van der Helm, P. A., & Leeuwenberg, E. L. J. (1994). Integrating global and local aspects of visual occlusion. *Perception, 23,* 883–903.

Weiskrantz, L. (1986). *Blindsight: a case study and implications.* New York: Oxford University Press.

Williams, L. R., & Jacobs, D. W. (1997). Stochastic completion fields: A neural model of illusory contour shape and salience. *Neural Computation, 9,* 837–858.

Würtz, R. P., & Lourens, T. (2000). Corner detection in color images by multiscale combination of end-stopped cortical cells. *Image and Vision Computing, 18,* 531–541.

Yin, C., Kellman, P. J., & Shipley, T. F. (1997). Surface completion complements boundary interpolation in the visual integration of partly occluded objects. *Perception, 26,* 1459–1479.

Yin, C., Kellman, P. J., & Shipley, T. F. (2000). Surface integration influences depth discrimination. *Vision Research, 40,* 1969–1978.

Received March 8, 2006
Revision received June 21, 2006
Accepted July 11, 2006 ■

Postscript: Identity and Constraints in Models of Object Formation

Philip J. Kellman
University of California, Los Angeles

Patrick Garrigan
University of Pennsylvania

Thomas F. Shipley
Temple University

Brian P. Keane
University of California, Los Angeles

As this exchange concludes, we believe that the account of interpolation and object formation proposed by Kellman and Shipley (1991), further developed in recent years (Kellman, 2003; Kellman, Guttman, & Wickens, 2001), and most recently extended to 3-D interpolation (Kellman, Garrigan, & Shipley, 2005) and spatiotemporal object formation (Palmer, Kellman, & Shipley, 2006), remains viable. Here we briefly note some progress in this discussion, including positions taken by Anderson (2007a) that have since been abandoned. We address the new positions that Anderson (2007b) takes, which now focus on interpolations that switch between modal and amodal appearance, data on interpolated contour shape, evidence and methodological concerns about early interpolation, and physiological evidence.

Anderson's initial commentary attacked our theory of relatability, yet the arguments against these empirically supported geometric constraints seem to have been dropped, and no other account has been offered of which geometric relations of edges in two or three dimensions supports interpolation in unit formation. Arguments about the identity hypothesis have changed significantly. For example, at first, Anderson (2007a) cited results suggesting that luminance constraints can block modal but not amodal inter-