COMMENTS

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)

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P. J. Kellman, P. Garrigan, and T. F. Shipley’s (2005) theory of 3-dimensional object interpolation asserts that existing data, as well as logical considerations, support the view that an identical contour interpolation process underlies the interpolation of partially camouflaged and partially occluded objects (modal completion and amodal completion, respectively). Here, the author argues that recent data show that this theory is incorrect and that the logical arguments offered in support of the identity hypothesis depend on specific unverified models of the phenomena in question. Alternative explanations of these effects are developed to show that such phenomena do not logically implicate an identity hypothesis and, in some cases, provide strong evidence against the identity hypothesis. Finally, the author describes several completion phenomena that reveal that the relatability criteria embodied in Kellman et al.’s model are neither necessary nor sufficient for understanding the interpolation processes the model was designed to explain.

Keywords: completion, filling in, depth, occlusion

In a recent article, Kellman, Garrigan, and Shipley (2005) proposed a simple three-dimensional (3D) extension of the model that Kellman and Shipley (1991) developed previously to account for a variety of interpolation phenomena using (primarily) monocular two-dimensional (2D) images. The main assertions of the recent article were identical to those articulated previously but had been generalized to contour orientations that fall in any 2D plane in 3D space. There are two main ingredients to the theory they have advocated. First, Kellman and colleagues assert that there is an identical boundary completion mechanism that underlies various forms of interpolation (the identity hypothesis). Second, they argue that there are simple geometric criteria that are used to determine which contours can (and cannot) be interpolated (which they have dubbed edge relatability). In both its original and most recent formulations, the potential theoretical contribution of these principles rests on their putative ability to account for an array of seemingly distinct phenomena. The most significant generalization involved what Michotte, Thines, and Crabbe (1964/1991) termed modal completion and amodal completion: Amodal completion refers to the apparent connection of partially occluded objects; modal completion refers to the formation of illusory contours, surfaces, and objects. In their recent article, Kellman et al. (2005) once again assert that both empirical evidence and logical arguments support the identity hypothesis and their relatability criteria. In this article, I argue that, in contrast to Kellman et al.’s (2005) claims, there is now substantial counterevidence to the identity hypothesis and the relatability criteria in predicting when completion occurs in modal and amodal displays. In particular, I make the following arguments:

1. The identity hypothesis asserts that an identical mechanism is responsible for contour completion in both modal and amodal displays. This predicts that the shapes of modally and amodally interpolated contours should not change if the geometric inputs to the completion process are identical in the two cases. This prediction has been shown to be incorrect (Anderson, Singh, & Fleming, 2002; Singh, 2004).

2. It is well known that modally and amodally completed figures generate different percepts (indeed, this is why they were given different names). The identity hypothesis asserts that these differences are due entirely to factors that lie outside the contour completion process. Given the known differences in modal and amodal appearances, this assertion implies that the identity hypothesis can only be sustained if the contour completion process can be shown to be entirely separable from all other completion processes and, moreover, that the contour completion process is

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I refer to “Kellman and colleagues” when claims that were made in Kellman et al. (2005) have been stated in previous work from his laboratory as well.
independent of the type of completion (i.e., modal or amodal). There is currently strong evidence against this view.

3. In a series of articles (Kellman, 2003; Kellman et al., 2005; Kellman, Yin, and Shipley, 1998), Kellman and colleagues have repeatedly argued that logical considerations of several phenomena confirm the veracity of the identity hypothesis. These include Petter's (1956) effect, "quasi-modal" displays (i.e., displays containing half-modal- and half-amodal-inducing elements), and depth-spreading phenomena. I argue that their logical claims follow only from a specific model of the phenomena in question and, hence, do not provide any logical evidence for the identity hypothesis. Moreover, I argue that published data show the failure of completion in quasi-modal displays; that Petter's effect actually provides evidence for fundamental differences in modal and amodal contour completion; and that depth-spreading phenomena exhibit striking asymmetries that provide evidence against the identity hypothesis.

4. Kellman and colleagues' work has placed an increasing emphasis on the use of a particular method to assess contour completion processes (i.e., Ringach & Shapley's [1996] fat–thin task). A large variety of critical evidence that bears negatively on the identity hypothesis has either been dismissed or not considered because investigators used subjective methods (see, e.g., the discussion of Tse's [1999a, 1999b] work on p. 587 of Kellman et al.'s [2005] article). I will show that recent studies provide compelling evidence that the objective task championed by Kellman et al. (2005) may have nothing to do with contour completion processes. Indeed, recent data—including data from Kellman and colleagues' laboratory—suggest that this method is strongly influenced by general processes of visual grouping or task strategies and, hence, do not provide any direct insight into the representations underlying modal and amodal completion.

5. Kellman et al.'s (2005) recent version of the identity hypothesis asserts that the visual system initially completes all relatable contour segments ("promiscuous contour interpolation," p. 600). In this model, all relatable contour segments are completed, and inappropriate links between contours are subsequently removed (or somehow perceptually hidden from experience). The primary justification for this assertion is a set of negative results with the fat–thin methodology that failed to establish performance differences between displays that elicit percepts of completed contours and those that do not. I argue that the more parsimonious account of these results is that the fat–thin task simply does not provide a tool for assessing contour completion processes. Moreover, if the promiscuous contour interpolation hypothesis is accepted, then it implies that Kellman et al.'s model is simply a grouping cue and is no more an explanation of modal and amodal completion phenomena than other grouping cues initially identified by the Gestalt psychologists (such as grouping by similarity of color).

6. I will show that a broad range of data shows that the relatability criteria are neither necessary nor sufficient for predicting when completion occurs. I argue that a theory of modal and amodal completion requires a consideration of the full range of geometric and photometric contexts in which such completion phenomena occur, not of a particular local image cue such as contour relatability that does not successfully predict when contours do and do not complete.

Evidence Against the Identity Hypothesis

Kellman et al. (2005) considered two variants of an identity hypothesis: strong and weak.² Kellman et al. (2005) stated:

A weak version of the identity hypothesis would hold that the same geometry governs amodal and modal completion. A strong version of the hypothesis would hold that the actual process and the mechanisms of interpolating contours across gaps are common to both 3D modal and amodal completion. (p. 596)

Kellman et al. (2005) then discussed evidence and logical arguments that led them to conclude that the strong version of the identity hypothesis is correct. I argue that Kellman et al. (2005) did not consider pertinent data in attempting to make their case and that data now exist that show that the strong version of the hypothesis—the one that they have advocated since their original article on this topic (Kellman & Shipley, 1991)—is incorrect.

In their (brief) discussion of the relevant empirical data bearing on the identity hypothesis, Kellman et al. (2005) stated that “in 2D interpolation, a number of experimental results indicate similar determinants . . . , time course . . . , and strength of interpolation . . . in occluded and illusory displays that are equivalent (in that they have the same physically specified contours and gaps between them)” (p. 596).³ Kellman et al. (2005) then went on to mention recent contradictory evidence from our laboratory, but they dismissed this evidence by stating that such data may not be relevant because “they may not involve the interpolation process per se” (p. 596). They then clarified that the identity hypothesis does not assert that all aspects of modal and amodal completion are identical, but rather that the identity hypothesis only applies to the specific process of generating contour connections across gaps. The structure of their argument suggests that their previous work (Anderson et al., 2002) did not appreciate the scope of the identity hypothesis, which is simply incorrect. It is therefore important to discuss the nature of the counterevidence and its impact on the identity hypothesis to avoid having it be so casually and summarily dismissed.

Modal Completion and Amodal Completion Occur Under Different Stimulus Conditions

Anderson et al. (2002) described two sets of experiments on the identity hypothesis. In one set of experiments, an objective contour alignment paradigm was used; in the other, observers were required to report the perceived structure of comparable modal and amodal displays. I consider each in turn.

In the contour alignment paradigm, observers viewed a series of dark and light bars (a square-wave grating) through two circular apertures, one above the other. Binocular disparity was added in a manner that caused the grating (or portions thereof) to appear in

² The distinction between strong and weak versions of the identity hypothesis has previously been made by Singh (2004) with a different meaning that should not be confused with that introduced more recently by Kellman et al. (2005).

³ It is ironic that time course data are mentioned as supporting the identity hypothesis because the first experiments with the fat-thin task championed by Kellman and colleagues revealed significant differences in the latency of modal and amodal completion.
front or behind the circular apertures (see Figure 1). Observers were required to perform a discrimination task to detect misalignment of the contours in the two displays. Our critical manipulation involved varying the surround luminance of the experimental displays to modulate the strength of the modal completion. The logic of this design was simple: Modal completion involves the camouflage of nearer surfaces by more distant surfaces and, hence, depends critically on the luminance relationships in the image. In contrast, the partial occlusion of a more distant surface by a nearer surface can occur for any combination of luminance values. Kellman and colleagues have argued that the contour completion process is insensitive to luminance and chromatic relationships (see, e.g., Yin, Kellman, & Shipley, 1997; and arguments in Kellman et al., 2005). Thus, a contour alignment task should be unaffected by this manipulation (assuming that such tasks only involve contour interpolation processes, as Kellman and colleagues have argued most forcefully in their recent hypothesis on promiscuous contour interpolation; see below). However, if the contour interpolation process was differentially affected by these manipulations (by making the modal contour completion weaker), then performance in the modal condition should be significantly worse than in the amodal condition. To test this hypothesis, we set the surround luminance equal to one set of stripes in the square-wave pattern in one stimulus condition (Figure 1a); in the other, the surround luminance fell between the two luminance values of the square-wave pattern (Figure 1b). In this latter condition, the luminance relationships are not compatible with modal completion because neither set of stripes satisfy the conditions for camouflage, so we expected performance on this contour alignment task to be significantly worse in this condition. This is precisely what we found: Both subjective ratings of completion and objective performance in the two-alternative forced-choice alignment task were substantially worse in the modal than in the amodal condition (note that the images used for both modal and amodal displays are the same; we created the two depth conditions by simply swapping the images in the two eyes).

Thus, in these experiments, clear asymmetries were observed between modal and amodal completion when the luminance conditions did not support modal surface or contour interpolation. A number of interpretations of this result are possible. The differences we observed could have been because our luminance manipulation (a) negatively affected both contour and surface completion, (b) negatively affected the contour completion process, (c) negatively affected the surface completion process, or (d) introduced confounds that differentially limited performance in the modal and amodal conditions. Possibilities A and B both involve differences in contour interpolation mechanisms, so this cannot be the view of Kellman et al. (2005) (although they have never provided any account of these results). If the surface interpolation process was the only one affected (Possibility C), then this implies that contour alignment tasks do not provide any experimental leverage in assessing the identity hypothesis, because surface interpolation processes would be shown to affect contour alignment tasks. Given the strong reliance on such methods in their recent articles, however, it would seem unlikely that Kellman et al. (2005) subscribe to this view. Moreover, as we will see below, Kellman et al. (2005) have argued that contour interpolation occurs in all displays containing relatable contours and have claimed that these interpolated contours account for equivalent performance in contour alignment tasks, just like those in our study. Thus, Kellman et al. (2005) must accept that the differences observed in our contour alignment task arose because (a) there are different underlying mechanisms for modal and amodal contour completion, (b) such methods do not allow any direct inference about contour completion mechanisms, or (c) there are confounds that interfere with performing the task that led to the modal–amodal difference.

One possible confound that might account for the difference in performance that we observed with our stimuli was that our manipulation of surround luminance transformed the L-junctions in our camouflage consistent display (Figure 1a) into T-junctions (Figure 1b). To control for this difference, we substituted sinusoidal gratings for the luminance gratings in Figure 1, thereby generating equivalent junction structure in all of our luminance conditions. As before, we found that observers were significantly worse at judging alignment in the modal completion condition that was inconsistent with camouflage. Of importance, the average

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**Figure 1.** The stereoscopic stimuli used by Anderson et al. (2002) to test the identity hypothesis. Observers were required to discriminate when the contours in the top and bottom halves of a stereopair were aligned. (a) When the two left images are cross-fused, the square-wave pattern appears behind the circular aperture; when the right two images are cross-fused, the light gray bars appear in front of the surround and two dark gray disks. (b) These stereograms do not satisfy the luminance relationships for modal completion. When the left two images are cross-fused, the grating appears behind the circular apertures, whereas the two right images do not generate any clear percept of completion. No difference in discriminating contour alignment was observed between the modal–amodal contours with the images in Figure 1a, whereas the amodally completed contours were discriminated more accurately than their modal counterparts in Figure 1b. Note. From “The Interpolation of Object and Surface Structure,” by B. L. Anderson, M. Singh, and R. Fleming, 2002, *Cognitive Psychology, 44,* p. 170. Copyright 2002 by Elsevier. Reprinted with permission.
differences in these two functions 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. These results suggest that there are either significant differences between modal and amodal contour completion mechanisms or that such objective methods do not allow one to make inferences about contour completion processes. I will return to this issue in the section on objective methods and contour completion processes below.

Modal Completion and Amodal Completion Can Generate Different Shapes

A more direct piece of counterevidence to the identity hypothesis was obtained in a display that showed that the switch between modal and amodal completion generated very different shapes of interpolated contours (Anderson et al., 2002). The identity hypothesis explicitly asserts that the switch between modal and amodal figures is simply a matter of changing the perceived depth of objects that have been formed via contour interpolation processes and, hence, the shapes of the completed objects should remain unchanged. Indeed, Shipley & Kellman (1992) explicitly state that the identity hypothesis “would be unavailable if the units in the array or the shapes of interpolated boundaries changed when the modal–amodal switch occurred. Such changes do not appear to occur” (p. 117). In direct contrast to this claim, we showed that the stereo figure depicted in Figure 2 (the “serrated edge” illusion) undergoes a dramatic change in shape when it shifts from a modal to an amodal appearance (note again that the images in the two cases are identical; the two half-images are simply swapped in the two eyes to create the depth inversion). In one configuration, observers reported six black circular disks behind an irregularly shaped occluding surface. In the other configuration, only two holes, not six, were consistently reported (see Figure 3). Four of the inducers that appeared as separate objects in the previous depth configuration formed a continuous serrated occluding edge when depth was inverted. Thus, the switch from modal to amodal completion generated a large shift in the interpolated shapes in these displays, directly contradicting the predictions of the identity hypothesis. It is therefore difficult to understand Kellman et al.’s (2005) assertion that this phenomenon “may not involve the interpolation process per se” because it is precisely the kind of phenomena that the theory was designed to address. Indeed, Kellman and colleagues previously identified (Kellman et al., 2005) this type of result as exactly the kind of information needed to disprove the identity hypothesis. To date, they have offered no explanation of this counterexample, despite claims that “these apparent discrepancies have been discussed elsewhere” (Kellman et al., 2005, p. 596).

A number of possible interpretations of this result are possible, but none of them supports an identity hypothesis. One interpretation is simply that the contour interpolation processes underlying modal and amodal completion are different, leading to the different shapes in these displays. This conclusion would entail a rejection of the identity hypothesis. Another possibility is that border ownership plays a role in the different shapes observed in these displays. For example, in the display that appears as six black disks (or separate objects), the black side of the contour appears to own the borders of the circular arcs. In contrast, in the reversed-depth configuration, the white side of the circular arcs owns the border (along the right side of the display). It is possible that such shifts are somehow involved in the different shapes perceived in this display. However, if this were true, it would imply that a surface property—border ownership—contributes to the perception of contour shape, which would directly contradict the independent contour interpolation process embodied in the identity hypothesis. So presumably, this cannot be Kellman et al.’s (2005) view.

Some more recent evidence provides more compelling data that show that the contour interpolation processes are different for modal and amodal completion. Singh (2004) presented displays containing pairs of triangular inducing elements (see Figures 4a and 4b). Stereoscopic depth was added to the inducing elements, so that they appeared either in front (modal condition) or behind (amodal condition) a central vertical oval (Figure 4a) or in
Kanizsa-style displays (Figure 4b). The task of the observers was to adjust the shape of a comparison stimulus to match the perceived shape of the modally or amodally completed figure. All of the inducing elements in these displays satisfied the relatability criteria articulated by Kellman and colleagues, so if the identity hypothesis is correct, the perceived shapes of the interpolated figures in these experiments should be the same. The results did not support this view: The perceived shapes of the modal and amodal displays were consistently and systematically different for the modal and amodal variants of these displays. Specifically, observers perceived the amodally completed contours to be more angular than their modal counterparts. It is unclear how Kellman et al. (2005) can account for this result because no discussion of it has yet been offered. On the face of it, the conclusion that follows from these results seems inescapable: The identity hypothesis, as stated by Kellman and colleagues, is simply incorrect, which is precisely what Singh (2004) concluded. However, it could be argued that their hypothesized global-processing stage could provide some potential explanation of this result. I therefore consider this possibility next.

Local and Global Processes in Completion

A longstanding problem faced by the supporters of the identity hypothesis has been the existence of data and phenomena that reveal differences in the shapes of modal and amodally completed contours. There are now several reports showing that so-called global factors can play a critical role in determining interpolated shape in amodal displays, even when relatable contours would predict a completely different interpretation. In this context, the term global is intended to refer to any property of a partially occluded shape that is not captured by local edge orientations at the points of occlusion. Some examples of the meanings applied to this term include symmetry (Sekuler, Palmer, & Flynn, 1994; van Lier, van der Helm, & Leeuwenberg, 1995), the completion of 3D volumes (Tse, 1999a, 1999b; Tse & Albert, 1998; van Lier, 1999; van Lier & Wagemans, 1999), and the “fuzzy completion” of irregularly shaped figures (van Lier, 1999). These counterexamples have led Kellman et al. (2005) to conclude that “global recognition and local interpolation processes are distinct and operate at different levels” and that “contour interpolation on the basis of relatability operates for both illusory and occluded displays, but global processes apparently do not” (p. 603). The theory that global processes are involved in amodal completion, but not in

Figure 3. Schematic of the percepts obtained in Figure 2. The top row indicates the percepts that are typically reported; the bottom indicates percepts that are rarely or never reported. Note the correspondence of the interpolated contours of Figure 3a with those of Figure 3d and the correspondence of the interpolated contours of Figure 3b with those of Figure 3c. The contour interpolations in the two cases are very different. Note. From “The Interpolation of Object and Surface Structure,” by B. L. Anderson, M. Singh, and R. Fleming, 2002, Cognitive Psychology, 44, p. 185. Copyright 2002 by Elsevier. Reprinted with permission.

Figure 4. The displays used by Singh (2004) to test the identity hypothesis. (a) Two triangular inducers were used to induce contour interpolations, and relative depth was introduced to cause the inducers to generate either modal (right two half-images cross-fused) or amodal (left two images cross-fused) interpolations. (b) Kanizsa-shaped inducers of the same display. The data showed that observers consistently perceived the amodal figure as meeting at a more cornerlike angle than their modal counterparts in both inducer types. Note. From “Modal and Amodal Completion Generate Different Shapes,” by M. Singh, 2004, Psychological Science, 15, pp. 457, 459. Copyright Blackwell Publishing. Reprinted with permission.
modal completion, already suggests a significant difference in how these two types of completions are processed. If it is acknowledged that amodal completion involves two kinds of mechanisms and modal completion only one, then the identity hypothesis can only be sustained if it can be shown that the two hypothesized mechanisms of amodal completion operate completely independently of each other. In what follows, I argue that there are no data to support this view. Moreover, it does not seem that any psychophysical data would be capable of establishing such independence, which would render the identity hypothesis psychophysically untestable.

Let us consider the logic by which Kellman et al. (2005) argued that local and global interpolation processes are distinct and operate on separate levels. Kellman et al. (2005) stated, “One indication comes from the identity hypothesis, which posits a common interpolation step in the formation of occluded and illusory contours” (p. 603). They then presented a series of modal variants of some amodal displays that have been shown to generate representations that are not predicted by their relatability criteria, many of which contain relatable contours. Now it would seem fairly straightforward to conclude from these data that something is fundamentally wrong with the identity hypothesis, which Kellman et al. did acknowledge, but only to a point—by postulating a separate and distinct process that affects only amodal completion. But how did they know that it is a separate and distinct process? Their logic was to argue that the process is separate and distinct because the identity hypothesis tells them that there is something that is identical, so the part that is different must be separate and distinct. The circularity of this argument should be evident. Kellman et al. (2005) attempted to buttress their view that the global recognition process (that putatively occurs only for amodal completion) is processed independently from mechanisms responsible for contour relatability by showing that the precision and accuracy of boundary localization is greater in displays containing relatable contours than in displays that are influenced by global factors. There are a number of problems with this line of argument. Virtually any reasonable theory would predict that the precision and accuracy of contour localization would exhibit less precision and accuracy for more complex interpolations than for simple contour interpolations that have a uniform sign of curvature. 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. So data of this kind do not seem useful for distinguishing one theory of interpolation from any other. Second, even if it could be shown that interpolations involving global factors are less precise than when such factors are absent, this does not provide any evidence that local and global processes are in fact independent (or distinct), as is required for the identity hypothesis to be sustained. It is not clear how this problem can be circumvented. If there are two processes that operate in amodal completion and only one in modal, then there does not seem to be any way to create a behavioral paradigm that could prevent both processes from always contributing to the amodal percept, at least not without bringing additional assumptions to bear on how these putatively separate processes each contribute to the final percept (such as assumptions about the time course in which the hypothetical separate processes contribute to the final percept). Such views would make the identity hypothesis inherently untestable. If differences in the shapes of modally and amodally interpolated contours are found, they can be attributed to a second (and putatively distinct) process that operates only on amodal contours. If no differences are found, such results could be interpreted as providing support for the identity hypothesis. This has been precisely the interpretative pattern that Kellman and colleagues have adopted to deal with counterexamples to the identity hypothesis.

With these considerations in mind, let us reconsider the data reported by Singh (2004). How would Kellman et al. (2005) account for such a result? Presumably, their only recourse is to assert that the modal contours were formed on the basis of the relatability criteria alone, whereas the amodal contours were the consequence of two distinct processes (their relatability criteria plus a global recognition process). Now it does seem inescapably true that the different shapes generated by the interpolated contours indicate that distinct processes are at work here. However, no data have yet been offered that show that the observed differences in this display can be attributed to an entirely separable process; this conjecture is offered simply as a means of avoiding the demonstrated fact that the identity hypothesis fails to predict perception in a host of amodal displays.

In sum, there is currently large body of data showing that amodal interpolations are often not predictable by the relatability criteria articulated by Kellman and colleagues. I contend that if none of the data reported to date can be used to reject the identity hypothesis, then none of the data putatively used to support it bear on the hypothesis either. If such is the case, the identity hypothesis is simply untestable, at least psychophysically. This point will be made even more forcefully below, when I consider the most recent data emerging from Kellman’s and others’ laboratories using the objective methods championed by Kellman and colleagues (i.e., the fat–thin task developed by Ringach & Shapley, 1996).

Logical Arguments and the Identity Hypothesis

In keeping with previous claims, Kellman et al. (2005) assert that a number of logical considerations show that “an identical contour-connection process underlies what observers ultimately experience as modal and amodal completion” (p. 596). Indeed, they have placed so much emphasis on these logical arguments that they have used them to discount physiological and psychological data that are inconsistent with their views.4 These logical considerations therefore play a critical role in upholding the identity hypothesis. Here, I show that such logical considerations do not follow from the phenomena in question but rather depend on very specific models of the phenomena under consideration. The only leverage that logic can give in upholding a particular model is if it can be shown that all other conceivable models are illogical.

4 Indeed, in a recent chapter discussing these effects, Kellman (2003) stated, “[W]e currently lack a sufficiently detailed mapping of computations onto cortical layers to use this data to rule out a common interpolation step. Given the logical considerations following from Petter’s effect (1956), quasi-modal displays and depth spreading displays, as described, putative data suggesting separate visual processes of amodal and modal interpolation must be treated with skepticism. No claim of separate processes can make much sense without giving a new account of the three phenomena and their logical implications. To my knowledge, no such account has been proposed” (p. 175).
None of the arguments that Kellman et al. (2005) present accomplishes this goal. The arguments that they offer are linked by a common theme: That certain phenomena show that (contour) interpolation necessarily precedes the appearance of a contour or surface as modal or amodal. In what follows, I argue that none of these phenomena requires the sequence of computations that they assert; hence, there is no logical force that can be derived from these phenomena to uphold the identity hypothesis.

Self-Splitting Objects and Petter’s Rule

Several 2D displays have played a critical role in shaping the identity hypothesis that Kellman and Shipley (1991) labeled self-splitting objects. These displays contain homogeneous colored regions and a number of L-junctions (see Figure 5). Such objects are perceived to split into two separate objects, and the perceived depth of these surfaces can appear to fluctuate in time. Petter (1956) noticed that the contour that completed over the shorter distance would be more likely to appear in front (i.e., as the modally completed figure). Kellman and colleagues have repeatedly argued, oddly enough, that this bias provides support for the identity hypothesis. The oddity in this statement is that Petter’s rule explicitly expresses an asymmetry between modal completion and amodal completion. Why should there be any preference for one of the surfaces to appear in front of the other if the very same contour completion mechanism is responsible for the unity of both? Indeed, the phenomena described by Petter seem to provide clear evidence that there is something fundamentally different in the interpolation strength of modal and amodal boundaries. Petter’s effect has never been explained by Kellman and colleagues, but since publication of the article by Kellman, Yin, and Shipley in 1998, they have argued that it logically implicates an identical contour completion mechanism. I argue that the logic that has led them to this conclusion is flawed.

The argument offered by Kellman et al. (2005) to use Petter’s effect as a source of support for the identity hypothesis is that the visual system must first interpolate the two sets of contours so that their interpolated lengths can be subsequently compared:

The registration of interpolation sites and lengths must precede the determination of depth ordering. It follows that in at least some cases, contour-interpolation processes must operate prior to the processes that determine final depth ordering of the constructed contours. This, in turn, implies that there cannot be separate mechanisms for the interpolation of contours in front of and behind other surfaces. (p. 598)

To be sure, this would be one way to implement Petter’s rule, but it is clearly not the only way. First, it is not at all clear why a mechanism that compares distance to determine the modal or amodal appearance of a contour would have to operate after contour interpolation has occurred. If their assertion is simply that possible interpolation lengths are compared to decide which contour will be modally or amodally interpolated, then their logic simply fails, because this does not imply anything about whether there are separate mechanisms that perform the interpolation once the decision about the modal–amodal appearance has been made. Second, there is a general fallacy in Kellman and colleagues’ interpretation of Petter’s effect. Kellman and colleagues interpret Petter’s rule as a processing or mechanistic model, but it is not, or at least it need not, be so interpreted. Petter’s rule simply expresses a rule of thumb that allows one to predict a particular perceptual outcome; it does not state how this outcome is achieved, as is the case for a processing model. Indeed, Petter’s effect is presumably the consequence of some processing constraint on modal and amodal completion, not a rule that is arbitrarily applied to these particular displays. Despite Kellman and colleagues’ repeated claims, nothing about Petter’s effect logically rules out models that do not embrace their identity hypothesis. To make this point, all that is required is a single alternative model that does not involve an explicit comparison of interpolated contour lengths before depth is assigned and that does not involve any logical contradictions. The following is one such account.

A key element of the account to be described is that modal and amodal completion phenomena actually represent the output of two different forms of continuation processes. From this perspective, modal and amodal completion phenomena are special cases of two forms of continuation processes that are initiated locally, which may be enhanced by the presence of other (locally initiated) contours or surfaces (see, e.g., Anderson, 1994; Anderson & Julesz, 1995; Gillam, 2003; Rubin, 2001). Consider a model containing two separate contour continuation mechanisms, one modal and the other amodal. Note that this distinct-mechanisms model assumes that modal and amodal completion processes occur at a representational stage at which relative depth information is available (which is required for any model that is capable of distinguishing between modally and amodally completed figures). At each L-junction, two contour continuation processes are initiated for each of the contour segments. In this model, the modal continuation mechanism is assumed to have a relatively weak extrapolation strength that declines rapidly with interpolation distance; the amodal continuation mechanism is assumed to decline more gradually with distance. This makes intuitive sense: The conditions

Figure 5. Examples of Petter’s displays and self-splitting objects. These solid figures are typically perceived to split into two separate objects, with the shorter contour interpolation typically appearing in front of the longer interpolated segment (Petter’s effect). Note. From “Object Interpolation in Three Dimensions,” by P. J. Kellman, P. Garrigan, and T. F. Shipley, 2005, Psychological Review, 112, p. 598. Copyright 2005 by the American Psychological Association.
for camouflage are more difficult to achieve than the conditions for occlusion, so the likelihood that a camouflaged object is present should decline more rapidly with distance than the likelihood that a partially occluded figure is present.\(^5\) I further assume that the strength of the completed contours for both the modal and amodal mechanisms is determined by whether each locally induced contour continuation process joins with a mechanism of the same type (we will see in the following section that this assumption can be relaxed). At each L-junction, two types of competitive processes are assumed to be present: a competition between the modal and amodal contour continuation mechanisms of the same inducing contour (enforcing a constraint that a given contour cannot be simultaneously modally and amodally interpolated at the same location in space) and another competition in which the two different contours that form the L-junction compete for modal and amodal appearances (enforcing a constraint that only one of the contours at an L-junction can be of a given type). What would such a mechanism predict? Contours spanning a short distance would generate little difference in their modal and amodal interpolation strengths, because they do not have much distance to traverse. Hence, the modal and amodal contour strengths would be roughly equivalent. In contrast, contours spanning a longer distance would generate a stronger response in the amodal completion mechanism than in the modal completion mechanism because of its greater extrapolation strength.

In the competitive model outlined above, the amodal interpolation of this contour would suppress the modal interpretation of the same contour (because of the competition between the modal–amodal mechanisms encoding the same contour), and it would simultaneously suppress the amodal interpretation of the other, shorter contour segment (because of the competition between the two different sets of contours). This pair of competitions would correctly predict Petter’s effect, causing the shorter contour to be seen as the modal segment. Note, however, that in this model, there is nothing that explicitly compares the lengths of contours or anything that requires interpolation to occur prior to the designation of a contour as modal or amodal. Rather, in this model, Petter’s effect emerges as a consequence of the different extrapolation strengths of the two forms of continuation processes initiated at contour junctions and the competition between these separate contour mechanisms for precedence.

This alternative model shows that there is nothing in Petter’s effect that logically implicates an identical contour interpolation mechanism. The phenomenon discovered by Petter (1956) is important, and any complete model of completion must address it. However, it should be emphasized that absolutely nothing in the identity hypothesis or any other aspect of Kellman and colleagues’ model predicts Petter’s effect; it is treated as a separate decision rule that simply describes the behavior that is meant to be explained but is in no way justified or explained by Kellman et al.’s (2005) theory.

It is also worth noting that the alternative model of Petter’s effect described above can provide an account of the differences in the perceived shapes of modally and amodally completed surfaces reported by Singh (2004) that are completely outside the scope of Kellman et al.’s (2005) theory. Singh found that the amodal completion of two laterally displaced triangular inducers were perceived to form more angular completions than their modal variants. He noted that this result could be explained if amodal completion mechanisms had greater extrapolation strength than their modal counterparts, because such a mechanism would cause the linear segments of the inducing figures to propagate over a longer distance before turning to meet the other inducer.

In closing, it should be emphasized that the preceding arguments against using Petter’s effect as logical support for an identity hypothesis do not rest on the particular model that was articulated; it is simply one possible model among an indefinitely large number of possible models. Its importance lies in showing that logical considerations of Petter’s effect do not provide support for the identity hypothesis, as claimed by Kellman and colleagues.

### Quasi-Modal Completion

Kellman et al. (2005) have also asserted that hybrid or quasi-modal displays provide evidence for the identity hypothesis. An example of a quasi-modal display is presented in Figure 6. Kellman et al. (2005) have contended that in these images, a partially occluded contour can appear to link with a partially camouflaged contour. They stated that “neither the requirements for illusory contour formation nor those for occluded contour formation are met” (p. 597). Now it is unclear how such a claim can be made, because to date I am unaware that the necessary and sufficient conditions for either type of completion have been identified (and as will be seen below, neither the identity hypothesis nor the relatability criteria provide either). Indeed, the very goal of this kind of research is to determine the conditions that must exist for completion to occur. Presumably, this claim is made because Kellman et al. (2005) believe that modal and amodal completion are distinct from modal and amodal continuation. Irrespective of motivation, there are (at least) two possible lines of argument that can be levied against the notion that quasi-modal displays provide logical support for an identity hypothesis. One line of argument questions whether these contours are, in fact, processed identically (i.e., either the strength or shapes of the interpolated contours could differ for these displays or, worse, there could be no actual connection formed between these elements; they may just be perceptually grouped); the other line of argument questions whether completion in these displays provides any evidence for an identity hypothesis. I consider both possibilities.

One of the simplest ways to challenge the significance of quasi-modal displays is to question whether any explicit modal or amodal completion actually occurs in these images. The concept of completion in Kellman and colleagues’ model involves the synthesis of additional contour segments that fill in the gaps in the image created by occlusion and camouflage. When contour segments are camouflaged, the completion process generates visible contour segments; when they are occluded, they unify objects but are perceptually invisible. Kellman and colleagues have never explicitly articulated the relationship between contour-completion mechanisms and contour-grouping mechanisms that have been documented by investigators using aligned Gabor patches or line segments (e.g., Field, Hayes, & Hess, 1993; Geisler, Perry, Super,

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\(^5\) Indeed, this difference in the ecological conditions that gives rise to occlusion and camouflage is arguably one of the most important reasons to suspect that different interpolation constraints underlie modal and amodal completion.
Gallogly, 2001). When these latter results are discussed, they have been typically treated as if they were the same mechanism. This is problematic, however, because contour-grouping mechanisms do not evoke percepts of either occlusion or camouflage. It is possible that quasi-modal displays do not involve completion processes of the kind observed in modal displays—in which contour segments are generated in the gaps—or whether they reflect processes that group individual elements without the actual synthesis of missing contour segments. Although Kellman et al. (2005) attempted to assert that new contour segments are synthesized in quasi-modal displays by noting that they “confer the same advantages and the same pattern of processing in an objective performance paradigm as do equivalent illusory and occluded displays” (p. 597), there is now compelling data that suggest that these performance measures do not actually tap into contour completion processes (see below).

Even more critically, however, Kellman et al. (2005) failed to consider data by Rubin (2001) who presented clear counter-evidence to the claim that completion occurs in quasi-modal displays. A variant of one of her displays is presented in the stereograms in Figure 7. In this image, a stereo Kanizsa figure is presented such that it appears in front of the black inducing elements. However, in this figure, small occluding dots are placed in the image so that they appear to occlude the stereoscopic L-junctions where the interpolated contours should form. In Kellman et al.’s (2005) model, these tiny occluding disks should have essentially no impact on the formation of illusory contours; the contour interpolation mechanism should interpolate a contour across the gap separating the relatable contour segments, beginning as an amodal contour segment and then continuing as an illusory contour between the small occluding disks. This prediction was directly violated by Rubin’s (2001) data: Subjects reported that no illusory contours formed along the sides of the figure between the small occluding disks but were clearly present along the sides of the figure that did not contain these dots (similar effects were reported with kinematic variants of these displays). Kellman and colleagues have never provided any explanation of this result, despite the fact that these data provide a direct counterexample to the claim that completion occurs in quasi-modal displays.

Even if one granted that completion occurs in quasi-modal displays, this in no way provides evidence for an identical contour completion process. Indeed, something has to explain why the different portions of the segment appear different. It may be something intrinsic to the contour interpolation process, or it may only arise after contour completion has occurred (as Kellman and colleagues claim). Kellman et al. (2005) acknowledged that quasi-modal completion does not logically entail a common interpolation mechanism because it could be asserted that there is a third mechanism that underlies it. However, that is not the only way that distinct mechanisms could underlie modal and amodal completion.

Figure 6. Quasi-modal or hybrid displays. Viewing these figures, observers typically report a unified object (which is enhanced by cross-fusing the two displays). Note. From “Object Interpolation in Three Dimensions,” by P. J. Kellman, P. Garrigan, and T. F. Shipley, 2005, Psychological Review, 112, p. 597. Copyright 2005 by the American Psychological Association.

Figure 7. A stereoscopic figure adapted from Rubin (2001) showing that completion does not occur in quasi-modal displays in the manner predicted by Kellman and colleagues (cross-fusers should fuse the left two images, divergers the right two images). In this figure, small occluding dots are placed over the junctions along two of the sides of the Kanizsa figure. Rubin (2001) found that vivid illusory contours are seen on the two sides that are not occluded by the dots, whereas no illusory contours were reported on the sides of the display containing the dots that occluded the stereoscopic L-junctions. Note. From “The Role of Junctions in Surface Completion and Contour Matching,” by N. Rubin, 2001, Perception, 30, p. 356. Copyright 2001 by Pion. Reprinted with permission.
and still support completion in quasi-modal displays; a model similar to that developed in the preceding section on Petter’s effect could also explain quasi-modal completion.

The alternative model developed above to explain Petter’s effect only allowed modal contours to link with modal contours and amodal contours with amodal. However, this is not necessary. A model could be fashioned in which modal contours could link with amodal contours, whereas the rest of the proposed completions remained the same (there could be some bias for like forms of contours to link, but it need not be an all-or-none constraint). In a model of this kind, the constraint imposed on the interpolation process is that any given inducing contour segment can only generate a single type of continuation process (modal or amodal) at the junction at which interpolation is initiated. In this model, the completion of a contour is the consequence of two continuation processes that operate locally on the relative depth of contour junctions, not a single completion process (which requires a pair of inputs). Such a model could clearly handle quasi-modal completion without postulating a new class of completion mechanisms; indeed, by allowing either type of continuation mechanism to join with the other, this model by definition allows quasi-modal completion. Note also that this modification does not affect the model’s capacity to explain Petter’s effect. In Petter’s displays, each contour forms a possible modal and amodal contour continuation at each of the junctions (because of the ambiguity in the L-junctions). As before, the amodal completion process decays less rapidly with distance. When the separation between contours becomes sufficiently large, the different decay rates of the modal and amodal continuations at the two junctions cause the longer interpolation distance to be biased to appear amodally, because both of the contributing contour segments would propagate over longer distances. The rest of the competitive processes would remain the same, yielding Petter’s effect. Thus, both Petter’s effects and quasi-modal displays can be explained without postulating an identical contour interpolation mechanism.

It could be argued that the preceding model is essentially the same as a model that asserts a single contour interpolation process because a given inducing element could receive inputs from either type of inducer. There are, however, important differences between a model of this kind and that proposed by the identity hypothesis. First, in the alternative model described here, there is no assumption of an explicit modal or amodal completion mechanism. Rather, both modal and amodal completion are assumed to arise from two kinds of continuation processes that are initiated at their respective junctions. Note that much of what motivates the arguments by Kellman and colleagues is their belief in a mechanism that is designed solely to perform contour completion, rather than the idea of completion as a special case of modal or amodal continuation processes (despite the fact that single inducing elements have been shown to induce illusory contours [Anderson, 1994; Anderson & Julesz, 1995] or that many if not most forms of occlusion lead to amodal completion without completion [see Gillam, 2003]). Second, the alternative model described here assumes that the extrapolation strengths of the two types of completion mechanisms are intrinsically different, whereas an identity hypothesis, by its very definition, asserts that the extrapolation strengths of the contour mechanism are the same. Such differences lead to distinct predictions. The distinct mechanism model implies that it should be possible to generate quasi-modal displays that generate interpolated contours with shapes different from either their modal or amodal counterparts, whereas the identity hypothesis would predict that this is not possible.

In sum, there is nothing in quasi-modal displays that logically entails an identical completion process (as Kellman et al., 2005, duly noted but for different reasons). First, there is clear counter-evidence against the claim that completion actually occurs in these displays. Second, even if one granted that contour completion occurred in these displays, such phenomena can be explained with a model containing two distinct contour continuation processes.

**Depth Spreading**

The final logical argument used to support the identity hypothesis is a phenomenon Kellman and colleagues have designated *depth spreading*. I am in agreement with Kellman and colleagues that depth-spreading phenomena provide critical insights into the processes of modal and amodal completion. However, I argue that there is nothing in the particular display on which they base their argument to support their claim that depth-spreading phenomena provide evidence for an identity hypothesis. Indeed, I contend that this display, as well as a host of related phenomena, provides some of the most compelling evidence that different constraints underlie the way in which depth spreads from contours that are relatively near than those that are relatively far and that these asymmetries also apply to modal and amodal completion and continuation processes.

First, let us consider the depth-spreading display that Kellman et al. (2005) deemed decisive in supporting the identity hypothesis. In Figure 8, binocular disparity is introduced on the left and right vertical edges of the central figure, causing the left side to appear in front of the surrounding regions and the right side to appear behind. When fused, this figure can appear as a rectangle slanted in depth, completing modally in front of a thin vertical (amodally interpolated) bar on the left and behind a thin (modally interpolated) vertical bar on the right. Kellman et al. (2005) asserted that this percept provided evidence that a boundary completion process must have occurred before depth could spread in this figure. Their argument runs thus: (a) Contour interpolation produces a bounded rectangle, (b) depth spreads within this bounded object, and (c) relative depth determines which portions of the figure appear modally or amodally complete. Their assertion that this phenomenon provides evidence for an identity hypothesis rests on two assumptions: first, that the three steps that they outline actually constitute the sequence of computations that must have occurred in

![Figure 8.](image-url)
generating the percept of this figure and, second, that depth spreading is restricted to the regions bounded by the rectangle. I contend not only that there is no evidence to support these conjectures, but that Claim 1 is at odds with their current model and that Claim 2 is simply wrong.

Claim 1 asserts that boundary interpolation must precede depth spreading and, therefore, the determination of the modal or amodal appearance of the central rectangle. It is not at all clear what the basis of this assertion is, and it seems completely at odds with Kellman et al.’s (2005) 3D theory of interpolation. If relative depth is used to determine which contours can and cannot be interpolated, as Kellman et al.’s (2005) theory asserts, then how can Kellman and colleagues also claim that the information needed to determine the modal and amodal status of interpolated contours is not available during the interpolation process? If the relative depths of contour segments are the very ingredients of the contour interpolation process, then why isn’t there sufficient information to determine the modal and amodal status of the interpolated contours from the outset? All these displays demonstrate that relative depth plays a role in determining how contours and surfaces are interpolated, which includes their modal and amodal status. I can see no means by which a sequence of computations can be established from a description of a (possible) percept of these displays. Strangely, the one they have offered seems to contradict their own theory of 3D interpolation.

Claim 2 asserts that depth spreading only occurs within objects and continuous surfaces. Kellman and colleagues’ analysis of their depth-spreading display only considered how depth is attributed to the central interpolated rectangle in their display. A more thorough analysis of this and related figures reveals that depth only spreads within the rectangle when it is in front of the inducing elements but that it spreads throughout the black inducing elements when it appears behind. For example, in the right side of the display, the depth of the (far) contour is not restricted to the rectangular central figure but rather spreads to the black regions of the inducing elements, causing them to appear behind the ground plane (similar effects are observed in the middle of the display when the central region appears behind the ground plane). This, too, is a form of depth spreading, but there are no interpolated contours that guide or restrict the manner that depth spreads in these regions.

Kellman and colleagues have never provided any explanation of this form of depth spreading, and it has a significant impact on their theory. Indeed, I have recently shown that the manner that depth spreads in stereograms is a consequence of the inherent asymmetry that arises from the geometry of occlusion (Anderson, 2003; Anderson et al., 2002). In particular, I showed that the geometry of occlusion requires that depth spreads differently for near and far contours (and other local contrast signals), which has significant consequences for modal and amodal completion and depth-spreading phenomena. To see this, consider Figure 9. In this figure, stereoscopic depth has been added to the small wedge-shaped “mouths” of the inducing elements, causing them to appear in front of (left pair of images cross-fused) or behind (right pair of images cross fused) the circular arcs of the inducing elements. When the edges appear in front of the figure, they appear as five isolated occluding wedges occluding five black disks. However, when depth is reversed, both the black and the white regions of the inducing elements appear behind the ground plane (i.e., depth spreads to both sides of the far contour). This depth spreading, in turn, causes a large shift in the perceptual organization of the figure: Observers now report that the figure predominantly appears as a single irregular black “star,” and the disparity is used to determine which contours can and cannot be interpolated. To see this, consider Figure 9c. In this configuration, the unity of the occluded figure emerges from depth spreading; it is not a consequence of contour interpolation processes. Note. From “The Interpolation of Object and Surface Structure,” by B. L. Anderson, M. Singh, and R. Fleming, 2002, Cognitive Psychology, 44, p. 167. Copyright 2002 by Elsevier. Reprinted with permission.
bar, observers were much more likely to report that the horizontal bar simply appeared occluded, lying in a frontoparallel plane. Here, the modal status and the amodal status of the bar play a critical and asymmetric role in depth spreading, in direct contrast to the claims of the identity hypothesis.

In sum, a substantial body of data now shows that depth-spreading phenomena are at odds with the predictions of the identity hypothesis. Moreover, the order of computations that Kellman et al. (2005) have asserted as occurring in their depth-spreading display seems to directly contradict the main tenet of their 3D theory of contour interpolation: that the 3D positions and orientations of contour segments are the very elements that determine what is and what is not interpolated. When considered as a whole, the body of work on depth spreading and the logical inconsistency of their position on the constraints underlying contour interpolation provide some of the most striking evidence of the fundamental differences in modal and amodal completion phenomena.

Methodological Issues in Assessing Models of Completion

One of the main issues in evaluating any theory involves assessing the methods used to test it. Kellman and colleagues (2005) have placed an increasing emphasis on objective performance methods to investigate completion processes. They argued that these methods are of greater value than subjective measures such as demonstrations and perceptual reports because the latter are “limited by demand characteristics and by the influences of cognitive strategies in addition to the perceptual processes they aim to assess” (p. 591). This sentiment is not unique to Kellman et al. (2005), and a large portion of the vision community finds subjective methods to be suspect (despite the fact that so much of vision is dedicated to understanding the nature of perceptual experience). This debate could form the basis of a separate article, but some consideration of this issue is critical to the consideration of Kellman and colleagues’ theory, given the amount of phenomena and data that they have discreted because they failed to satisfy such objective criteria (such as the large body of phenomena reported in Tse and colleagues’ work; cf. Tse, 1999a, 1999b; Tse & Albert, 1998). Despite their expressed concern about data obtained via subjective methods, Kellman and colleagues have actually relied heavily on a variety of phenomenological demonstrations to uphold many of their claims about completion and the identity hypothesis. For example, their arguments about Petter’s effect and depth-spreading displays depend exclusively on claims about subjective experience. Thus, their critiques of subjective methods seem displaced, given the repeated emphasis that they have placed on phenomena that have not been measured in any objective manner.

It is clear, then, that Kellman and colleagues have relied heavily on both subjective and objective methods in defending their views, although they have placed greater stock in objective methods when faced with counterevidence. It is therefore critical to determine whether objective methods actually provide greater insight into contour completion phenomena, given that many of their claims about the identity hypothesis hinge on purely negative results using such methods. In what follows, I will show that there is now sufficient evidence to conclude not only that the objective methods championed by Kellman et al. (2005) are of no greater value in assessing completion but moreover that such methods may actually provide no insight into modal and amodal completion at all.

Let us begin by considering the general logic of applying objective methods to the study of completion phenomena. The goal of an objective task is to find some technique whereby observers can be either right or wrong so that their performance in the task can be objectively gauged. This works fine for many experimental questions, and much of psychophysics is based on such techniques. However, when such techniques are used to assess processes of perceptual organization, a significant interpretation problem arises—to determine whether the data generated by a performance measure have anything to do with the process the experimenter is actually attempting to study. After all, a discrimination task can be performed on the basis of any information in the display that is available to make the judgment, so the experimenter must perform appropriate control experiments to demonstrate that the property of interest (here, contour completion) is actually the factor that limits observers’ performance. If other factors play a significant (or primary) role in limiting observers’ performance, then it becomes essentially impossible to determine whether differences between experimental conditions are due to the property of interest (here, contour completion) or any of a number of other factors. This is particularly problematic when the phenomena under investigation involve assessing conceptual distinctions that have been made solely on phenomenological grounds, such as modal and amodal completion.

The main objective technique exploited by Kellman and colleagues to assess completion phenomena is Ringach and Shapley’s (1996) fat–thin paradigm. In this technique, the inducing elements of a square Kanizsa pattern are rotated in a manner that causes the interpolated figure to either bow outward or inward along its vertical sides (appearing fat and thin, respectively). It is clear that a completed figure is not required to perform tasks of this kind; observers could simply judge the relative orientations of the inducing elements to perform the task (indeed, related tasks form the basis of a plethora of visual acuity studies). Thus, the inference that such methods primarily tap into contour interpolation processes can only be made by comparing performance in displays that generate percepts of interpolated contours with those that do not. But how do we know that completion has occurred in a given display? We must turn to phenomenology for this answer (which is, of course, a subjective judgment). Thus, the entire logic by which “objective” paradigms provide insight into modal and amodal completion rests on evidence that such tasks are performed differently when interpolated contours are perceived (a subjective judgment) and when they are not (another subjective judgment).

The question, then, is whether there is any compelling evidence to support the claim that performance on the fat–thin task is exclusively (or even primarily) limited by contour completion processes. The answer to this question is, at best, highly mixed. Consider, for example, the work that has emerged from Kellman and colleagues’ laboratory. In an earlier report, Kellman et al. (1998) found that both modal, amodal, and quasi-modal variants of Kanizsa figures produced comparable reactions times using Ringach and Shapley’s (1996) fat–thin task, whereas outline Kanizsa figures (that do not produce percepts of interpolated counters) were processed less rapidly. This led Kellman et al. (1998) to argue that the fat–thin task is a valid means of studying...
completion processes, precisely because the displays generating percepts of interpolated contours were performed more proficiently than those that did not. More recently, however, Kellman and colleagues (Guttman & Kellman, 2005; Kellman, Guttman, & Wickens, 2001) found that the very same outline figures (and other displays that did not elicit percepts of completion, such as simple L-shaped inducers) either generated identical performance levels in a fat–thin task or that performance differences between outline and filled inducers occurred when the outline condition was performed prior to the filled condition (thereby revealing that task strategies play a critical role in limiting performance). Presumably, the purpose of including the outline figures was to show that displays that elicit percepts of completion (modal and amodal Kanizsa displays) are performed more accurately than displays that do not elicit such percepts (the outline inducers), given that this was the reason for their inclusion in previous studies (Kellman et al., 1998). Yet this is not at all what they found. Logical consistency would seem to require a revision of Kellman et al.’s (1998) previous claim that this method actually taps into completion processes, yet no such conclusion was offered. Rather, Kellman et al. (2005) recently have asserted that such data support a promiscuous contour interpolation process wherein all relatable contours are initially interpolated, and inappropriate connections are only subsequently eliminated (although the means by which they are eliminated—or how they could influence performance if they are ultimately eliminated—have not been explained). The more parsimonious explanation of this data is simply that the fat–thin method does not provide an uncontaminated measure of contour-completion processes and, hence, cannot be used to assess the identity hypothesis or contour-completion processes.

Further evidence that the fat–thin task may simply reflect task strategies rather than the existence of completed contours has emerged from research using response classification techniques to explore completion phenomena (Gold, Murray, Bennett, & Sekuler, 2000). A detailed explanation of this technique is beyond the scope of this article, but its basic logic is as follows: Observers are shown two displays that they are asked to discriminate (here, fat and thin Kanizsa figures) embedded in a noise pattern. The contrast of the Kanizsa figure is chosen to be at a value that keeps observers’ performance at some criterion level (here, 75%), so that the noise limits their performance. The task of the observers is to simply classify a given trial image (Kanizsa figure + noise pattern) as either fat or thin. On some trials, however, the noise causes the fat stimulus to look thin and vice versa. To determine which image regions influence the observers to respond “fat” or “thin,” the correlation between the contrast at each pixel in the noise fields and the observers’ response are computed across all trials. This correlation generates a “classification image” that reveals which image pixels in the noise pattern influence observers’ responses. Gold et al. (2000) found that the pixels between the inducing contours influenced the fat–thin classification in both the modal and amodal variants of their displays and initially suggested that such data provided evidence that observers were basing their decisions on a perceptually completed representation of the stimulus.

However, a series of follow-up studies (Murray, 2002) has cast doubt on this conclusion. A critical piece of data that led to this change in interpretation was the finding that essentially identical classification images were obtained when the Kanizsa inducers were replaced with simple L-shaped inducing elements that do not generate percepts of completed contours. Although Kellman et al. (2005) argue that such results reflect the existence of invisible promiscuous contour interpolation processes, these results clearly reveal that such methods do not correlate with the perception of completed contours or with the strength of perceived interpolated contours. Rather, a simpler explanation of the results is that observers perform the task by mentally imposing a square template onto a given stimulus and then respond “fat” or “thin” on the basis of deviations from this template (see, e.g., Gold & Shubel, 2006).

Thus, recent data reveal either that the fat–thin task does not provide an uncontaminated measure of contour-completion processes or that contour interpolation occurs for all relatable contours (as suggested by Kellman et al.’s (2005) promiscuous contour interpolation hypothesis). However, acceptance of the promiscuous contour interpolation hypothesis poses a host of problems for both the theory and the methods advocated by Kellman et al. (2005). Methodologically, it implies that it is essentially impossible to determine whether the fat–thin task has anything to do with contour-completion processes. In order to assess whether this method actually taps into modal or amodal interpolation, one must compare it with conditions that possess similar geometric features (namely, contour orientations and positions) that can be performed with comparable strategies but that do not generate completed contours. If the promiscuous contour interpolation hypothesis is correct, then no such comparison can ever be made, because such control stimuli would always, by hypothesis, generate interpolated contours. Although Kellman and colleagues (cf. Guttman & Kellman, 2005) attempted to circumvent this problem by comparing displays containing relatable contour segments with displays containing unrelatable contour segments, there is a host of problems with this control condition. Guttman and Kellman (2005) found that the fat–thin discrimination is more difficult in unrelatable contour displays than in relatable contour displays, but there are several reasons that this could occur other than the promiscuous interpolation of contour segments that they suggested. For one, the distance between the inducing elements was not equated across these conditions, so there is no reason to expect equivalent performance between the relatable and unrelatable contour segments (and it is not clear how to predict what the deficit should be). Additionally, there are good reasons to expect that this task should be harder even if no contour completion was occurring in these displays (and distance was somehow equated). For example, in the relatable contour segment displays, observers could simply impose a mental template of a vertical contour as a framework against which rotations of the inducing elements could be judged, effectively giving them two chances of detecting a rotation (cf. Murray, 2002). No comparable strategy would be available in their offset conditions. Thus, this control experiment in no way establishes that contour completion is occurring in all displays containing relatable contour segments. Rather, it simply shows that certain judgments are more difficult when positional noise is added to a display requiring judgments of relative orientation.

Significant theoretical problems also arise for the model articulated by Kellman and colleagues during the past 16 years if the promiscuous contour interpolation hypothesis is accepted. If contours are interpolated between all relatable contour segments, then discontinuities—which they have previously regarded as critical for initiating contour interpolation—are now rendered ir-
relevant. According to Kellman et al.’s (2005) theory, interpolation processes happen for all 3D relatable contour segments, whether or not first-order discontinuities are present. Their theory therefore reduces to a claim that all contours that can be interpolated with a monotonic curve that turns through no more than 90° will be so interpolated. If this is their view, then their theory is simply a restatement of the Gestalt grouping principle of good continuation, which is not a theory but rather just a (previously identified) grouping principle. Thus, if the promiscuous contour interpolation process is correct, boundary interpolation is no more an explanation of modal and amodal completion than any other grouping principle (such as, say, grouping by color similarity).

In conclusion, recent data using the fat–thin methodology introduced by Ringach and Shapley (1996) reveal one of two possibilities: Either the method does not provide any direct information about the representations used to perform the task, or contour interpolation occurs for all appropriately aligned contour segments. If the first possibility is correct, a large body of data is rendered irrelevant to understanding the relationship between modal and amodal completion. If the second possibility is correct, then Kellman and colleagues’ theory reduces to just one of many grouping principles.

When Is 3D Information Used in Completion?

The key assertion of the identity hypothesis is that contour interpolation occurs before relative depth information determines whether interpolated contours are assigned a modal or an amodal appearance. This view emerged from Kellman and colleagues’ explorations of 2D displays in which the relative depth of image features was ambiguous. In this setting, it does not seem particularly unreasonable to hypothesize that contours that determine modal and amodal appearance might be interpolated before ambiguous depth relationships are resolved. However, Kellman et al.’s (2005) theoretical extension of this model to 3D greatly strains such a view. In the 3D version of their model, the very ingredients of contour interpolation are the relative depths and orientations of 3D features. If the relative depths and orientations of 3D features are used at the outset to perform contour interpolation, why would the visual system not use the same relative depth information at the outset to determine the modal or amodal status of interpolated contours? Why would contour interpolation precede the designation of a contour as modal or amodal when all of the information available to do both is already available? I can see no justification for this view, and a host of data suggests that it is incorrect.

Does the preceding rule out the possibility that a common boundary interpolation process underlies modal and amodal completion? The answer depends on the meaning given to “common.” A large body of data militates against the view that an identical contour formation process underlies modal and amodal completion. However, this does not imply that contour interpolation processes do not play a role in both forms of completion (but see below). It is possible, for example, that a contour interpolation process operates in both modal and amodal completion, but if so, its modal or amodal status must be used to constrain the shapes that form from the interpolation process (cf. Singh, 2004). This is a critical difference because the main assertion of the identity hypothesis is that the modal and amodal status of the contour is determined only after completion has occurred. To my knowledge, there are currently no data to reject the possibility that a common contour interpolation process that is constrained by its modal or amodal status plays a significant role in modal and amodal completion. Nonetheless, there are theoretical reasons to question whether the division of computational labor into contour and surface mechanisms provides a reasonable framework for understanding the range phenomena from which the problems of modal and amodal completion arose. I turn to this issue next.

Are Contours and Surfaces Processed Separately?

In assessing Kellman et al.’s (2005) theory, it is important to say what the theory is about, and what it is not. Although it addresses topics in modal and amodal completion, it is not a general theory of either type of completion. The theory articulated by Kellman et al. (2005) emerged from consideration of forms of completion that arise in images containing a particular set of features, that is, contour segments to which the Gestalt notion of good continuation could be applied. Thus, by definition, this theory can only provide insight into forms of completion that involve oriented contour segments that form links along the paths to which they are oriented. Although such relationships can arise from the images projected by natural scenes, they are not the only kind of completion processes that have been documented, and the failure to consider the broader range of completion phenomena greatly restricts the scope of Kellman et al.’s (2005) theory. However, before turning to these issues, it is worth considering the ecological context in which the problems of modal and amodal completion arise, because it suggests that the division of computational labor into contour and surface processes that form the heart of their model may be misguided at the outset.

The ecological context from which the problems of modal and amodal completion arise is in the computation of occlusion relationships. Occlusion creates many difficulties in scene interpretation, but they are all related to the fact that occlusion breaks the symmetry of relative depth: Nearer surfaces occlude more distant surfaces, not vice versa. On occasion, more distant surfaces camouflage nearer surfaces, but this occurs with much less frequency than occlusion because it requires a greater set of ecological coincidences. The need for modal and amodal completion (or continuation) arises because depth differences and occlusion relationships cause the image data to be fragmented. Given their common link to occlusion, it is likely (or at least possible) that a general understanding of modal and amodal completion may emerge via a deeper understanding of the range of problems generated by occlusion and by considering the wealth of data on the variety of ways the visual system solves these problems.

With this thought in mind, let us reconsider the problem of completion within the broader context of occlusion processes. One of the core ideas in Kellman and colleagues’ model is that the computational processes used to resolve occlusion relationships can be separated into two distinct mechanisms: one that computes contours and another that computes surface properties. This division of labor is not unique to Kellman et al.’s (2005) model (see, e.g., the many incarnations of the boundary contour system–feature contour system [more commonly known as the BCS–FCS] model of Grossberg and colleagues [Grossberg, 1994, Grossberg & Mingolla, 1985]). But does this division of computational labor
make sense in the context of occlusion relationships? There is some reason to think it does not. Occlusion only occurs when a surface or object has some physical extent; contours per se cannot occlude anything. Thus, an “occluding contour” is something of a misnomer when the “contour” component is treated as a separate construct from the surface to which it is attached. Viewed in this light, it would seem to be a computationally inefficient strategy to create two entirely separate mechanisms to compute occlusion relationships, because they would always co-occur in natural scenes. Thus, one potential reason for the failure of the identity hypothesis and the relatability criteria in predicting perception may be because they assume a false dichotomy of processing stages from the outset.

In addition to theoretical considerations that suggest that the division into contour and surface processes may be incorrect, there is also a wealth of data that shows that the relatability criteria are neither necessary nor sufficient to explain when completion does and does not occur. Although a complete review of all of the data pertinent to this point is beyond the scope of this article, the following provides some particularly important results that bear on Kellman and colleagues’ theory and highlight the need to consider other forms of completion phenomena when attempting to craft a theory of modal and amodal completion.

The Insufficiency and Nonnecessity of Contour Relatability: The Role of the Occluded Contour in Modal Completion

The variants of illusory contour completion considered by Kellman et al.’s (2005) model is driven entirely by mechanisms that receive input from visible contour segments that occur along the length of the occluding contour. However, it has been known for decades that illusory contours can be induced from thin line ends that do not have any measurable orientation along the direction that the illusory contours form (see Figure 10; cf. Gillam, 1987). Such phenomena receive no explanation in Kellman et al.’s (2005) model, because they involve contours that are induced by the occluded contour segments, whereas Kellman and colleagues’ entire theory of modal completion rests on the role of the nearer, occluding contour.

Additional forms of illusory contours induced by partially occluded surfaces and contours arise in stereoscopic displays. The interocular displacement of the two eyes allows one eye to see around occluding surfaces more than the other, generating features along the more distant surface that are visible in only one of the two eyes (so-called half occlusions). Anderson (1994) and Anderson and Julesz (1995) showed that binocular occlusion junctions generate unpaired contour segments and showed that partially occluded contours elicit vivid illusory contours that appear both oriented and in depth. Malik, Anderson, and Charowhas (1999) subsequently derived a quantitative model of binocular junction geometry and showed that unpaired contour segments of partially occluded contours generate quantitative perceptions of illusory contours that appear in depth with a specific orientation. Of importance, the perceived orientation of the illusory contours did not exist in either the monococular or binocular images, and hence, the mechanisms driving illusory contour formation in Kellman et al.’s (2005) model cannot play any role in these phenomena. Moreover, these demonstrations revealed that illusory contours can be induced by a single inducing element, whereas Kellman and colleagues’ model assumes the need for a pair of inducing elements to generate modal or amodal contours (see Anderson & Julesz [1995] for a discussion of this problem). It is striking that no mention is made of the role binocularly unmatched features play in their 3D stimuli, as such features are needed to explain why percepts of occlusion are perceived in any of Kellman et al.’s (2005) stereoscopic displays. Indeed, although there is unequivocal evidence showing that unpaired features of partially occluded features are used to construct illusory contours in stereo images, there are currently no data that independently show the importance of the nearer, relatable contour segments in generating modal percepts in such displays (see Anderson & Julesz, 1995).

Gillam and Nakayama (2002) also reported forms of stereoscopic illusory contour displays that reveal the critical role of occluded contour segments. They created stereograms containing two sets of randomly oriented, abutting line segments that terminated along a single horizontal contour (see Figure 11). The relative depths of the contours in the top and bottom halves of the display were varied. In one half of the display, the contours were assigned a range of random depths (the “forest”) that appeared either behind or in front of the contours on the bottom of the display (which appeared in a single plane). They found that a vivid illusory contour formed when the plane appeared in front of the forest, but when the forest appeared in front of the plane, the illusory contour was essentially abolished. Moreover, when a small gap was introduced between the top and bottom of the display or when the two halves were interleaved, the illusory contour always appeared to terminate along the positions of the occluded forest, not along the occluding surface, again confirming the critical role of the occluded contours in illusory contour synthesis.

![Figure 10. Illusory contours induced by thin line segments (after Gillam, 1987). Vivid illusory contours are induced by thin line segments that do not have any relatable contour segments along the direction of the illusory contours. These contours are also reported to be much stronger when the line segments are randomly oriented (as in Figure 10a) than when they are all parallel (as in Figure 10b).](a)

![Figure 10.](b)
In addition to these stereoscopic phenomena, a number of monocular displays also provide significant challenges to the theory articulated by Kellman and colleagues. Early work by Gillam (1987) revealed that illusory contours induced by thin contours were much stronger when the contours were randomly oriented relative to their points of termination than when they were oriented perpendicular to these contours (Figure 10). This phenomenon cannot be understood with relatability criteria (since the contours are too thin) or with any model that simply emphasizes the local properties in these displays (indeed, most models would predict the opposite result; see the numerous variants of Grossberg and colleagues’ model; e.g., Grossberg, 1994; Grossberg & Mingolla, 1985). The idea motivating the design of these displays is that illusory contours reflect the operation of general mechanisms that compute occlusion relationships. Gillam’s (1987) hypothesis is that the perception of illusory contours should be stronger whenever there is information suggesting that a set of objects is occluded, whether or not relatable contour segments are present. Specifically, Gillam and Chan (2002) argued that occlusion interpretations, and hence illusory contours, should be more likely when edges (or line terminations) are aligned in a set of otherwise unrelated elements than when the elements are related (say, by their relative orientations). In support of this hypothesis, Gillam and Chan (2002) showed that much stronger illusory contours and percepts of occlusion were observed in displays in which the inducing elements were oriented randomly relative to a common terminating contour than in displays that contained similarly oriented inducing elements (Figure 12). Relatable contour segments were present in all of these displays, so Kellman and colleagues cannot provide any explanation of the differences in the percepts of contours observed in these images. This result clearly shows the insufficiency of relatable contour segments in predicting when illusory contours will form. Indeed, the critical image properties modulating the appearance of illusory contours in these displays is not the relatability of the contour segments along the length of the illusory contour per se but rather the regularity of the relatable contour segments relative to the pattern of orientations exhibited by the inducing elements. These results provide striking evidence that the mechanisms that underlie these phenomena depend on statistical properties of the occluded objects, not simply on the presence of relatable contour segments along the potential occluding surface.

Finally, in addition to these geometric constraints on illusory contour formation, a number of reports have also shown that the strength of illusory contours is strongly modulated by the contrast polarity of amodally interpolated occluded contours (a photometric constraint). He and Ooi (1998) showed that the vividness of illusory contours was substantially weakened if the polarity of the amodally completed inducers was reversed, whereas polarity reversals along the occluding (modally completed) contour had little impact on illusory contour strength (Figure 13). Here, too, properties of the occluded contours and surfaces play the primary role.

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in generating illusory contours, not the occluding contours that figure exclusively in Kellman and colleagues’ (2005) model.

Conclusions

In this article, I have argued that a broad range of data shows that the identity hypothesis is incorrect and that contour relatability is not necessary, sufficient, or even highly predictive of whether or when modal and amodal completion occurs. I contend that if the counterexamples against the identity hypothesis do not provide evidence that it is incorrect, then no psychophysical data can be brought to bear on the problem and, hence, that the identity hypothesis is simply untestable, at least with behavioral paradigms. Indeed, if Kellman and colleagues have abandoned their previously articulated criteria for disproving the identity hypothesis, then they need to specify exactly what kind of information would disprove their model for it to be regarded as a testable theory.

Kellman and colleagues argued that Petter’s effect, quasi-modal completion, and depth-spreading phenomena provide logical evidence for the veracity of the identity hypothesis. In the preceding sections, I have shown that the logical considerations offered by Kellman and colleagues depend either on fallacious assumptions or on specific models of the phenomena in question and, hence, in no way prove the existence of an identical contour interpolation process. Indeed, I have argued that these phenomena actually provide some of the strongest counterexamples to the identity hypothesis. Finally, I have also shown that an abundance of data shows that the reliability criteria, which form the heart of Kellman et al.’s (2005) theory, are neither necessary nor sufficient to explain completion phenomena. Further evidence for this claim was presented by Tse (1999a, 1999b).

Finally, I have argued that the recent promiscuous contour interpolation hypothesis has been primarily hypothesized because Kellman and colleagues have failed to find differences using the fat–thin task between displays that exhibit completion and those that do not. A more parsimonious interpretation of this and related results (Murray, 2002) is that the fat–thin task simply reflects processes of perceptual grouping. More critically, if the promiscuous contour interpolation process is accepted, then the theory articulated by Kellman and colleagues degenerates into the grouping principle of good continuation first articulated by the Gestalt psychologists and is therefore no more a theory of object interpolation than any other grouping principle.

In concluding, it should be noted that the critiques levied here are not intended to encompass the full range of data that bears negatively on the identity hypothesis or relatability criteria (see, e.g., Anderson et al., 2002; for further arguments). Indeed, although the discussion herein has focused on behavioral and phenomenological data, there is also a range of physiological data that directly challenges the identity hypothesis. I suggest that a much more fruitful approach to studying and modeling modal and amodal completion is to consider these phenomena within the broader context of occlusion computations and to consider all of the forms of modal and amodal completion that have been observed when attempting to fashion a theory that purports to explain these computations.

References
