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Investigating global effects in visual occlusion: from a partly occluded square to the back of a tree-trunk

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Abstract

'Classic' occlusion examples, such as a square partly occluded by a rectangle, have given rise to so-called local and global accounts of amodal completion. Without denying the influence of local configurations, I take the position that, in the long run, any theory of amodal completion should account for global properties. After a brief review of local and global accounts, two extensions of the stimulus domain are proposed to further illustrate the necessity of global accounts. The first is the domain of so-called fuzzy regularities, i.e., regularities which are not based on metrical identities. It is argued and demonstrated that observers are even susceptible to these fuzzy regularities and that they complete partly occluded shapes accordingly. The second extension is towards 3D object completion. Theories of object representation that describe intrinsic regularities of objects appear to be most suitable to predict relative preferences of alternative object completions. Consequently, fuzzy object completions, such as the completion of the back of a tree-trunk, can be explained better by global constraints. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

In our visual world, objects usually occlude parts of themselves and parts of other objects. Yet we do not have the idea of being surrounded with just object fragments. Somehow, the visual system is able to give us the impression of complete objects. In such cases, perceptual interpretations clearly exceed the information that is present in the retinal image.

In Fig. 1A, a typical textbook example of visual occlusion is shown. In principle, this pattern could be interpreted in many different ways. Usually, observers prefer a partly occluded square (Fig. 1B), which is preferred to other possible interpretations such as the 'mosaic' (Fig. 1C) or a rather arbitrary completion (Fig. 1D). This phenomenon of occlusion was first studied by Chapanis and McCleary (1953); Dinnerstein and Wertheimer (1957) and Michotte, Thinès, and Crabbé (1964). The latter scientists specifically studied the apparent ability of the visual system to fill in the missing or occluded parts and referred to it with the – still frequently used – term 'amodal completion'. Nowadays, the study of amodal completion receives considerable attention and is recognized more and more as a fundamental issue in visual perception (e.g., Boselie, 1988, 1994; Boselie & Wouterlood, 1989; Bruno, Bertamini & Domini, 1997; Buffart, Leeuwenberg & Restle, 1981; Gerbino & Salmaso, 1987; Kellman & Shipley, 1991; Sekuler & Palmer, 1992; Shore & Enns, 1997; Van Lier, Van der Helm & Leeuwenberg, 1994, 1995a).

One way to investigate preferred completions is to just ask observers to draw their interpretation of occlusion patterns (e.g., Boselie, 1988; Buffart, Leeuwenberg & Restle, 1981). This procedure has the advantage of obtaining many different spontaneous interpretations but has the disadvantage of potential sensitivity to irrelevant task influences (e.g., drawing capacities). In other studies the perceptual relevance of amodal completion has been tested by more refined experimental paradigms. For example, Gerbino and Salmaso (1987) showed the functional equivalence of partly occluded shapes and complete shapes by means of a simultaneous matching task. On

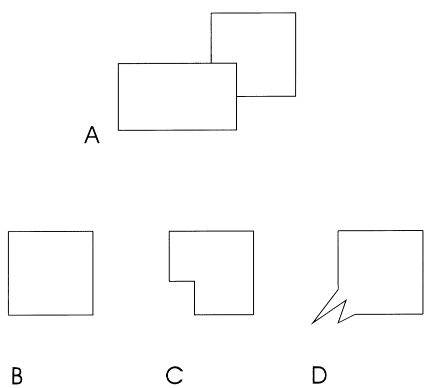


Fig. 1. A 'classic' occlusion example. Pattern A is interpreted by most observers as a rectangle which is partly occluding a square (B). Other interpretations as in C or D are also possible but less likely.

the basis of their experimental results, Gerbino and Salmaso (1987) argued that partly occluded shapes were perceived as complete by means of a possible 'automatic transformation of the visual code'. Additionally, Sekuler and Palmer (1992) studied the time course of completion by means of the primed matching paradigm. Their main result was that within a short period of time (as short as 200 ms) a partly occluded figure is perceptually represented as complete.

We take the above as support for the perceptual relevance of amodal completion (further on in this paper we will briefly return to this issue) and focus on the figural properties that determine completion. Our starting point here is the observation that when looking at a pattern such as in Fig. 1, most observers have a clear preference for one specific occlusion interpretation. Generally, there is broad consensus and consistency with respect to the preferred completions. To explain and predict perceived completions, a distinction between 'local' and 'global' accounts has often been made in the literature. In the following, I will first briefly discuss the impact of local and global figural properties and after that examine their impact on two potential extensions of the (hitherto) rather limited stimulus domain in amodal completion research.

2. Local versus global accounts

Local accounts strongly rely on the impact of local cues such as specific discontinuities of contours at points of occlusion. As a proponent of a local account, Kanizsa (1975, 1979, 1985) emphasized the role of Good Continuation in amodal completion, generally taking place at so-called T-junctions. Rock (1983) implicitly accounted for the effect of T-junctions by stating that the visual system avoids a coincidental meshing of borders: Generally, a continuation of the occluding contour at a T-junction avoids such a coincidental meshing. In recent years, Kellman and Shipley (1991) greatly influenced completion research by means of the so-called relatability criterion. This criterion predicts completion by a smooth curve whenever virtual linear extensions of contours meet behind the occluding surface at angles equal or larger than 90°.

In a critical review, however, Boselie and Wouterlood (1992) pointed out several drawbacks of the relatability criterion, and additionally demonstrated that the relatability criterion does not always predict the perceived shape correctly. Their counterexamples fall into classes such as 'relatable edges, but no completion perceived' and 'non-relatable edges, but completion perceived'. Moreover, the status of linear extensions, coterminating in one common angle, as in the 'square' interpretation of Fig. 1, is not clear in Kellman and Shipley's model. In addition, Wouterlood and Boselie (1992) developed their own local completion model, exclusively based on the principle of Good Continuation. Depending on the type of junctions between two surfaces, their model predicts either a mosaic of surfaces or a completion of one of the surfaces. In the latter case the completion always proceeds by means of a linear extension of the contours. In spite of their local account, Wouterlood and Boselie (1992) acknowledged the influence of pattern regularities on the perceptual outcome. To avoid regularity-based influences they therefore restricted the predictive domain of their model to completely irregular patterns. So, in fact, the example of Fig. 1 lies outside the stimulus domain for which Wouterlood and Boselie's (1992) model has been designed.

In contrast to local approaches, global approaches take into account shape regularities such as symmetries. Within Structural Information Theory (SIT), initiated by Leeuwenberg (1969, 1971) and further developed since then, this tendency has been operationalized by means of a regularity-based coding system. Within SIT, visual patterns are encoded by means of three different coding rules; Iteration, Symmetry and Alternation (see Van der Helm & Leeuwenberg 1991, 1996; Van der Helm, Van Lier & Leeuwenberg, 1992), and proceeds as follows. First, the encoding of a visual shape requires a mapping of the shape to a symbol series. Heuristically, this can be done by tracing the contour of the shape after having labelled all edges and angles such that equal edges and equal angles obtain equal symbols. Second, the symbol series is reduced by extracting the maximum amount of regularity from such a series (e.g., the symbol series *aaaa* can be encoded into $4*(a)$ by means of the Iteration rule; the series *abba* into $S[(a)(b)]$ by the Symmetry rule; and the series *akal* into $\langle(a)\rangle/\langle(k)(l)\rangle$ by the Alternation rule). Third, the interpretation with the simplest code, or the smallest amount of descriptive parameters (see Van der Helm et al., 1992), is predicted to be preferred. It should be noted here that the SIT account is not to be taken as an actual process account (e.g. Van der Helm & Leeuwenberg, 1996; Van Lier, 1996), but rather as an operational tool to determine regularity-based rankings of alternative pattern interpretations. Notice further that any regularity account obviously depends on the specific type of regularities that are considered (compare, for example, SIT's regularity specification with Feldman's (1999, this issue) account of potential coincidental regularities). Buffart, Leeuwenberg and Restle (1981) were the first to apply SIT to occlusion patterns. They demonstrated that completions tend to yield the most regular shapes (i.e., having the simplest codes). According to this approach, the predicted background shape of Fig. 1 would be a square as well (as it is more regular than any other interpretation). Other researchers, in turn, showed that observers do not always perceive the most regular shapes (e.g. Boselie, 1988; Boselie & Wouterlood, 1992; Rock, 1983).

Considering the debate on local and global completions, it is not surprising that both tendencies are, to a certain extent, operative in completion processes. In Van Lier, Van der Helm and Leeuwenberg (1995a) we investigated these tendencies by considering local completions (on the basis of linear good continuation, differing from, e.g., Kellman and Shipley's proposal) and global completions (considering the whole shape) for patterns in which these tendencies result in different interpretations. Figs. 2A and B shows the two patterns (derived from Van Lier, Van der Helm and Leeuwenberg, 1995a) together with their local (A1, B1) and global (A2, B2) completions. Using a drawing task and a simultaneous matching task, analogously to Gerbino and Salmaso (1987), it appeared that local and global completions were rather competitive in Pattern 2A, whereas there was a strong tendency towards the global completion in Pattern 2B. Further studies using the primed matching paradigm (Sekuler & Palmer 1992; Sekuler, Palmer & Flynn, 1994; Van Lier, Leeuwenberg & Van der Helm, 1995b) also showed that the tendency towards reg-

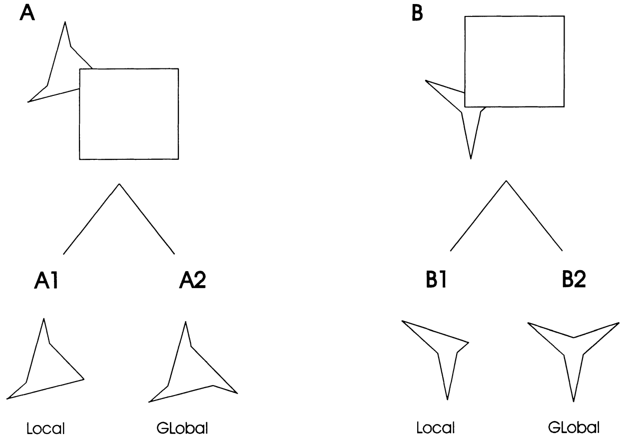


Fig. 2. Two examples of patterns for which the global completion differs from the local completion. In A, the global and local completion are competing more with each other than in B where the global completion is highly preferred.

ular completions cannot be ignored. Sekuler, Palmer and Flynn (1994), for example, concluded that global completions dominate in perceptual completion processes. In addition, Sekuler (1994) showed that the presence of certain symmetries in a completed shape facilitates that specific completion. In Van Lier, Van der Helm and Leeuwenberg (1994, 1995a) we have discussed in what way the tendencies towards regular shapes, good continuation, and the avoidance of coincidence can be unified in one regularity-based framework. I do not elaborate on those specific proposals here, but conclude this section by remarking that there is considerable evidence that strictly local accounts cannot cover the whole domain of amodal completion.

In the remainder of this paper, I discuss two extensions of the stimulus domain which pose new challenges to completion research, and which further strengthen the view that such completion models should account for global pattern properties.

3. 'Fuzzy' completion

3.1. Fuzzy regularities, fuzzy completions

In the man-made world there are many regular shapes, varying from the plug of an electronic device to a razor blade, a stapler or a fancy cookie. In many natural cases, however, perfect regularities like bilateral symmetries are exceptions. Does this imply that global completions are restricted to these man-made objects or to carefully designed laboratory stimuli? If so, local completions should be even more prevalent when regularities are just 'fuzzy'. Consider Fig. 3.

Pattern A is readily conceived as a rectangle in front of a rather ill-defined shape. How would this partly occluded shape be completed? Consider for example, Shapes B1 to B3 in Fig. 3. They are all different from each other, but all seem to be

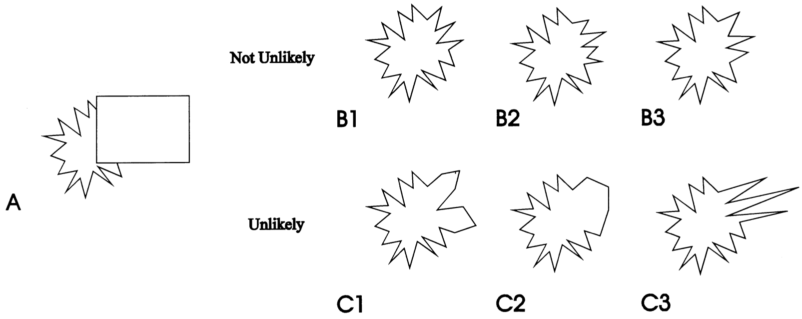


Fig. 3. Pattern A comprises a random shape partly occluded by a rectangle. B1 to B3 are all completions that are not-unlikely, whereas C1 to C3 are unlikely completions.

'reasonable' completions, although it would be remarkably surprising if an observer would produce exactly one of the depicted completions. To account for that, I will not refer to these completions as 'likely', but rather as 'not-unlikely'. In a way, the completed Shapes B1 to B3 belong to a 'family' of completions which all fit with the visible part of Pattern A. The obvious question now is, what properties determine whether a specific completion belongs to that family? Perhaps this can best be illustrated by means of a few completions which definitely do not belong to that family and which can be considered as rather unlikely (see Fig. 3, C1 to C3). In C1 and C2 the angular variation of the completed part does not seem to fit with the visible part of the shape, whereas in C3 the edges are apparently too long. In a way, only completions with edges of 'about the same size' alternating with concave and convex angles (as in B1 to B3) have a certain plausibility.

Despite this plausibility, current accounts do not predict completions as depicted in B1 to B3. As the edges at points of occlusion meet at obtuse angles, the occluding contours should be connected by means of a smooth continuation according to Kellman and Shipley's (1991) relatability criterion. Also the linear extensions as predicted by Wouterlood and Boselie's (1992) local completion model would result in rather implausible completions. So, completions like B1 to B3 are not predicted by these local accounts. However, due to the absence of perfect regularities, current global completion models would not predict B1 to B3 either. In SIT encodings, as specified thus far, Pattern A would reveal no regularity-based classification according to which B1 to B3 are to be considered as not-unlikely completions. Clearly, if the same procedure as described previously would be followed to encode Pattern A, all symbols would be different from each other and no regularity could be extracted from that series.

3.2. Toward a global account of fuzzy completion

Although current local and global accounts fail to predict fuzzy completion, only a global approach seems to allow an incorporation of that domain. To illustrate in what way fuzzy completion could be dealt with, a tentative alternative procedure to map contours to symbol series is proposed. In such an alternative semantics (i.e., mapping), different symbols do not indicate any longer whether edges or angles are metrically identical, but merely indicate different a priori categorized properties. For example, an a priori distinction could be made between concave and convex angles. In this way, the contour of the partly occluded shape in Fig. 3 can be described by means of edges of a certain length (e) alternating with concave (c) and convex angles (v). Now, the visible part of the occluded shape in Fig. 3 can be conceived as a repetition of the subseries *ecev*, or $R(ecev)$ (with the symbol R indicating an unspecified number of iterations), which can further be encoded by means of the Alternation rule into $R(\langle e\rangle/\langle(c)(v)\rangle)$. Notice that Completions B1 to B3 all fit with this code, whereas Completions C1 and C2 are not in concordance with this code. The exclusion of C3, however, would require an additional further rough distinction between 'short edges' and 'long edges'.

In Fig. 4, five other patterns are shown. Again, the edges at points of occlusion are relatable with each other. As in the previous example, we distinguish between concave (c) and convex (v) angles, but now, additionally, a rough distinction is made between short (s) and long (l) edges. The contour of the visible part of the occluded shape of Pattern 1 can now be characterized, for example, as a fuzzy repetition of a fuzzy symmetric protrusion in which a long edge, a convex angle, and a short edge are 'mirrored' about a concave angle, followed by a concave angle. The corresponding symbol series can be encoded as $R(S[(l)(v)(s),(c)]c)$ (the last concave angle

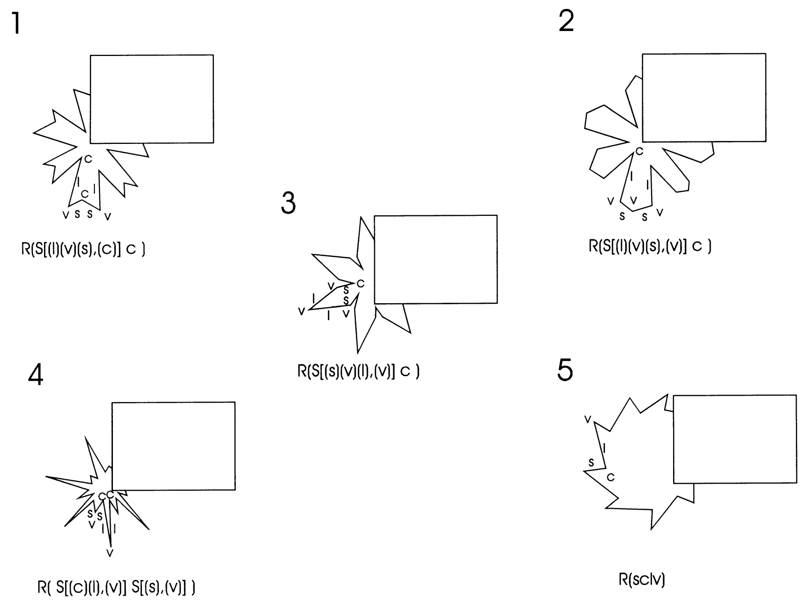


Fig. 4. These patterns all reveal partly occluded shapes that can be regarded as 'irregular' as there are no perfect metrical identities. The codes below each pattern are based on a categorical distinction between Long edges (L) versus Short (S) edges and Concave angles (C) versus Convex (V) angles.

is not included in the symmetrical substructure as such an inclusion would imply a double specification of this angle). In Fig. 4, the codes expressing the global fuzzy regularities on these binary categories are shown below each pattern.

3.3. A small fuzzy-completion experiment

In a small experiment, 15 students at the University of Leuven were asked to draw their most spontaneous completion of Pattern A in Fig. 3, and of Patterns 1–5 in Fig. 4 (presented on separate sheets of paper in random order); a procedure which has been applied more than once in the past (e.g., Buffart, Leeuwenberg & Restle, 1981; Boselie, 1988; Boselie & Wouterlood, 1989, Van Lier, Van der Helm & Leeuwenberg, 1995a). It appeared that 77% of all drawn completions fitted with classifications according to the above 'fuzzy' encodings (for Pattern A of Fig. 3, and for Patterns 1–5 of Fig. 4, the percentages were 73%, 73%, 94%, 80%, 87%, and 53%, respectively). Only 6% of all completions could be classified as local (all curved smoothly; percentages for Pattern A of Fig. 3, and for Patterns 1–5 of Fig. 4: 14%, 7%, 0%, 0%, 7%, and 7%, respectively). The remaining drawings did not fit with the global or the local notion. It should further be remarked that the drawn completions all showed clear variations in the sizes of angles and edges.

These results first of all show that the drawn completions depend on global pattern properties even while there are no perfect regularities. They further show that such an account allows classifications that agree with the drawn completions. Notice that, analogously to the application of SIT's descriptive coding system on patterns with metrical identities, SIT's encoding of fuzzy completions is to be regarded as a means to describe a class of completions based on global figural properties and does not imply actual process steps. In future research it would be worthwhile to further investigate fuzzy completion by more refined paradigms allowing to control for temporal properties (e.g., simultaneous matching paradigm, primed matching paradigm) to investigate the perceptual relevance of these completions.

3.4. More global fuzziness

In the above examples, the description and predicted completions depend on the contours in terms of edges and angles. There are, however, many other implicit shape characteristics that are extended to the completed part. Some of them may be so obvious that they are not even conceived as such. For example, the above shapes are never completed with, let us say, dashed contours (if, however, the visible contours were dashed, instead of continuous, then the completed contours would probably be dashed as well!). In the same way, the color and surface texture are likely to be extended behind an occluder (Grossberg & Mingolla, 1985; Kellman & Shipley, 1991). For example, a grey surface is likely to be continued with the same greyness (see Fig. 5A) and a textured surface is likely to be continued with the same texture (see Fig. 5B). In a recent series of experiments, Yin, Kellman and Shipley (1997) further demonstrated the visual system's tendency to complete partly occluded surfaces with the same surface features such as color or texture, or even with appropriate color gradients.

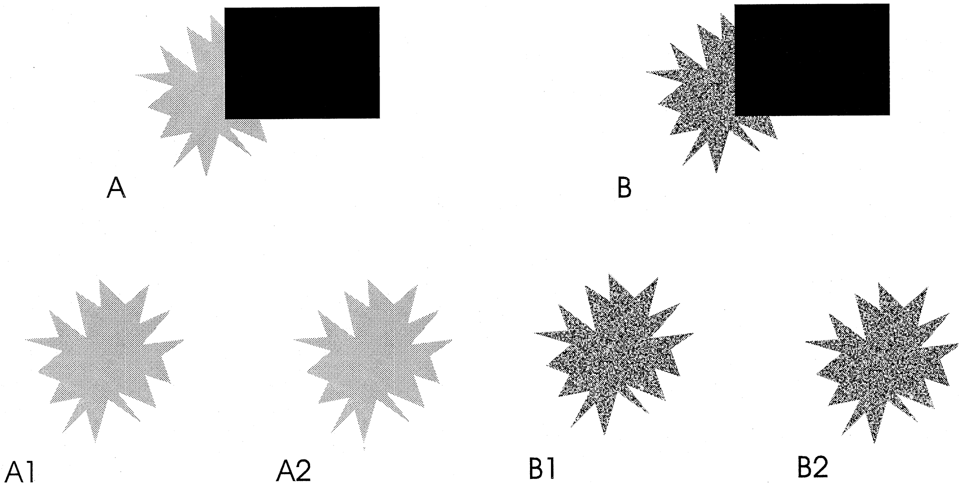


Fig. 5. The completed part of a surface has similar surface characteristics as the visible part of that surface. Therefore A1 (not A2) is a plausible completion of A, and B1 (not B2) is a plausible completion of B.

As a demonstration that completion of surface texture is susceptible to global properties as well, consider the three completions of texture elements behind the vertical bar in Fig. 6A. Panel B simply connects textural elements with each other by means of Good Continuation; Panel C completes the partly occluded oval elements, similar to the other visible oval elements; and Panel D both completes the partly occluded oval elements and adds new oval elements behind the occluder as well. There is no doubt that, of these three completions, the first is perceived as rather odd, the second as a little better, and the third as most probable.

It should, however, be noticed that there might be complex interactions between, for example, the relative size of the surface elements and the perceived completion. Kanizsa (1979), for instance, demonstrated that relatively small textural elements that seem to belong to the surface (such as the oval elements in Fig. 6) are likely to be repeated behind an occluder, whereas larger elements that are not conceived as surface texture are much more susceptible to local completion.

3.5. A compatibility criterion

In general, it can be said that the visual system's susceptibility for global pattern properties, which was already acknowledged for contour completions with metrical identities (as in Figs. 1 and 2), also holds for classes of patterns without such identities. A relevant question now is: Which completions are actually generated by the perceptual system? We previously suggested (Van Lier, Van der Helm & Leeuwenberg, 1995a) that perceived completions constitute *compatible extensions* of the visible part, thereby distinguishing between two kinds of compatibility: compatibility of elements and compatibility of regularity. Roughly, these compatibilities hold that the extended contour consists of the same elements and regularities as the visible

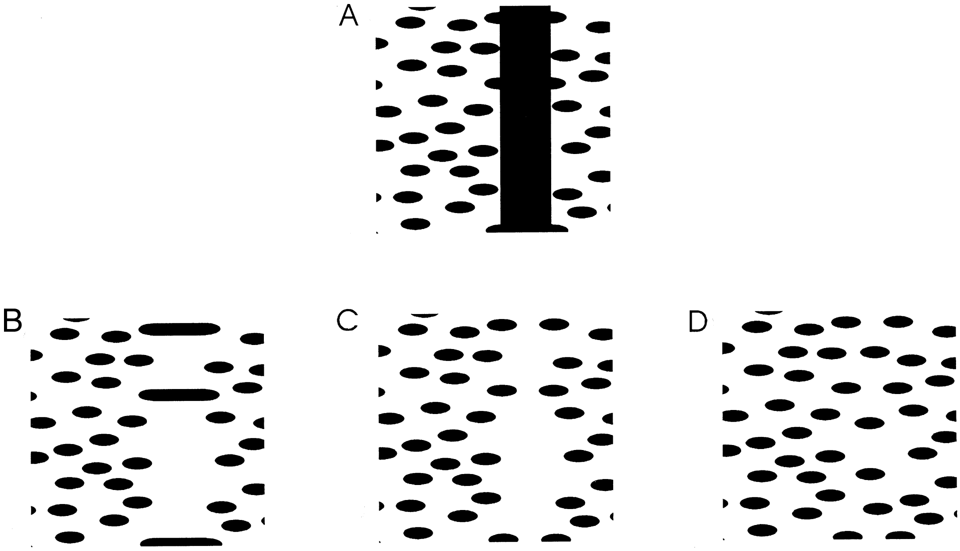


Fig. 6. In A, a textured surface, occluded by a vertical black bar, is shown. In B, an unlikely local completion of texture elements, connecting collinear edges, is shown. In C, the elements are completed globally, avoiding connection of collinear elements, but the display still reveals an unlikely white gap at the position of the occluded bar. D represents a plausible completion as the elements are completed globally and additional elements are filled in.

contour. In principle, this notion can be broadened to the fuzzy completion domain as well. By doing so, the 'elements', on which the regularity-based classifications are based, should be substituted by the categorized properties above (short edge versus long edge, concave angle versus convex angle). It is certainly not assumed that the visual system generates each and every not-unlikely completion, but it merely generates constraints on possible completions. These constraints can thus be modelled by an account of the positional distribution of certain a priori categorized properties. In future research, however, the question of which categorizations are perceptually relevant has to be subject of further investigation.

Clearly, this account of fuzzy regularities allows a more flexible modelling of the regularities in our surrounding world. In my view, allowing regularity-based description models to capture such fuzziness would further increase their perceptual relevance. Above all, it should be noted that the extension of the amodal completion domain as advocated in this section again shows that global influences play an important role.

4. Object completion

4.1. From surfaces to objects

An important further restriction of previous experimental research on amodal completion is that it always concerned completion of surfaces (either contour

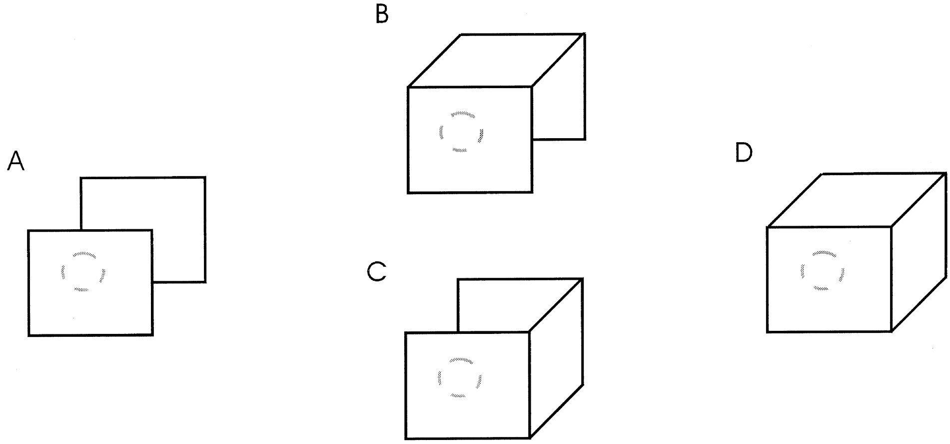


Fig. 7. Each of the four patterns (A–D) readily evoke an occlusion interpretation (e.g., a square, a table, a folded band, and a cube, respectively). The grey circle in each pattern indicates the location of the virtual angle (or vertex).

drawings or texture/color filled images), preferably arranged in parallel depth planes. It is somewhat peculiar that solid 3D objects are hardly considered in completion research. Recent studies to bridge the gap between surface completion and object completion have been made by Van Lier and Wagemans (1999) and by Tse (1999). This restriction of the stimulus domain may have influenced models on visual completion and vice versa. However, ultimately, an all-embracing explanatory completion model has to face the full domain of visual occlusion. Obviously, the completion of 3D objects belongs to that domain. Let us again consider the impact of local and global properties.

Each of the patterns in Fig. 7 easily evokes an occlusion interpretation. Pattern A is by most perceivers seen as two squares arranged in depth, one occluding another, whereas Patterns B to D are readily seen as 3D objects (e.g., a table, a folded band, and a cube, respectively). The completion in A can be explained by a local account according to which edges are linearly extended at both T-junctions and comprises a virtual angle (indicated by the grey circle in Fig. 7). In B and C there is just one such local cue, yet there still is a compelling occlusion interpretation comprising a virtual angle. Finally, in Pattern D there is no local occlusion cue at all. Nevertheless, the cube interpretation should in fact also be considered as an occlusion interpretation (comprising a virtual vertex located at the same 2D position). Considering these examples, it is clear that in the absence of local occlusion cues, occlusion interpretations may still be rather compelling.

4.2. *Global versus local object completion*

As a further demonstration that nonlocal properties intermediate in completions of self-occluded parts, consider the images in Figs. 8A and B (derived from Van Lier & Wagemans, 1999). These images are readily interpreted as three-dimensional objects; cubes with two indentations, one at the front and one at the back. In A, the height of the front indentation is one third of the side of the 'cube' (short indentation), whereas in B it stretches from top to bottom (long indentation). For both objects, the rear indentation is rather ambiguous as only the width and the depth are visible. Notice that, locally, the edges near that indentation are the same for A and B. Two possible completions of the rear indentation are made visible by a depth-rotation of the objects about the vertical axis. In A1 the completion implies a repetition of the short front indentation and can be regarded as a completion following global simplicity. The completion in A2 can be considered as locally simplest as it consists of only straight contours (and lacks the additional horizontal rear surface as in A1). Completion B1 can be regarded as both globally and locally simplest as it repeats the front indentation (as in A1) and consists of simple straight contours (as in A2). Finally, completion B2 can be regarded as rather anomalous.

In Van Lier and Wagemans (1999) a matching task was employed to test preferences for one or the other completion on a variety of stimuli as discussed above. In the experiments, two different 2D images were shown. One of the images always had an ambiguous rear indentation (as in Figs. 8A and B), whereas in the other image this rear indentation was disambiguated by a depth-rotation (as in A1, A2, B1, and B2). Participants were asked to respond whether the two images could be of the same object (Yes/No). It appeared that completions that were both Global and Local were highly preferred to completions that were both Non-Global and Non-Local, and that there was much more competition between the Global/Non-Local and Non-global/Local completions (these results persisted after having experimentally controlled for potential effects of different complexities due to the specific completions). Moreover, the preference for global completions depended on the degree of object symmetry obtained by that completion. As there are no local differences between the contours that constitute the rear indentation, Van Lier and Wagemans (1999)

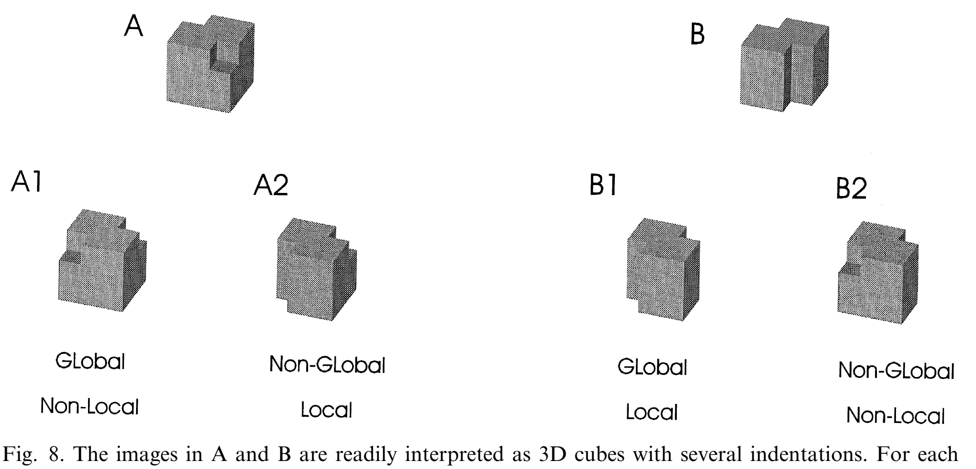


Fig. 8. The images in A and B are readily interpreted as 3D cubes with several indentations. For each object, two completions of the ambiguous rear indentation are shown (A1, A2, B1, and B2) by means of a depth-rotation of that object.

concluded that global inferences accounting for different intrinsic object properties (such as symmetries) must have caused these relative preferences. This pattern of results is in line with Sekuler (1994) and Van Lier, Van der Helm and Leeuwenberg (1995a) in which the competition between global and local completions was already acknowledged for 2D contour completion. Given this relevance of global and local completions and given the fact that there are no differential local cues, it is clear that any adequate explanation of this pattern of results should account for intrinsic object regularities.

4.3. Toward a global account of object completion

As intrinsic object regularities appear to play a crucial role in object completion, the SIT approach seems to be an appropriate candidate to predict specific completions for the above images. SIT's object descriptions can be regarded as a 3D extension of its 2D descriptions and often imply a decomposition into hierarchically related components (for a discussion, see; Leeuwenberg & Van der Helm, 1991; Leeuwenberg, Van der Helm & Van Lier, 1994; Van Lier, Leeuwenberg & Van der Helm, 1997; Van Lier & Wagemans, 1999). The determination of the specific complexities of the global and local object completions (which is actually performed in Van Lier & Wagemans, 1999) would lead beyond the scope of this article, but it will be clear that, just as with 2D patterns, interpretations with high intrinsic regularities generally reveal low complexities. The quantitative analysis of Van Lier and Wagemans (1999) showed that, on the whole, the larger the difference in object regularities between alternative completions of a specific image was, the greater was the preference for the simplest interpretation. Beside this observed tendency to complete objects in regular ways, Van Lier and Wagemans (1999) further found some indication that regularities in the top surface of an object are most important with respect to the perceived completion. With that, findings on object completion almost inevitably touch issues that are closely related to ongoing research on object recognition such as viewpoint dependency versus viewpoint independency (see for example: Biederman & Gerhardstein 1993; Tarr, 1995; and see for related papers on this topic in this issue: Kourtzi & Shiffrar, 1999; Lawson, 1999; Wraga, Creem & Proffitt, 1999). We argued (Van Lier & Wagemans, 1999) that viewpoint independent descriptions (as in SIT) are most suitable for explaining the visual system's susceptibility to complete objects in globally, intrinsically regular, ways. In future studies, however the precise nature of, and eventual interactions between, viewpoint independent and viewpoint dependent properties on object completion would be an important goal.

4.4. More global object completions

As with surface completion, one important result in this line of research stands out, namely that, again, purely local accounts cannot hold. As global accounts aim at a description of the whole (i.e., complete) object, instead of just the completed part of that object, the predicted completion is necessarily much more integrated in the

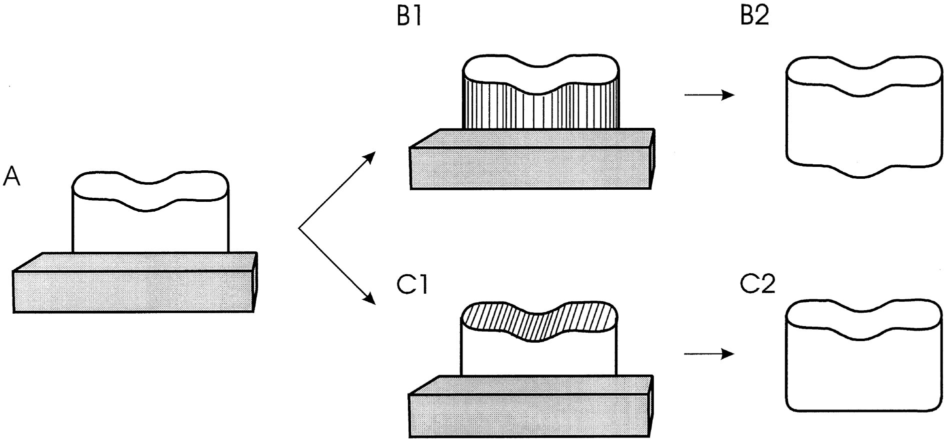


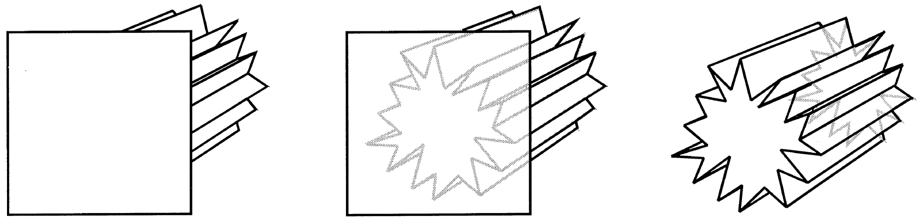
Fig. 9. In A, one object is partly occluded by another object. The completion actually depends on the way the curvature in this object is interpreted: frontwards (B_1, B_2) or downwards (C_1, C_2).

way images are actually interpreted. In Fig. 9A, for example, the exact shape of the curved object and – with that – its completion clearly depends on the specific 3D interpretation. If in Fig. 9A, the curvature in the partly occluded object is interpreted as 'frontwards', inclined towards the observer as suggested in B1, then the perceived completed part is likely to be as in B2. If, however, the curvature is interpreted as 'downwards', as suggested in C1 (like a flat battery), then the perceived completed part could very well be as depicted in C2 (in the same way, the perception of the back of the objects obviously depends on the specific interpretation as well). Again, the competition between these object completions cannot be derived from local cues such as the specific junction types at points of occlusion, but is an inextricable part of the specific global object interpretations, guided by figural properties (which may have considerable spatial distance from the occluded part itself).

As with fuzzy 2D completion discussed previously, the influence of global properties also holds for 'irregular' 3D object completions. This can easily be demonstrated, as illustrated in Fig. 10A. The drawing is readily perceived as an irregular object, partly occluded behind a vertical screen. A 'not-unlikely' completion behind the screen is given in Fig. 10B. Additionally, in Fig. 10C the corresponding completion of the self-occluded back of the object is made visible. Just as with the previously discussed fuzzy 2D completions, the shown object seems to be exemplary for a whole family of not-unlikely completions (other not-unlikely object completions can easily be imagined by the reader).

4.5. Fuzzy 3D completion: a perceptual phenomenon?

For rather simple partly occluded shapes, such as a partly occluded square, it has not only been shown that they are preferred as being complete when observers are asked to give their preferred interpretation, but it has also been shown in more



A B C

Fig. 10. Pattern A shows an irregular object behind a vertical screen. Although there is only very little visible of this object, most observers have clear ideas about its shape. In B, a not-unlikely completion of the object part occluded by the screen is shown. In C, the corresponding completion due to self-occlusion is shown. It is not clear how a local completion model could account for these completions.

refined perceptual tasks that they are perceptually treated as complete (Gerbino & Salmaso, 1987; Sekuler & Palmer, 1992). Despite this functional equivalence between partly occluded shapes and complete shapes one may still question how 'visual' amodal completion is. This is not a simple question and it is actually not unique for amodal completion. In the domain of 'mental imagery', (i.e., the ability to mentally 'see' a scene or object), this question was also raised by various researchers (e.g., Farah, 1988). Modality specific areas in the cortex appear to be involved in both sensory visual perception and mental imagery (see for an overview: Farah, 1995). Without claiming the equivalence between imagery and completion, it seems reasonable that the latter phenomenon shares subsets of the brain's visual areas as well. This is perhaps even more plausible if one considers that amodal completion is typically cued visually and not verbally (as is often the case in imagery).

Object completions in daily life certainly go beyond local and global completions as specified thus far. The trunk of a tree, for example, may consist of holes and humps with varying textures, different gradients of colors, cleaved with shallow and deep grains, curling unpredictable routes in many different directions. Most of us will now have a visualized idea, a mental image, about this tree-trunk. Replacing the above description by a picture representing one specific view, again would evoke a representation of a complete trunk. In spite of the seeming complexity of the visible parts we have very clear ideas about the unseen side of the trunk; the extension always resembles certain characteristics of its visible part. Now, let us compare this tree-trunk picture with the partly occluded square drawing. To what extent does the perception of the back of a tree-trunk differ qualitatively from the perception of a partly occluded square? Certainly, the latter leads to a much more unique interpretation which is shared by most observers, but does this mean that the completion of an occluded square is more perceptual than the completion of the back of a tree-trunk? Can we still regard such rather vague interpretations as output of the perceptual system?

In my view, the answer lies in a distinction between the perceptual constraints on completions and the specific post-perceptual choice for one or the other completion.

In this view, perception runs its own course and is not affected by knowledge (e.g., Kanizsa, 1985; Kanizsa & Gerbino, 1982). Such knowledge-independency fits in with the previously discussed notion that the perceptual system's output imposes compatibility constraints on possible completions. Whenever these constraints imply that the class of possible completions consists of just a limited number of completions, the completions are typically very compelling. In such rather simplified cases the process may only *seem* to be more perceptual than for example in fuzzy surface completion (as in Fig. 3) or fuzzy object completion (as in Fig. 10, or the tree-trunk case) which, in turn, may only *seem* to be less perceptual. Whereas, for both the partly occluded square and the tree-trunk the descriptive class of not-unlikely completions can be regarded as a product of the perceptual system, the choice for any *specific* not-unlikely completion goes beyond this point and belongs to the post-perceptual domain. The larger the family of not-unlikely completions, the greater the subjective impression will be that the visual system leaves the occluded part unspecified and that the completion is 'invented' by the cognitive system. Nevertheless, the choice for a specific fuzzy object completion is, in my view, initially determined by the perceptual output. However, notice that this view does not exclude that, in a post-perceptual stage, stored knowledge of real-world objects may further affect the ultimate observer's preference for a specific interpretation.

The question of which visuo-cognitive processes are involved in the actual selection of one specific interpretation provides an interesting future research issue (which will certainly not be an easy task to fulfil as, for example, visual cortex activations might even be triggered by intentional post-perceptual selections of interpretations). So far, however, the convergence from all possible completions to a small set of preferred completions, the intra/inter observer consistency of these preferences, and their dependency on figural properties, clearly justify the study of completion preferences as such. The broadening of the stimulus domain further shows the decisive influence of global figural properties in visual occlusion and amodal completion.

5. Conclusion

Research on visual occlusion and amodal completion has been traditionally constrained to a rather limited stimulus domain. To bridge the whole range of stimuli between extremes like a partly occluded square and the back of a tree-trunk, strictly local explanations fall short. Although a full account cannot be given so far, global approaches have the best chances to provide accurate predictions on the discussed fuzzy and 3D completion phenomena.

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References

Biederman, I., & Gerhardstein, P. (1993). Recognizing depth-rotated objects: evidence and conditions for three-dimensional viewpoint invariance. *Journal of Experimental Psychology: Human Perception and Performance*, *19*, 1162–1182.

Boselie, F. (1988). Local versus global minima in visual pattern completion. *Perception & Psychophysics*, *43*, 431–445.

Boselie, F. (1994). Local and global factors in visual occlusion. *Perception*, *23*, 517–528.

Boselie, F., & Wouterlood, D. (1989). The minimum principle and visual pattern completion. *Psychological Research*, *51*, 93–101.

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

Bruno, N., Bertamini, M., & Domini, F. (1997). Amodal completion of partly occluded surfaces: Is there a mosaic stage?. *Journal of Experimental Psychology: Human Perception & Performance*, *23*, 1412–1426.

Buffart, H., Leeuwenberg, E., & Restle, F. (1981). Coding theory of visual pattern completion. *Journal of Experimental Psychology: Human Perception and Performance*, *7*, 241–274.

Chapanis, A., & McCleary, R. (1953). Interposition as a cue for the perception of relative distance. *Journal of General Psychology*, *48*, 113–132.

Dinnerstein, D., & Wertheimer, M. (1957). Some determinants of phenomenal overlapping. *American Journal of Psychology*, *70*, 21–37.

Farah, M. (1988). Is visual imagery really visual: Overlooked evidence from neuropsychology. *Psychological Review*, *95*, 307–317.

Farah, M. (1995). The neural basis of mental imagery. In M. Gazzaniga, *The cognitive neuroscience* (pp. 963–975). Cambridge, London: MIT Press.

Feldman, J. (1999). The role of objects in perceptual grouping. *Acta Psychologica*, *102,* 137–163.

Gerbino, W., & Salmaso, D. (1987). The effect of amodal completion on visual matching. *Acta Psychologica*, *65*, 25–46.

Grossberg, S., & Mingolla, E. (1985). Neural dynamics of form perception: boundary completion, illusory figures, and neon color spreading. *Psychological Review*, *92*, 173–211.

Kanizsa, G. (1975). The role of regularity in perceptual organization. In Flores d'Arcais, *Studies in perception* (pp. 48–66). Firenze, Italy: Martello.

Kanizsa, G., (1979). *Organization in Vision: Essays on Gestalt Perception.* New York: Praeger.

Kanizsa, G. (1985). Seeing and thinking. *Acta Psychologica*, *59*, 23–33.

Kanizsa, G., & Gerbino, W. (1982). Amodal completion: Seeing or thinking? In J. Beck, *Organization and representation in perception* (pp. 167–190). Hillsdale, NJ: Erlbaum.

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

Kourtzi, Z., & Shiffrar, M. (1999). The visual representation of three dimensional, rotating objects. *Acta Psychologica*, *102*, 265–292.

Lawson, R. (1999). Achieving visual object constancy across plane rotation and depth rotation. *Acta Psychologica*, *102*, 221–245.

Leeuwenberg, E. (1969). Quantitative specification of information in sequential patterns. *Psychological Review*, *76*, 216–220.

Leeuwenberg, E. (1971). A perceptual coding language for visual and auditory patterns. *American Journal of Psychology*, *84*, 307–349.

Leeuwenberg, E., & Van der Helm, P. (1991). Unity and variety in visual form. *Perception*, *20*, 595–622.

Leeuwenberg, E., Van der Helm, P., & Van Lier, R. (1994). From geons to structure. A note on object representation. *Perception*, *23*, 505–515.

Michotte, A., Thinès, G., & Crabbé, G. (1964). Les compléments amodaux des structures perceptives The amodal completion of perceptive structures. *Studia Psychologica.* Louvain, Belgium: Publications Universitaires de Louvain.

Rock, I. (1983). *The logic of perception.* Cambridge (MA): MIT Press.

Sekuler, A. (1994). Local and global minima in visual completion: effects of symmetry and orientation. *Perception*, *23*, 529–545.

Sekuler, A., & Palmer, S. (1992). Perception of partly occluded objects: a microgenetic analysis. *Journal of Experimental Psychology: General*, *121*, 95–111.

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

Shore, D., & Enns, T. (1997). Shape completion time depends on the size of the occluded region. *Journal of Experimental Psychology: Human Perception and Performance*, *23*, 980–998.

Tarr, M. (1995). Rotating objects to recognize them: a case study on the role of viewpoint dependency in the recognition of three-dimensional objects. *Psychonomic Bulletin and Review*, *2*, 55–82.

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

Van der Helm, P., & Leeuwenberg, E. (1991). Accessibility, a criterion for regularity and hierarchy in visual pattern codes. *Journal of Mathematical Psychology*, *35*, 151–213.

Van der Helm, P., & Leeuwenberg, E. (1996). Goodness of visual regularities: a non-transformational approach. *Psychological Review*, *103*, 429–456.

Van der Helm, P., Van Lier, R., & Leeuwenberg, E. (1992). Serial pattern complexity: irregularity and hierarchy. *Perception*, *21*, 517–544.

Van Lier, R. (1996). *Simplicity of visual shape: A structural information approach.* Ph.D. Thesis, University of Nijmegen.

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

Van Lier, R., Van der Helm, P., & Leeuwenberg, E. (1995a). Competing global and local completions in visual occlusion. *Journal of Experimental Psychology: Human Perception and Performance*, *21*, 571–583.

Van Lier, R., Leeuwenberg, E., & Van der Helm, P. (1995b). Multiple completions primed by occlusion patterns. *Perception*, *24*, 727–740.

Van Lier, R., Leeuwenberg, E., & Van der Helm, P. (1997). In support of hierarchy in object representations. *Psychological Research*, *60*, 134–143.

Van Lier, R., & Wagemans, J. (1999). From images to objects: Global and local completions of self-occluded parts. *Journal of Experimental Psychology: Human Perception and Performance*, in Press.

Wraga, M., Creem, S., & Proffitt, D. (1999). The influence of spatial reference frames on imagined object- and viewer rotations. *Acta Psychologica*, *102*, 247–264.

Wouterlood, D., & Boselie, F. (1992). A good-continuation model of some occlusion phenomena. *Psychological Research*, *54*, 267–277.

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