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From Images to Objects: Global and Local Completions of Self-Occluded Parts

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When solid objects are viewed from only 1 direction, some parts are necessarily occluded. Expectations about possible completions of novel objects (cubes with indentations) were measured by the response times to determine whether 2 images could be 2 depth-rotated views of the same object. Completions are considered global if the completed indentations are identical to the visible indentations (i.e., they are globally simple because of the repetitions) and are considered local if they are locally simple (e.g., straight contours with a minimal number of additional surfaces). The results of 3 experiments showed that local and global completion tendencies that were well established for 2-dimensional surfaces appear valid for 3-dimensional objects as well. Also, it is shown that structural object aspects play an important role in object completion.

The interpretation of the visual environment typically exceeds the information that meets the eye. Objects occlude parts of other objects and parts of themselves. Yet, people do not experience an incomplete, fragmented world. In Figure 1, two examples of visual occlusion are given. Most perceivers will readily interpret the pattern in Figure 1A as a configuration in which two surfaces are arranged in depth, one surface partly occluding another. Although many other interpretations are possible (e.g., the interpretation in Figure 1C), there is a general preference for just one interpretation, a square partly occluded by a rectangle (Figure 1B). In Figure 1D, an example of self-occlusion is given in which a three-dimensional (3D) object occludes part of itself. The drawing is spontaneously seen by most observers as a truncated cone, although other 3D interpretations are possible as well. Figure 1E and Figure 1F show two possible rotated views of D in which the rear becomes visible. Obviously, E is strongly preferred to F.

From examples such as the preceding, it is clear that observers spontaneously interpret certain visual patterns as cases of occlusion. Moreover, the visual system seems to be able to complete or to fill in the nonvisible parts. This capability of the visual system has gained considerable attention during past decades for flat surfaces arranged in depth (as in Figure 1A), but it has, to our knowledge, not been studied so far for 3D objects occluding parts of themselves (as in Figure 1D). This is rather surprising for a phenomenon that is so closely related to 3D object perception. In this article, we extend the study of completion to 3D object occlusion. Before elaborating on 3D object occlusion, we first review some relevant research in the domain of two-dimensional (2D) surface completion.

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Surface Completion

Within the domain of surface occlusion, several studies have investigated under which conditions occlusion occurs and what the preferred shapes of the background surface look like (e.g., Boselie, 1988; Boselie & Wouterlood, 1989; Bruno, Bertamini, & Domini, 1997; Buffart, Leeuwenberg, & Restle, 1981; Chapanis & McCleary, 1953; Dinnerstein & Wertheimer, 1957; Gerbino & Salmaso, 1987; Kanizsa & Gerbino, 1982; Kellman & Shipley, 1991; Michotte, Thinès, & Crabbé, 1964; Sekuler & Palmer, 1992; Shore & Enns, 1997; Van Lier, Leeuwenberg, & Van der Helm, 1995; Van Lier, Van der Helm, & Leeuwenberg, 1994, 1995; Wouterlood & Boselie, 1992). The kind of pattern in Figure 1A has been studied extensively in various experimental paradigms, including paper-and-pencil drawing tasks (Boselie, 1988; Buffart et al., 1981), simultaneous matching tasks (Gerbino & Salmaso, 1987), and the so-called primed-matching paradigm (Sekuler & Palmer, 1992). Although there were considerable differences in experimental and theoretical goals and achievements, all of these studies confirmed that

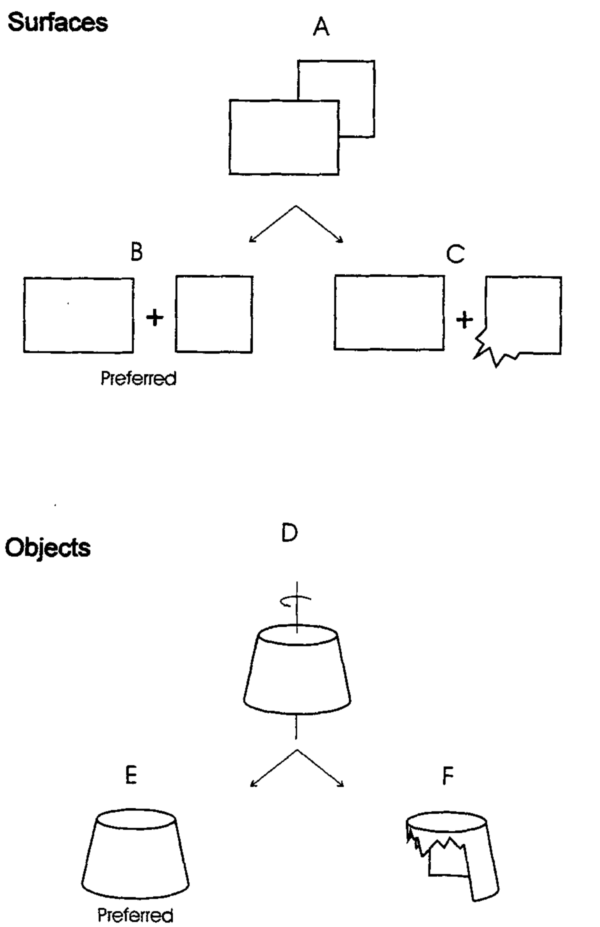

Figure 1. Two examples of occlusion and preferred completions. A is interpreted as 2 two-dimensional surfaces arranged in depth, a rectangle partly occluding another surface. Most observers strongly prefer B to C. D is interpreted as a three-dimensional object, a truncated cone occluding its rear. E and F represent two depth-rotated versions of D. Clearly, the rear as given in E is strongly preferred to the rear as given in F.

observers have very specific preferences for particular shapes.

Two kinds of surface completions are often distinguished: global completions and local completions (e.g., Boselie, 1988, 1994; Sekuler, 1994; Sekuler, Palmer, & Flynn, 1994; Van Lier, Leeuwenberg, & Van der Helm, 1995; Van Lier, Van der Helm, & Leeuwenberg, 1994, 1995). Typically, global completions depend on global properties such as overall regularities of the occluded shape, whereas local completions are mainly triggered by certain local cues and are not influenced by overall regularities. The prevalence of both types of completions in the past has led to theories stressing either one or the other tendency. Several researchers (e.g., Kellman & Shipley, 1991; Takeichi, Murakami, Nakazawa, & Shimojo, 1995; Wouterlood & Boselie, 1992) have proposed models in which the local tendency prevails, although their theories and implications differ widely. Other researchers (e.g., Buffart et al., 1981) have focused on an overall tendency toward global completions. Finally, in comparing global and local completions, several researchers have stated the relevance of both types of completion (e.g., Boselie, 1988, 1994; Sekuler, 1994; Van Lier, Leeuwenberg, & Van der Helm, 1995; Van Lier, Van der Helm, & Leeuwenberg, 1994).

In this article, we make a distinction based on the notions of global and local completions as used by Van Lier, Van der Helm, and Leeuwenberg (1995), focusing on the simplicity of the entire background shape in the case of global completion and the simplicity of the completed part of the background shape in the case of local completion. Patterns A and B in Figure 2 exemplify these notions. Each of four possible combinations of the presence or absence of a global completion tendency (indicated by G^+ and G^-, respectively) and the presence or absence of a local completion tendency (indicated by L^+ and L^-, respectively) is illustrated. A1 is classified as G^+L^- (the completion part repeats the "battlements" behind the occluder but is rather complex locally). In contrast, A2 is classified as G^-L^+ (no global completion tendency but a simple completed part based on a linear extension of the occluded contours). B1 is classified as G^+L^+ (it repeats the bottom contour and left contour behind the occluder and is based on a local completion tendency similar to A2). Finally, B2 is classified as G^-L^-. Note that we have illustrated global completions by means of just one type of regularity, namely repetition. Obviously, other types of regularity could be considered as well. For example, A1 and B1 also appear to be more symmetrical than A2 and B2, respectively.

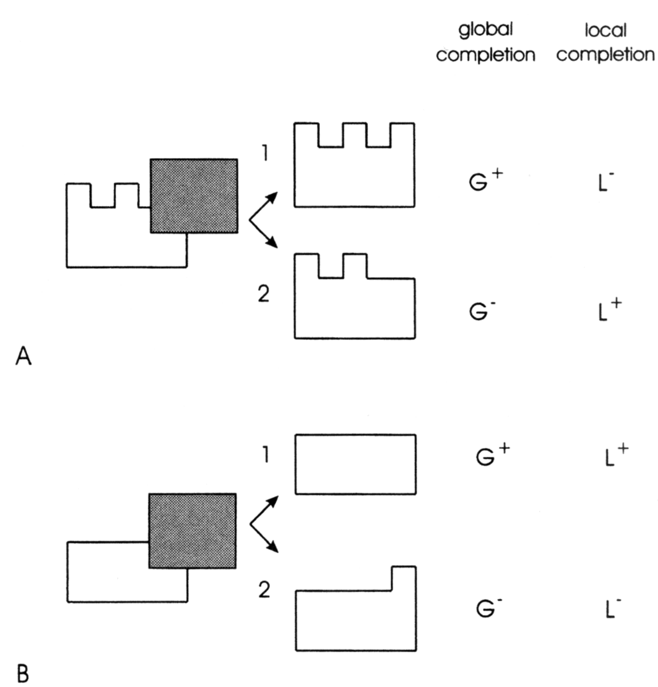

Figure 2. Two patterns with two possible completions. Each completion can be independently classified as global (G^+) or nonglobal (G^-) and as local (L^+) or nonlocal (L^-).

Considering Patterns A and B and their global and local completions, it can be seen that for Pattern A, global and local completion strategies diverge to different completions, whereas for Pattern B, they converge to the same completion. Van Lier, Van der Helm, and Leeuwenberg (1995) showed that completions for the first type of pattern were more ambiguous than completions for the latter type, supporting the notion of a competition between global and local completions. One aim of this article is to study the relevance of global and local completions in the domain of 3D object completion and to extend the global–local discussion from 2D surface completion toward 3D object completion.

Object Completion

The central question asked here is whether observers spontaneously generate global or local completions of the back of an object. In 3D visual space, expectations of the back of an object can be verified by two different actions. One is varying the viewer's position, and the other is varying the object's position (e.g., Lowe, 1987). In the present study, the back of an object is revealed by means of a depth-rotated view of the distal object. With respect to simple and highly symmetrical objects, such as the truncated cone of Figure 1D, it might be quite evident to most observers what the rear looks like. However, as with 2D surface completion, such a tendency toward one specific 3D interpretation is often less compelling. For example, Rock and DiVita (1987) and Rock, Wheeler, and Tudor (1989) asked whether observers could imagine how objects would look from other viewpoints. These studies, however, intentionally minimized possible effects of occlusion, in that the stimuli consisted of wire frames. Biederman and Gerhardstein (1993) more specifically tested the effect of occlusion on object matching. In one of their experiments, they asked participants to indicate whether two sequentially presented pictures were of the same object. It appeared that qualitatively different object views, as a result of differential occlusion of certain object parts (cf. Koenderink, 1990), were matched much slower and with less accuracy than if the different views were not qualitatively different. Typically, objects with the same qualitative view could be decomposed in the same volumetric components (i.e., geon components, in line with Biederman's [1987] recognition-by-components theory), whereas objects with different qualitative views revealed different volumetric components as a result of occlusion of the rear component. Biederman and Gerhardstein (1993), however, did not specifically investigate whether properties of the visible part of an object could have differential effects on the unseen rear part of an object, which is our main focus here. We exemplify our specific interest by means of the object views in Figure 3.

The left object view in Figure 3A is readily interpreted as an image of a cube with two indentations, one at the front and one at the rear (note that the terms *front* and *rear* refer not to object intrinsic qualities but simply to object sides as they appear in the 2D images in the 0° orientation). Whereas the depth, width, and height of the front indentation are clear

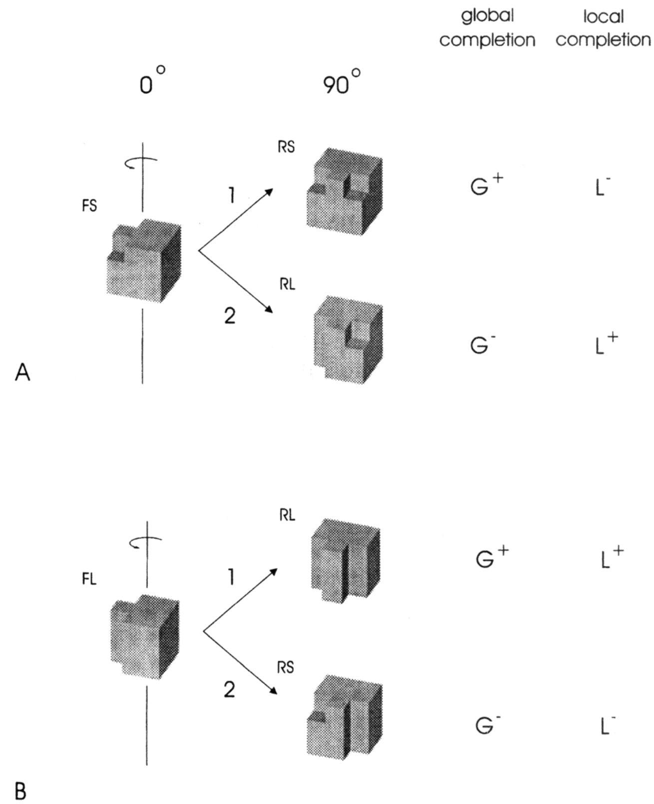

Figure 3. Two images of objects with two possible object completions. The objects can be regarded as cubes with different indentations. A: The object on the left has a short front indentation (FS). B: The object on the left has a long front indentation (FL). In A and B, the ambiguous rear indentations are disambiguated in the images on the right, revealing either a short rear indentation (RS) or a long rear indentation (RL). Each completion can be independently classified as global (G^+) or nonglobal (G^-) and as local (L^+) or nonlocal (L^-).

from the image, the shape of the rear indentation is ambiguous because, as a result of self-occlusion, only two dimensions (depth and width) are visible. In A1 and A2, two possible 90° depth-rotated versions of A are shown. Now, A's rear indentation is disambiguated because all dimensions of A's rear indentation become visible. Note that the resulting images can be regarded as different interpretations of A. A1 shows a short rear indentation identical to A's front indentation. A2 shows a long rear indentation extending from top to bottom. In the following, short and long rear indentations are referred to by RS and RL, respectively. In the same way, short and long front indentations are referred to by FS and FL, respectively. An example of the latter is given in Figure 3B, in which the 0° view has an FL. B1 and B2 are again two 90° depth-rotated versions in which the rear indentation is disambiguated. In B1 the rear indentation is identical to the front indentation, which now is the long indentation, whereas in B2 the rear indentation is the same size as in A1. We use these kinds of stimuli to examine whether different fronts (FS vs. FL) have differential effects on different completions (RS vs. RL) of identical ambiguous rears, comparable to the established global and local completions in 2D surface completion.

Global Versus Local Object Completions

As with surface completions, we consider global object completions to be dependent on overall regularities, whereas this is not the case for local object completions. To classify global object completions, we use a rather general but intuitively plausible notion of repetition-based regularity similar to the one applied with respect to the surface completions of Figure 2. If the completion of the rear indentation implies a repetition of the front indentation (i.e., if the front and rear indentation are the same), we consider the completion as global. In addition, a completion is referred to as local if the rear indentation consists of simple straight contours with a minimum of other surfaces. Thus, the local completion does not necessarily imply a repetition of the front indentation. Note that, as with surface completions, the various relative positions of equal front and rear indentations may induce other object regularities such as mirror symmetries. Obviously, the classification depends on the notion of regularity used. Other object regularities (e.g., mirror symmetry) could be considered as well. In a later section of this article, the role of these other object regularities in completion is investigated in greater detail.

Each of the completions in Figure 3 can be classified according to the preceding conventions. A1 is classified as G^+L^- (it repeats the front indentation at the rear, but the completion is rather complex in that it comprises an additional horizontal surface). In contrast, A2 is classified as G^-L^+ (different front and rear indentations but a simple completed rear indentation comprising only simple straight contours). B1 is classified as G^+L^+ (it both repeats the front indentation and has a simple completed rear indentation comparable to the completed rear indentation of A2). Finally, B2 is classified as G^-L^- (the completed rear indentation does not have either of these properties). Note further that, for the 0° view in Figure 3A, the global and local completion strategies diverge to different object interpretations, whereas, for the 0° view in Figure 3B, global and local completion strategies converge to the same object interpretation.

In the experiments described here, we examined whether the relevance and competition of global and local completions, previously demonstrated in the domain of surface completion, also hold for the domain of object completion. This issue is not only relevant to completion as such but is also of central importance to object perception in general. It may help to reveal spontaneous tendencies in the visual system to interpret 2D images as particular 3D objects. In the final part of this article, we investigate how well the observed completion tendencies can be explained by various notions of object regularity.

Experiment 1

To investigate relative preferences between global and local object completions, we used a simultaneous matching task. In a typical trial, two object images had to be compared with each other (such as in Figure 3). These object images could be two depth-rotated views of the same object (match condition) or of different objects (mismatch condition). Because the matching of depth-rotated views is used only as a method to investigate preferred completions, the task itself is kept fairly simple, and potential task-related influences are minimized. For example, to avoid differential effects on response times (RTs) of the rotation angle (i.e., the independent variable par excellence if one is interested in mental rotation; e.g., R. Shepard & Metzler, 1971), the angle is kept constant over all trials. Furthermore, because the choice of the orientation axis is known to affect RTs, all rotations are about the vertical axis, which has been proved to be rather easy for most observers (Pani, 1999; Parsons, 1995; Shiffrar & Shepard, 1991).

Method

Participants. Eighteen undergraduate students participated in the experiment. They were all naive with respect to the goal and the design of the experiment.

Stimuli. The stimuli were constructed with the aid of the 3DSTUDIO software package (Autodesk Inc.). Construction of the stimulus objects started with a "basic cube." The 2D projection of the cube was orthographic. Next, one or more indentations were made in the cube. As shown in Figure 3, the indentation could be of two possible sizes. The depth, width, and height of the shorter indentation equaled one third of the edge length of the basic cube. The longer indentation had the same depth and width as the shorter indentation, whereas its height equaled the size of the edges of the basic cube.

In Figure 4, all different object views are shown. In the first column, object views (0° view) that revealed an ambiguity with respect to the height of the rear indentation are shown. Two object views had an FL, and four had an FS. In addition, there was one object view with no front indentation, added for control purposes. The depth-rotated version of these objects always involved a rotation of 90° about the vertical axis. In the second and third columns of Figure 4, all 90° views are shown. For each rear indentation, there were always two possible solutions, an RS and an RL. In the following, each row of views in Figure 4 is referred to as a "set." Moreover, each of these completions can be classified as either G^+ or G^-, and either L^+ or L^-, according to the procedure outlined earlier.

The surfaces of the objects were homogeneously filled with one of six predefined gray values (G1–G6) having luminance values (cd/m^2) of approximately 9.55, 7.45, 5.15, 4.05, 2.20, and 1.50, respectively. The assignment of the different grays to the object surfaces was always the same. For the stimuli presented in Figure 4, the larger left surface was colored with G1, the larger top surface was colored with G3, and the larger right surface was colored with G5. The indented left surfaces were colored with G2, the indented top surfaces were colored with G4, and the indented right surface was colored with G6. So, for each specific side, the indented surfaces were a little darker than the main surface. No shadowing was applied. Note that all 0° views in Figure 4 have a rear indentation at the left side. As a means of avoiding observers' paying attention only to this part of the object, the actual stimulus set also contained a complementary subset of mirror versions of each object view, for which the rear indentation always was on the right side of the indented cube.

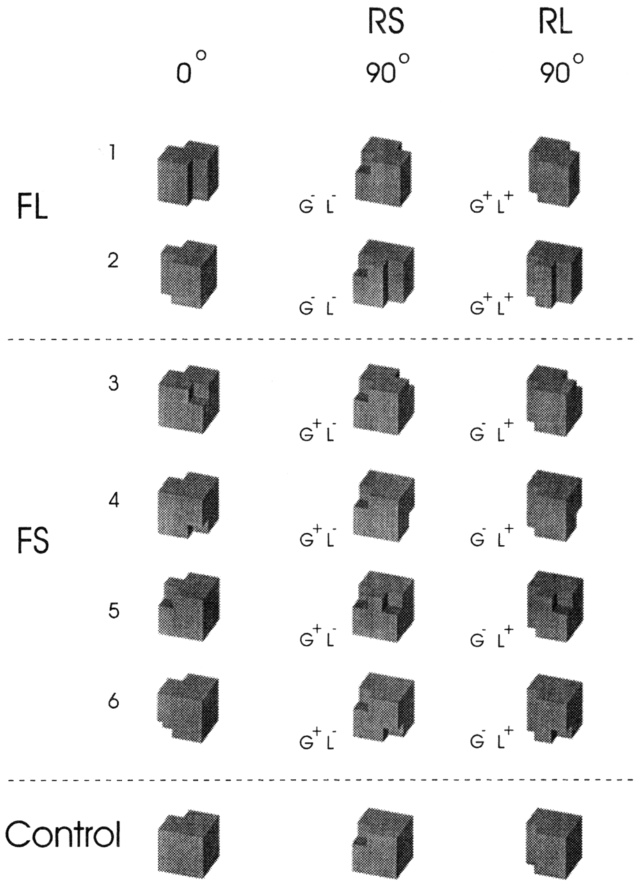

Figure 4. All object views of Experiment 1. There were six experimental sets (Sets 1–6) and one control set. The first column of images shows the 0° views. In Sets 1–6, two objects have a long front indentation (FL) and four have a short front indentation (FS). In the 0° views, the rear indentations are ambiguous. The 2nd and 3rd columns show the 90° depth-rotated versions. These 90° views reveal either a completion with a short rear indentation (RS; 2nd column) or a completion with a long rear indentation (RL; 3rd column). Each completion has been classified as global (G^+) or nonglobal (G^-) and as local (L^+) or nonlocal (L^-). Note that the different gray values of the object's surfaces as depicted here are approximations of the actual gray values and in fact were much more distinctive on the monitor screen.

Apparatus. The experiment was carried out on an IBM-compatible computer with a PENTIUM 133 processor. The stimuli were displayed on a 64K color monitor with a refresh rate of 70 Hz and a 1024 × 768 pixel display area.

Procedure. Each trial started with a black screen for 2,000 ms. After that, two object views appeared simultaneously on the screen (one on the left side of the screen and one on the right). The task of the participants was to indicate whether these object views could be two views of the same object by pressing one of two buttons (*yes* or *no*). The images remained on the screen until a response was given. The displays were viewed binocularly. Note that binocular viewing of pictorial 3D shapes may weaken the 3D percept and enhance interpretations comprising a mosaic of adjacent surfaces (e.g., Bruno et al., 1997). In our experiments, however, we did not deal with such so-called 2D mosaic interpretations; rather, we included different (i.e., global and local) 3D object interpretations. All of the experimental images (Figure 4) are readily interpreted as 3D objects. During the instruction phase, it was stressed that the task was to indicate whether the object views could possibly be of the same object rather than to judge whether it was likely that both views were from the same object. The participants were further instructed that the two different object views always involved a 90° rotation about the vertical axis. The two views to be compared always belonged to the same subset of mirror image versions. Within an experimental block, the left–right positions of the 0° view and the 90° view on the screen were balanced. Thus, each experimental pair of object views was presented twice, once with the 0° view on the left and the 90° view on the right and once with these positions reversed.

In addition to the match trials, in which the two views could be from the same object, mismatch trials, in which the two views could not be from the same object, were included. The mismatch trials consisted of objects with identical top surfaces and a 90° angular difference. For example, as a mismatch trial, the 0° view of Set 1 was combined with the RS completion of Set 3. Note, however, that given the restriction of a 90° angular difference, in two specific cases this cross coupling of views between sets would result in possible completions as well (i.e., Set 1, 0°, with Set 3, RL–90°, and Set 3, 0°, with Set 1, RS–90°). These combinations were therefore excluded from the mismatch subset.

Each participant received all trials twice, in two different blocks separated by a short break; all trials were randomized within one block. In the instruction phase, the participants were familiarized with the task on a set of approximately 25 trials randomly chosen from the complete set of trials. The height and width of an object picture on the monitor screen was about 6.5 × 6.5 cm. Participants were seated approximately 1.5 m away from the monitor screen. The two objects on the monitor screen were within 8.5° of visual angle. All objects were displayed against a black background.

Number of trials. In principle, 224 trials could be constructed: Set (7) × Completion (2) × Match (2) × Mirror Version (2) × Left–Right Balance (2) × Block (2). The exclusion of two cross couplings of views between sets in the construction of mismatch combinations reduced the total amount by 16 trials (Mirror Version [2 × 2] × Left–Right Balance [2] × Block [2]). Thus, in total, each participant saw 208 stimuli.

Results

In Figure 5, the mean RTs for both completions (RS and RL) within each set are shown. We first analyzed the data by means of a repeated measure analysis of variance (ANOVA) on the two-factorial Set (seven levels) × Completion (two levels) design; RT was the dependent variable.[1] The analysis was performed on within-cell averages for all correct responses for matching pairs (96.4% of all matching pairs). There was a main effect of set, $F(6, 102) = 20.95$, $p < .0001$, and a main effect of completion, $F(1, 17) = 6.12$, $p < .05$. The Set × Completion interaction was significant as well, $F(6, 102) = 15.71$, $p < .0001$. Note that this two-way interaction already indicates that effects on completion may depend on object-specific factors. A post hoc least significant difference (LSD) analysis ($p < .05$) was performed. In

[1] Because RT distributions are generally skewed, we have performed this and subsequent analyses on log-transformed RT values as well. In general, the statistical reliability of the results increased somewhat, but for the sake of clarity we report only the analyses on the untransformed RT values.

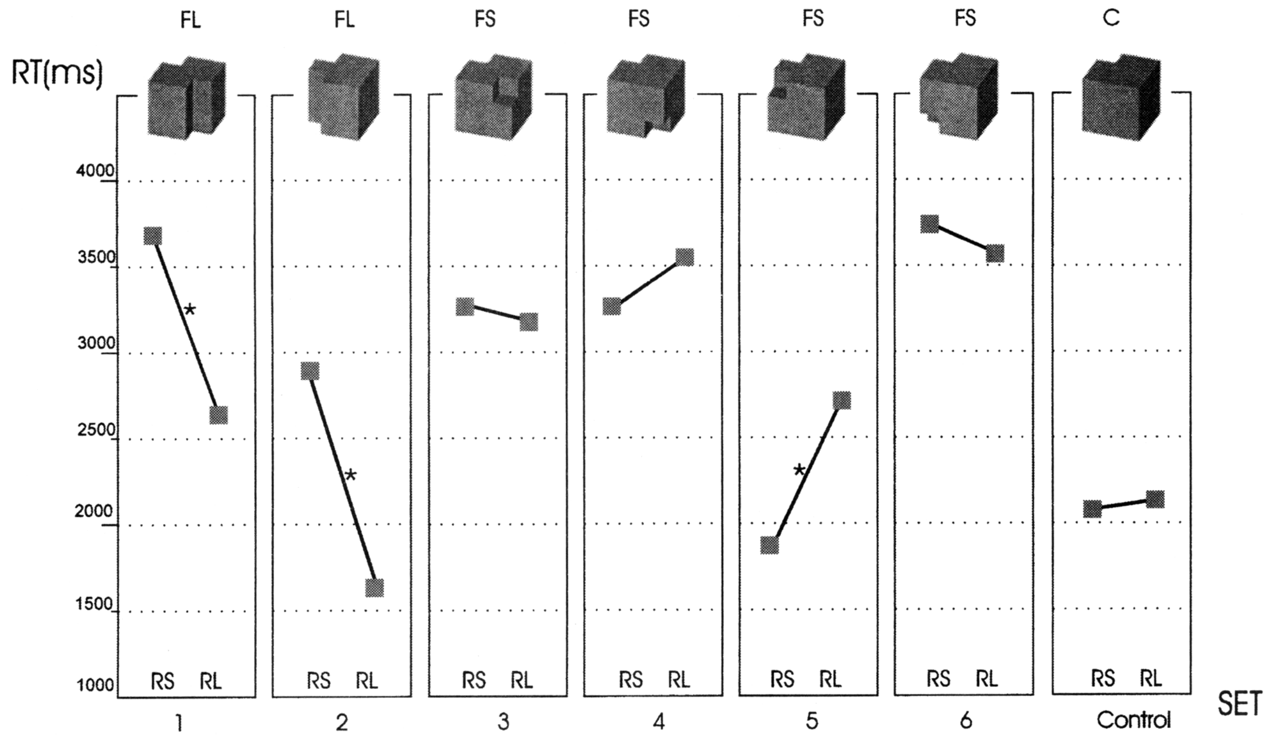

Figure 5. Results from Experiment 1. For each image set, the mean response times (RTs) for the short rear indentation (RS) completion and the long rear indentation (RL) completion are given. On top of the graphs, the 0° views are shown. Significant differences (least significant difference test, $p < .05$) within each set are indicated by an asterisk. FL = long front indentation; FS = short front indentation; C = control.

Figure 5, significantly different RTs between RS and RL completions within each set are indicated by an asterisk.

Because the objects in the control set had no indentation in front, the RTs for the RS and RL conditions in this control set can be regarded as baseline values for the differential influences of the various front indentations. We therefore computed RT values (RT′) in which, for each participant, we subtracted the RTs on the RS and RL conditions of the control set from the RTs on the corresponding RS and RL conditions of the other sets. Moreover, to get an idea of the relative similarities and differences between the objects, we performed an analysis on the RT′ values of the four possible combinations of front and rear indentations: FL–RL, FS–RS, FS–RL, and FL–RS. These combinations can be categorized as G^+L^+, G^+L^-, G^-L^+, and G^-L^-, respectively, as illustrated in Figure 4. In Figure 6, the mean RT′ values for these categories are shown. The repeated ANOVA measures with global and local as independent variables revealed the following results. There was a main effect of global $F(1, 17) = 101.91$, $p < .0001$; a main effect of local $F(1, 17) = 6.07$, $p < .05$; and a significant Global × Local interaction, $F(1, 17) = 12.49$, $p < .01$. Note that this interaction can be attributed to the relatively low RT′ values for completions that were both global and local (i.e., the G^+L^+ category). The special status of this category also was evident in a post hoc LSD analysis (see Figure 6). In Figure 6, pairwise differences between the various classes, which

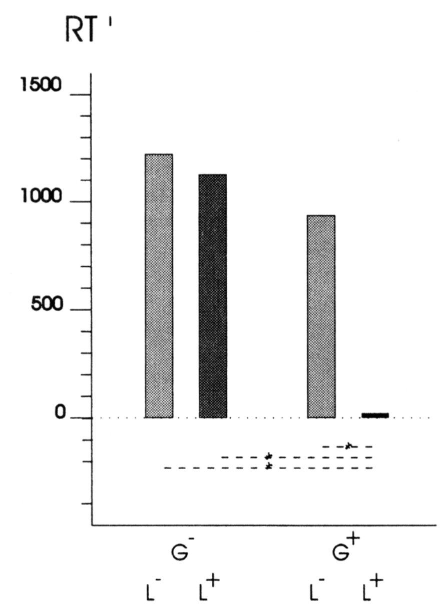

Figure 6. Results from Experiment 1. The data points represent the mean RT′ (see text) values on the variables global (G) and local (L). Significant differences (least significant difference test, $p < .05$) are indicated by a dashed line and an asterisk. RT = response time.

were found to be reliable according to such a post hoc analysis ($p < .05$), are indicated by a dashed line and an asterisk.

Furthermore, we analyzed the difference in RT′ between RS and RL within each set. These differences were significant for Set 1, $F(1, 17) = 11.29, p < .005$; Set 2, $F(1, 17) = 40.82, p < .0001$; and Set 5, $F(1, 17) = 15.20, p < .005$. The differences for the other sets were not significant (all $Fs < 1$).

Discussion

RTs to confirm that two images could be two depth-rotated versions of the same object varied significantly depending on the size and location of the indentation in the visible part of the object. When the 0° view had an FL (Sets 1 and 2), RTs were significantly faster when the 90° view revealed an RL than when it revealed an RS. In contrast, for objects with an FS (Sets 3–6), the RTs on one set (Set 5) were significantly faster when the 90° view revealed an RS than when it revealed an RL. For the other sets, the differences between RLs and RSs were unreliable.

When novel views of an object were categorized as global or local completions of the back of an object, both global and local tendencies appeared to play a role. There was a strong relative preference for a particular completion when global and local tendencies converged to the same completion (i.e., G^+L^+ vs. G^-L^-), whereas a weak, nonsignificant relative preference for a particular completion was obtained when global and local tendencies diverged to different completions (i.e., G^+L^- vs. G^-L^+).

Yet, caution must be exercised in drawing conclusions at this point. The significant effect of set indicates that mere object complexity can be an important additional but uncontrolled factor. It might be that, in addition to the disambiguation of the 0° view, different object complexities differentially affect RTs as well. That is, in addition to differential completion effects, the matching of two depth-rotated views may not be performed with the same speed for all objects (e.g., the rotation as such can be performed faster for simple objects than for complex objects). In the past, diverging results have been obtained with respect to the influence of stimulus complexity on shape matching. For example, Cooper and Podgorny (1976) reported no effect of stimulus complexity on "mental rotation speed" on a large set of 2D patterns. In contrast, Yuille and Steiger (1982) demonstrated that mental rotation speed could depend on complexity when using a modified set of R. Shepard and Metzler's (1971) objects. Subsequent research has shown that stimulus complexity and dimensionality can have complicated effects on performances in mental rotation experiments (e.g., Bauer & Jolicœur, 1996; Bethell-Fox & Shepard, 1988; Folk & Luce, 1987; S. Shepard & Metzler, 1988). Although our study did not address the issue of mental rotation as such, we did make use of a task in which two depth-rotated objects had to be compared with each other. Because of the diverging results on the influence of stimulus complexity on tasks such as these, it is expedient to control for this factor. This was done in Experiment 2.

Experiment 2

In the present experiment, three depth-rotated views were constructed from each object. The angular difference between two successive views was always 45°. A pair of object views could consist of either a 0° view and a 45° view or a 45° view and a 90° view (see Figure 7, in which, for each 0° view, the 45° views and 90° views are shown for both types of completion). Analogously to the views used by Biederman and Gerhardstein (1993) in a sequential matching task, there was a major qualitative difference in one pair of views, whereas this was not the case in another pair of views. Note that for the 0°–45° matches, hidden surfaces in the 0° view became visible in the 45° view, whereas for the 45°–90° matches, no surfaces were shown in the 90° view that were completely invisible in the 45° view.

We therefore propose that the matching of the first pair of object views (i.e., 0°–45°/RS or 0°–45°/RL) implies both a disambiguation of the rear indentation and a comparison of the object views. Because the dimensions of the rear indentation are visible in both the 45° view and the 90° view, there is no such disambiguation necessary in the second pair of object views (i.e., either 45°/RS–90°/RS or 45°/RL–90°/RL). Obviously, however, a comparison still has to be performed. Assuming that, for a given object with a given complexity, the RTs on views with the same difference in rotational angles are the same, the additional time needed for the completion can be estimated by the difference between the two RTs. Thus, whereas the control procedure used in Experiment 1 (referred to as *Control 1*) accounts for possible differential processing of RSs and RLs, the control just (proposed referred to as *Control 2*) takes account of possible differential processing due to the complexity of the whole object.

Method

Participants. Eighteen undergraduate students participated in the experiment. They were all naive with respect to the goal and the design of the experiment. One participant was excluded from the analysis because of extremely high RTs.

Stimuli. The same objects as in Experiment 1 were used (Figure 7). To maintain Control 1 and to allow a direct comparison with Experiment 1, we added the same control set as in Experiment 1. As in Experiment 1, the size of the actual stimulus set was doubled by adding a disjunct stimulus set of mirror image versions of the shown object views as well.

Procedure. The experimental procedure was the same as in Experiment 1.

Number of trials. In total, 448 stimuli could be constructed: Set (7) × Rotation (2) × Completion (2) × Match (2) × Mirror Version (2) × Left–Right Balance (2) × Block (2). For the same reason as in the previous experiment, the exclusion of two cross couplings between sets in the construction of mismatch combinations reduced the total amount by 16 trials (Mirror Version [2 × 2] × Left–Right Balance [2] × Blocks [2]). Thus, in total, each participant saw 432 stimuli.

Results

In Figure 8, the RTs for both completions (RS and RL) and both rotations within each set are shown. We first

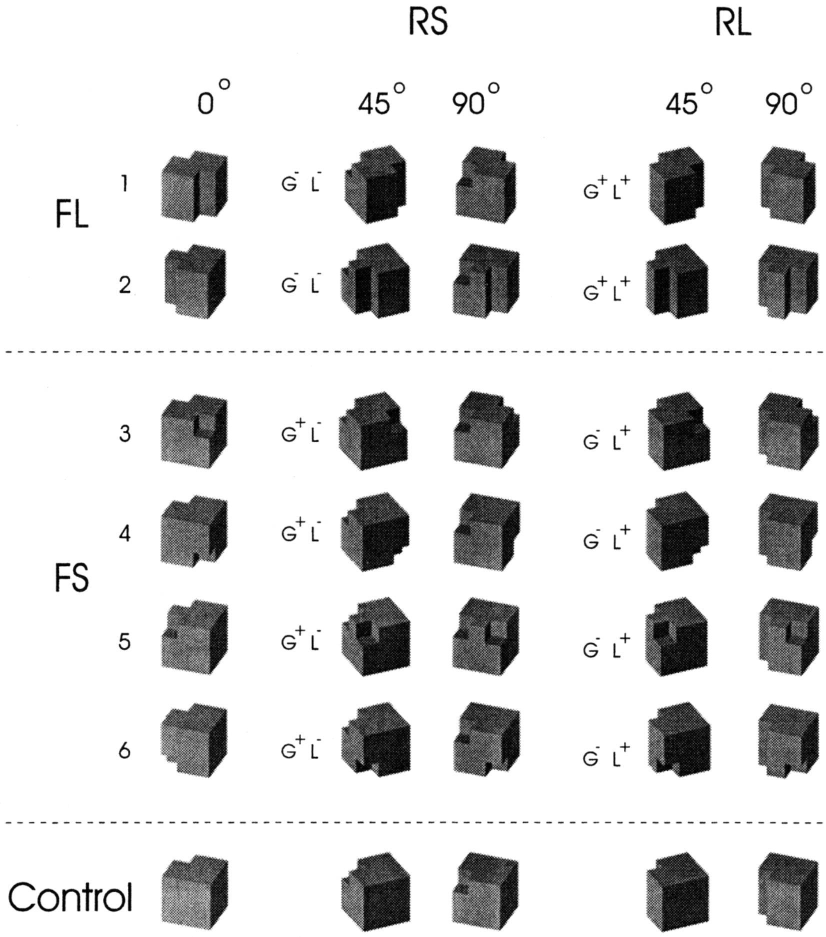

Figure 7. All object views of Experiment 2. As in Experiment 1, there were six experimental sets and one control set. The 1st column of images represents the 0° views. The 2nd and 3rd columns represent the 45° and 90° depth-rotated versions of the RS completion, and the 4th and 5th columns represent the 45° and 90° depth-rotated versions of the RL completion. Again, each completion has been classified as global (G^+) or nonglobal (G^-) and as local (L^+) or nonlocal (L^-). RS = short rear indentation; RL = long rear indentation; FL = long front indentation; FS = short front indentation.

analyzed the data by means of a repeated measures ANOVA on the three-factorial Set (seven levels) × Rotation (two levels) × Completion (two levels) design; RT was the dependent variable. The analysis was performed on within-cell averages on all correct responses for matching pairs (97.0% of all matching pairs). There was a main effect of set, $F(6, 96) = 58.17, p < .0001$; a main effect of rotation, $F(1, 16) = 28.01, p < .001$; and a main effect of completion, $F(1, 16) = 16.56, p < .001$. The following two-way interaction effects were significant: Set × Rotation, $F(6, 96) = 12.62, p < .0001$, and Set × Completion, $F(6, 96) = 17.92, p < .0001$. The Rotation × Completion interaction did not reach standard levels of statistical significance, $F(1, 16) = 3.23, p = .09$. The three-way Set × Rotation × Completion interaction was significant, $F(6, 96) = 2.28, p < .05$. Again, the significant interaction effects involving set clearly point to the relevance of particular object characteristics in the experimental task. A post hoc LSD analysis ($p < .05$) was also performed. In Figure 8, significantly different RTs between RS and RL completions within each set are indicated with an asterisk. Furthermore, significant differences between the 0°–45° match and the 45°–90° match for each RS completion and RL completion are indicated by an asterisk above the respective label on the horizontal axis of the graph.

To control for differential processing of RSs and RLs and to allow a better comparison with Experiment 1, we computed the RT′ values (Control 1), this time by subtracting the mean RTs on the 0°–45° match for the RS and RL condition of the control set from the corresponding RS and RL conditions of each set. A repeated measures ANOVA with global and local as independent variables and RT′ as the dependent variable produced the following results: a main effect of global, $F(1, 16) = 51.40, p < .0001$; a main effect of local, $F(1, 16) = 4.84, p < .05$; and a significant Global × Local interaction, $F(1, 16) = 51.80, p < .0001$.

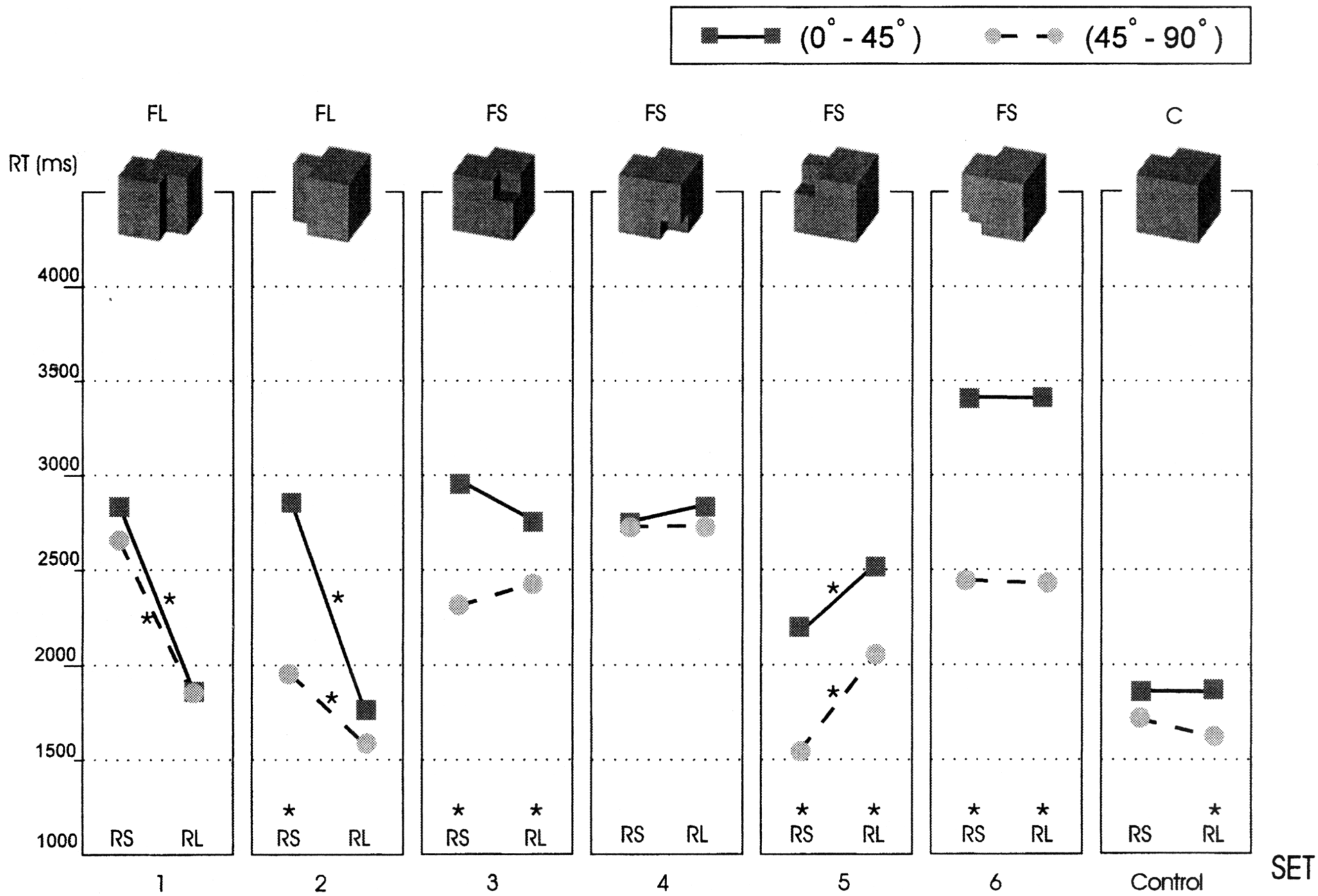

Figure 8. Results from Experiment 2. For each image set, the mean response times (RTs) for both rotations of the RS completion and the RL completion are given. On top of the graphs, the 0° views are shown. For each match, significant differences between RS and RL (least significant difference test, $p < .05$) within each set are indicated by an asterisk. An asterisk above RS or RL indicates that the difference between the 0°–45° comparison and the 45°–90° comparison is significant. FL = long front indentation; FS = short front indentation; RS = short rear indentation; RL = long rear indentation; C = control.

The mean RT′ values on the variables global and local are illustrated in Figure 9A. Significant between-classes differences (LSD test, $p < .05$) are indicated by a dashed line and an asterisk.

In the next analysis, the possible influence of object complexity on the matching of two depth-rotated views has been taken into consideration (Control 2). This was done by calculating RT values (RT″) in which, for each of two completions (RS and RL), the RT on the second rotation of a specific object (45°–90°) was subtracted from the RT on the first rotation of that object (0°–45°). A repeated measures ANOVA with global and local as independent variables and RT″ as the dependent variable produced the following results: no effect of global, $F(1, 16) = 2.98, p = .10$; a main effect of local, $F(1, 16) = 12.15, p < .01$; and a significant Global × Local interaction, $F(1, 16) = 7.85, p < .05$. The mean RT″ values for the variables global and local are illustrated in Figure 9B. Significant between-classes differences (LSD test, $p < .05$) are indicated by a dashed line and an asterisk. Note that both analyses (using either RT′ or RT″ as the dependent variable) confirm the special status of the G^+L^+ category.

Finally, we analyzed within-set differences. The difference in RT′ between RS and RL was significant for Set 1, $F(1, 16) = 13.38, p < .01$, and Set 2, $F(1, 16) = 14.38, p < .01$. The differences in RT′ for all other sets were nonsignificant, all Fs < 1, except Set 5, $F(1, 16) = 3.14, p = .10$. The difference in RT″ between RS and RL was significant for Set 2, $F(1, 16) = 12.60, p < .01$. The differences for all other sets were nonsignificant, all Fs < 1, except Set 3, $F(1, 16) = 4.21, p = .06$.

Discussion

In the match trials of Experiment 1, the two images presented side by side on the screen were two views of a single object that were always separated by a 90° depth rotation about the object's vertical axis. In the match trials of

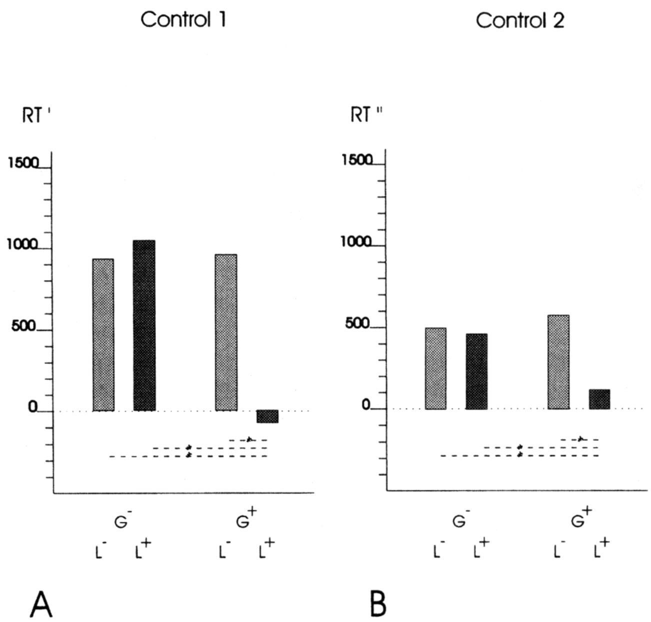

Figure 9. Results from Experiment 2. A: The data points represent the mean RT′ (see text) values (Control 1) on the variables global (G) and local (L). B: Mean RT″ (see text) values (Control 2). Significant differences (least significant difference test, $p < .05$) are indicated by a dashed line and an asterisk. RT = response time.

Experiment 2, the two images were object views that were always separated by a 45° rotation in depth. In one half of the match trials, the two views (0° and 45°) were qualitatively different in the sense that hidden surfaces became visible; in the other half, the views (45° and 90°) were qualitatively similar in the sense that no surfaces were shown in the second view that were completely invisible in the first view. Because the former trials require a disambiguation that is not needed in the latter trials, RTs were generally slower in the former. This result is in line with Biederman and Gerhardstein's (1993) data obtained with rather different novel objects (i.e., objects constructed from multiple volumetric components instead of cubes with short and long indentations) and a different procedure.

Note that the relative differences on the 0°–45° matches in Experiment 2 were similar to the 0°–90° matches of Experiment 1 (cf. the global–local analyses on RT′ or, more specifically, the graph of Figure 9A with the graph of Figure 6). In the analyses on RT′, possible differential processing due to the featural difference between RSs and RLs was implicitly accounted for. In contrast, the Control 2 procedure was of a more wholistic nature in that it accounted for the complexity of the entire object and, with that, assumed an integration of the completed part with the rest of the object.

Splitting the 90° depth rotation into two 45° rotations, one with disambiguation and one without, sheds some new light on the observed RTs. Consider, for example, the results for Set 5: The RS completion evoked the shortest RT for the 0°–45° match, but the same object also evoked the shortest RT for the 45°–90° match. This indicates that this faster RT was due not to a faster disambiguation of the 0° view as such but, rather, to the fact that the matching of depth-rotated views of the RS completed object (which, in this case, was the global completion) was faster than a similar comparison for the RL completed objects (which, in this case, was the local completion). Such faster matchings for global completions also appeared for Sets 1 (RL completion), 2 (RL completion), and 3 (RS completion). In Set 3, the trends for both comparisons were even in the opposite direction. The RTs on the views were almost parallel for all of the other sets. Of these, Set 4 was a rather special case because it actually had an ambiguous indentation in the 90° view as well (for the version shown in Figure 7, bottom right). This might explain why the RTs for Set 4 are so close to each other.

It can be argued that the experimental procedure in which both views were presented simultaneously reduced the necessity of a spontaneous disambiguation of the 0° view. This could explain, for example, the unexpected similar RTs on the 0°–45° match and the 45°–90° match for the RS completion of Set 1. In Experiments 1 and 2, the RTs can be taken as an indication of the level of "surprise" of a possible but unexpected match, but perhaps they differ less than RTs obtained on a comparison task that would always start with the 0° view. To enhance such spontaneous disambiguations, we conducted a third experiment in which the 0° view was always presented first.

Furthermore, it can be argued that the nonreliable effect of the variable global on RT″ was caused not by an insensitivity of the visual system to object regularities in object completion but to the fact that these regularities were simply not salient enough. This would be in line with previous research on 2D surface completions (Sekuler, 1994; Van Lier, Van der Helm, & Leeuwenberg, 1995) also showing that global completions are more prevalent if the completed surfaces are more regular. To test this for 3D object completion, we therefore extended the stimulus set with a few additional object sets for which the visible regularity was more compelling.

Experiment 3

Method

Participants. Eighteen undergraduate students participated in the experiment. All were naive with respect to the goal and the design of the experiment.

Stimuli and procedure. Before describing the additional stimuli, we first explain the adjusted experimental paradigm. As indicated already, there were two main procedural changes in comparison with the previous experiments. These involved a sequential presentation order of the two object views and the uniqueness of the rotation direction. This time, each trial started with either the 0° view or the 45° view. After 3 s, an additional image appeared on the screen (the first image remained on the screen). The 0° view was always followed by the 45° view, and the 45° view was always followed by the 90° view. The first object view could appear either on the left side of the monitor screen or on the right side of the monitor screen. The second object appeared on the empty screen half. Trials that started with an object view on the right screen half always involved object views from the disjunct subset of mirrored versions. The participants were instructed as follows. If a trial started with an object on the left screen half, then the next view should be a 45° right rotated version of the object (rotation about the vertical). If a trial started with an object on the right screen half, then the next view should be a 45° left rotated version of the object. Thus, a match response should be given if the object on the right was the 45° right rotated version of the object on the left, and vice versa. Participants were instructed to decide as quickly as possible when the second object appeared whether that object could be the demanded rotated version of the first object.

The same object views as in Experiment 2 were used. As already noted, we created three additional image sets (Sets 7–9), shown in Figure 10. In Set 7, there were more FLs in the visible part of the object. In Sets 8 and 9, there were more FSs visible. As in Experiment 2, there were three views (0°, 45°, and 90°) per object. Note that the actual images for the 90°–RL completion of Set 7 and the 90°–RS completions of Sets 8 and 9 were identical to their corresponding 0° views. However, because of the unique rotation direction, again a disambiguation of the ambiguous rear indentation was required only in the 0°–45° comparison. All other details of the procedure were exactly the same as in the previous experiments.

Number of trials. Each participant saw 320 stimuli: Set (10) × Rotation (2) × Completion (2) × Match (2) × Mirror Version (2) × Block (2). (Because of the unique rotation direction, no stimuli needed to be excluded from this total.)

Results

We first analyzed the data by means of a repeated measures ANOVA on the three-factorial Set (10 levels) × Rotation (2 levels) × Completion (2 levels) design; RT was the dependent variable. As in the previous experiments, the analysis was performed on within-cell averages on all correct responses for matching pairs (94.9% of all matching pairs). In Figure 11, the RTs are given for both completions and both rotations within each set. There was a main effect of set, $F(9, 153) = 13.79$, $p < .0001$; a main effect of rotation, $F(1, 17) = 57.13$, $p < .0001$; and a main effect of completion, $F(1, 17) = 8.92$, $p < .01$. The following two-way interaction effects were significant: Set × Rotation, $F(9, 153) = 3.39$, $p < .001$, and Set × Completion, $F(9, 153) = 13.64$, $p < .0001$. The Rotation × Completion interaction appeared not to be significant, $F(1, 17) < 1$. Finally, the three-way Set × Rotation × Completion interaction was significant, $F(9, 153) = 8.31$, $p < .0001$. Note that, as in the previous experiments, all interaction effects involving set were significant. A post hoc LSD analysis ($p < .05$) was also performed. In Figure 11, significantly different RTs between RS and RL completions within each set are indicated with an asterisk. Furthermore, significant differences between the 0°–45° match and the 45°–90° match for each RS completion and RL completion are indicated by an asterisk above the labels on the horizontal axis.

As in Experiments 1 and 2, we also performed analyses on the RT′ values (Control 1). The mean RT′ values for the variables global and local are illustrated in Figure 12A. This time, there was one additional variable referring to the redundancy of the front indention. This variable had two levels: low and high. *Low* refers to the objects with one front indentation (Sets 1 to 6), and *high* refers to the objects with more than one front indentation (Sets 7 to 9). In Figure 12A, the RTs on the corresponding conditions of the control set are considered as baseline values (Control 1). A repeated measures ANOVA with global, local, and redundancy as independent variables and RT′ as the dependent variable produced the following significant effects: redundancy, $F(1, 17) = 8.09$, $p < .05$; global, $F(1, 17) = 30.80$, $p < .0001$; local, $F(1, 17) = 5.52$, $p < .05$; Redundancy × Global, $F(1, 17) = 24.18$, $p < .005$; Redundancy × Local, $F(1, 17) = 6.71$, $p < .05$; and Global × Local, $F(1, 17) = 28.71$, $p < .0001$. The three-way Redundancy × Global × Local interaction was nonsignificant, $F(1, 17) < 1$. Significant

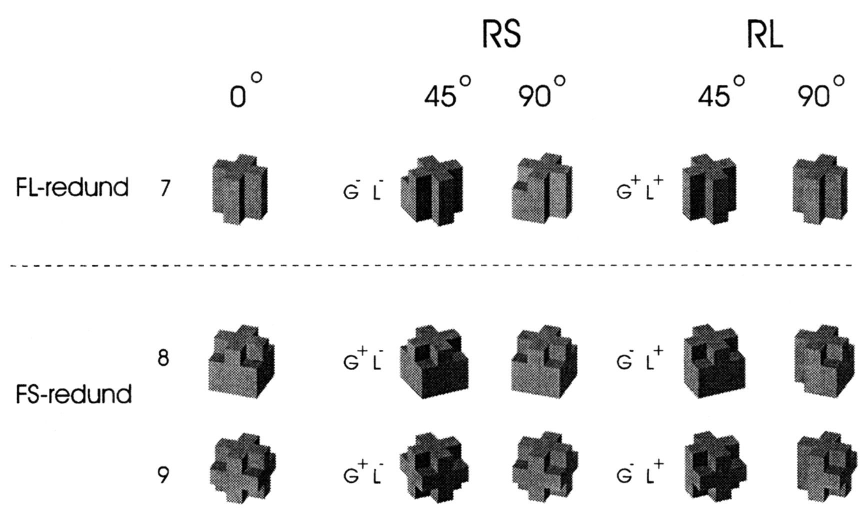

Figure 10. The stimuli of Experiment 3 in addition to those already shown in Figure 7. In Set 7, the long front indentation is redundantly present (FL-redund), and in Sets 8 and 9, the short front indentation is redundantly present (FS-redund). RS = short rear indentation; RL = long rear indentation; G = global; L = local.

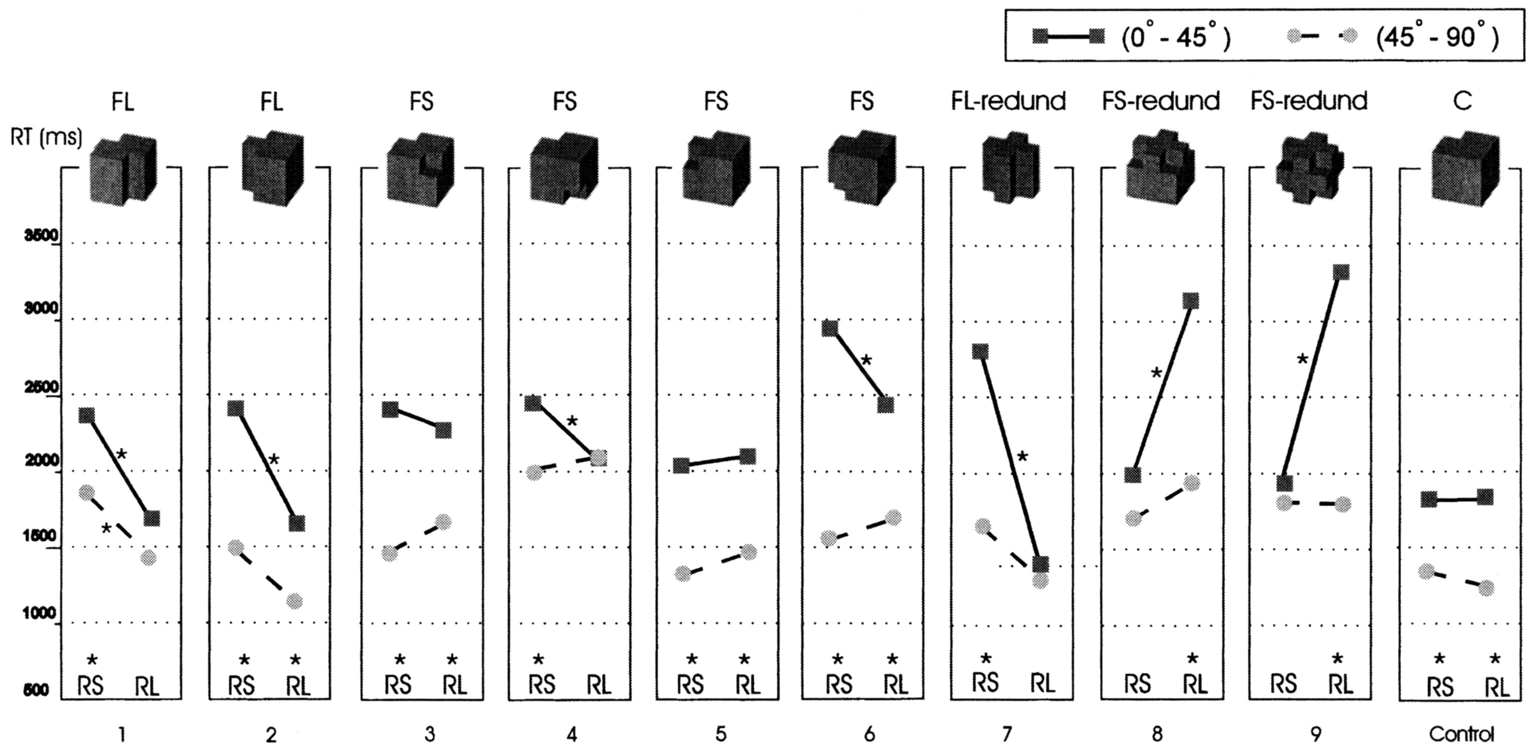

Figure 11. Results from Experiment 3. For each set, the mean response times (RTs) for both rotations of the RS completion and the RL completion are given. On top of the graphs, the 0° views are shown. For each match, significant differences between RS and RL (least significant difference test, $p < .05$) within each set are indicated by an asterisk. An asterisk above RS or RL indicates that the difference between the 0°–45° comparison and the 45°–90° comparison is significant. FL = long front indentation; FS = short front indentation; redund = redundant; C = control; RS = short rear indentation; RL = long rear indentation.

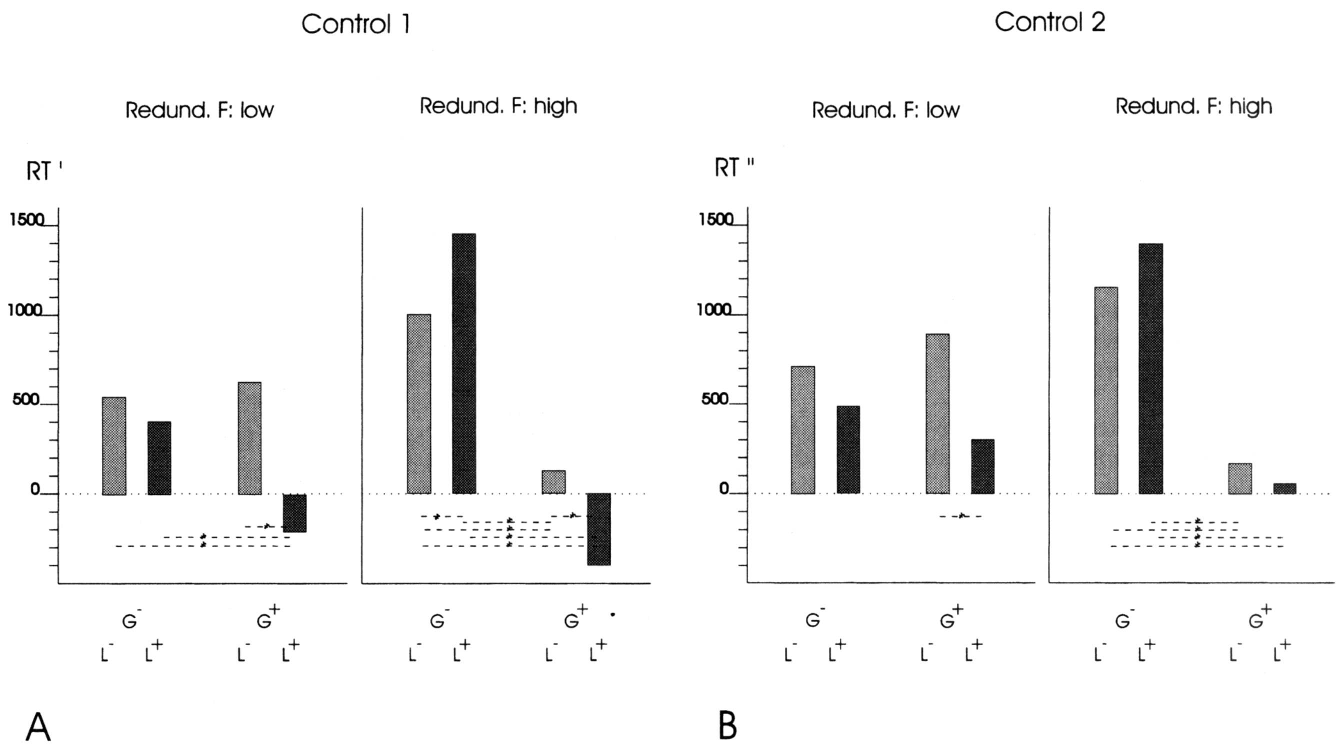

Figure 12. Results from Experiment 3. A: The data points represent the mean RT′ (see text) values (Control 1) for both redundancy (Redund.) levels on the variables global (G) and local (L). B: Mean RT″ (see text) values (Control 2). Significant differences (least significant difference test, $p < .05$) are indicated by a dashed line and an asterisk. F = front indentation; RT = response time.

between-classes differences (LSD test, $p < .05$) are indicated by a dashed line and an asterisk in Figure 12A.

The mean RT″ values (Control 2) on the variables global and local are illustrated in Figure 12B. A repeated measures ANOVA with global, local, and redundancy as independent variables and RT″ as the dependent variable produced the following significant effects: global, $F(1, 17) = 20.21, p < .005$; Redundancy × Global, $F(1, 17) = 25.23, p < .001$; Redundancy × Local, $F(1, 17) = 6.57, p < .05$; and Global × Local, $F(1, 17) = 5.36, p < .05$. The following terms were nonsignificant: redundancy, $F(1, 17) = 1.87, p = .19$; local, $F(1, 17) = 2.08, p = .17$; and Redundancy × Global × Local, $F(1, 17) < 1$. Significant between-classes differences (LSD test, $p < .05$) are indicated by a dashed line and an asterisk in Figure 12B. Again, the two-way Global × Local interactions were significant for both analyses (with RT′ and RT″ as dependent variables). Although the nonsignificant Global × Local × Redundancy interaction (on both RT′ and RT″) indicates rather similar Global × Local trends for both levels of redundancy, it is noticeable that especially the differential effect of global was much stronger for the high-redundancy class than for the low-redundancy class (e.g., see the highly significant Global × Redundancy interactions or the results of the post hoc analyses). In addition, it appears once more that the Control 2 procedure was the most severe one (e.g., the set of all significant post hoc differences when RT″ was used as the dependent variable was a subset of the significant differences when RT′ was used as the dependent variable).

Finally, we analyzed within-set differences. The difference in RT′ between RS and RL was significant for Set 1, $F(1, 17) = 6.27, p < .05$; Set 4, $F(1, 17) = 4.78, p < .05$; Set 6, $F(1, 17) = 5.63, p < .05$; Set 7, $F(1, 17) = 26.91, p < .0001$; Set 8, $F(1, 17) = 15.65, p < .005$; and Set 9, $F(1, 17) = 32.10, p < .0001$. The differences for all other sets were nonsignificant, all Fs < 1, except Set 2, $F(1, 17) = 3.30, p = .09$. The difference in RT″ between RS and RL within each set was significant for Set 6, $F(1, 17) = 7.03, p < .05$; Set 7, $F(1, 17) = 9.97, p < .01$; Set 8, $F(1, 17) = 9.00, p < .01$; and Set 9, $F(1, 17) = 34.76, p < .0001$. The differences for all other sets were nonsignificant: Set 1, $F(1, 17) = 2.07, p = .17$; Set 2, $F(1, 17) = 1.29, p = .27$; Set 3, $F(1, 17) = 1.73, p = .21$; Set 4, $F(1, 17) = 2.90, p = .11$; and Set 5, $F(1, 17) < 1$.

Discussion

As in Experiment 2, the main effects of set, completion, and rotation on RT were all significant. Furthermore, the same interaction effects appeared to be significant. At first glance, the results for the low-redundancy subset appear rather similar to those of Experiment 2, but there are a few noticeable differences as well. For example, the small difference between the RS completion and the RL completion of Set 1, observed in Experiment 2, disappeared. This might have been due to the fact that because of the sequential presentation in Experiment 3, spontaneous object completions played a more important role than in Experiments 1 and 2. The trends in Set 4 (in which there was an ambiguous indentation in the 90° view as well) also differed much more from each other than was the case in Experiment 2. This can be ascribed as well to the altered stimulus presentation, because the ambiguous rear indentation always appeared in the first presented image in the 0°–45° match, whereas it always appeared in the second image in the 45°–90° match. Furthermore, RT′ and RT″ on Set 6 were not significant in Experiment 2 but were significant in Experiment 3.

As might have been expected, there were strong effects of the redundancy of the indentations on the perceived completions. Indeed, for both analyses (RT′ and RT″), the Redundancy × Global and Redundancy × Local interactions were significant. The strong effects on Sets 8 and 9 illustrate that global completions can very well be generated by the visual system, although they seem to need more "configural support."

General Discussion

When observers have to determine whether two images presented side by side on a computer screen can be two views of the same 3D object, rotated in depth about its vertical axis, they respond faster with certain completions of the object's hidden parts than with others. We take these RT differences as evidence of spontaneous completion tendencies, and we examine how completion depends on visible object parts. In this section, we first summarize the most important findings from the three experiments with this paradigm. Because structural factors appear to determine completion tendencies, we then examine the role of such structural factors by means of different accounts of object regularities.

Summary of Results

In all of the experiments, RTs varied considerably depending on the type of indentation at the back of an object and how this related to the indentations at the object's front. In Experiment 1, objects with FLs (Sets 1 and 2) yielded the shortest RTs when the 90° rotated views revealed RLs. This preference was strong because global and local completion tendencies converged to the same object: An RL is categorized as a local completion because it consists of simple straight contours without any additional surfaces, and it can also be categorized as a global completion because for these sets it repeats the same indentation. When global and local tendencies diverged to different objects (because the object had an FS [Sets 3–6]), RTs did not vary as much; in fact, only one object (Set 5) produced a significant preference, namely one for a global completion. These trends were preserved when the RTs for a control object without front indentations were subtracted from the RTs for the test objects (Control 1). This control condition accounted for potential processing differences because of featural differences between RSs and RLs and could therefore be considered as a baseline control condition. In the subsequent experiments, an additional control was added in which the complexity of the whole object was accounted for, assuming an integration of the completed part with the rest of the object. This was done by introducing two different rotations, only one of which required completion.

In Experiment 2, in which the two views were separated by a 45° depth rotation, RTs continued to vary as a function of completion and object but also depended on the relations between the two views. When no new surfaces became visible (45°–90° matches), RTs were generally faster than when hidden surfaces became suddenly visible (0°–45° matches). Although the trends for the latter trials were rather similar to those of the 90° depth-rotated views in Experiment 1, subtracting the RTs for the former trials from them, to estimate completion as such (Control 2), reduced the number of significant differences between RTs for RSs and RLs.

In Experiment 3, the match trials always started with one particular view (either 0° or 45°) and then continued with a 45° depth-rotated version (45° or 90°) in a well-defined direction, and objects with multiple short and long indentations were added to the stimulus set. The procedural change generally tempered the RT differences for the low-redundancy objects (Sets 1–6), whereas the addition of high-redundancy objects (Sets 7–9) produced stronger completion preferences. When objects had multiple short indentations in the visible front surfaces (Sets 8 and 9), 45° depth-rotated versions that showed short indentations at the rear yielded much shorter RTs than those that showed long rear indentations; the opposite was true for the object with multiple long indentations (Set 7).

Structural Factors Determining Object Completion

Overall, the results of all three experiments showed strong and systematic differences between objects within a certain category of local or global completions. One would usually average out these differences statistically, but we found them interesting enough to be examined in more detail. In the course of varying the size of the depth rotation (from 0°–90° in Experiment 1 to 0°–45° and 45°–90° in Experiments 2 and 3), varying the presentation of the two views (from simultaneous in Experiments 1 and 2 to sequential in Experiment 3), and adding high-redundancy objects (in Experiment 3), subtle differences occurred in RTs that could be explained only by making reference to structural aspects of the objects and how these were presented in certain views. In the following section, we systematically study these structural aspects in terms of object regularities. First, we consider a mere symmetry account based on global planes of object symmetry. Second, we consider the structural information account, describing various types of object regularities (e.g., Leeuwenberg, 1971; Leeuwenberg & Van der Helm, 1991; Van der Helm & Leeuwenberg, 1991). After that, we further discuss several implications of both accounts.

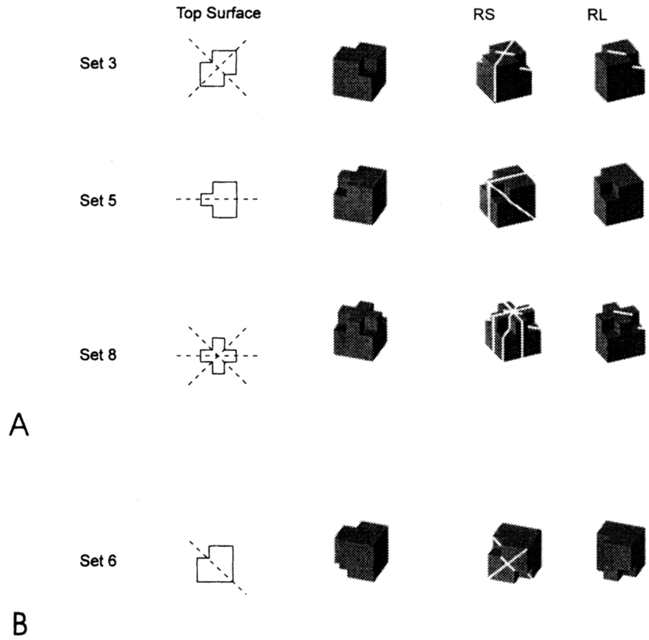

Figure 13. A: The 0° views of Sets 3, 5, and 8, together with the RS completions and RL completions. B: 0° view of Set 6 together with the RS completion and the RL completion. For each completion, the planes of symmetry are indicated with thick white lines. RS = short rear indentation; RL = long rear indentation.

Symmetry. As noted before, the various relative positions of the front indentations induce different symmetries within the objects. These different symmetries can be responsible for the relative RTs. However, it is clear that a description of mere object symmetry cannot fully explain the results because there is no overall preference for the most symmetrical completion in the low-redundancy subset. Yet, such an investigation may very well indicate the relative influences of certain object properties on the matching task. We focus on mirror symmetry (or bilateral–reflectional symmetry) within objects because, in many studies using 2D patterns, mirror symmetry has been found to be most perceptually prevalent (e.g., Bruce & Morgan, 1975; Corballis & Roldan, 1974; Julesz, 1971; Kahn & Foster, 1986; Palmer & Hemenway, 1978; Royer, 1981; Wagemans, 1993; Wagemans, Van Gool, Swinnen, & Van Horebeek, 1993). Vetter and Poggio (1994) recently drew attention to the special status of mirror symmetries in object recognition in that symmetric 3D objects can easily be discerned from a single 2D view. Moreover, previous research on 2D completion phenomena (Boselie, 1994; Sekuler, 1994) revealed a strong effect of mirror symmetry on perceived completions. Mirror symmetry therefore is often acknowledged to be the perceptually strongest type of symmetry (Wagemans, 1995, 1997).

We first explore some differences in symmetry between the objects of the experimental set. In Figure 13A, the 0° views of Sets 3, 5, and 8, together with the two completions, are displayed once more. For both completions within each set, all planes of symmetry are indicated. In each of these three sets, the RS completion has more planes of symmetry than the RL completion. Yet, of these three sets in Figure 13A, only Set 8 yielded a clear preference for the RS completion (Experiment 3). Indeed, inspecting the number of planes of symmetry, the RS completion of Set 8 appears to have the highest degree of symmetry. Furthermore, when considering the difference in RTs on the RS completion and the RL completion of Set 3 and Set 5, the RS completion of Set 5 appears to be most prevalent in all three experiments. Note that the competing RL completion of Set 5 does not have any planes of symmetry, whereas the competing RL completion of Set 3 has one plane of symmetry. Such initial observations support the idea that the difference in symmetry between the RS completion and the RL completion could be a predictor of the relative RTs, yielding an overall tendency toward the completion with the highest degree of symmetry.

To investigate the impact of symmetry further, we determined the number of planes of symmetry (S) for all RS and RL completions in Sets 1 to 9. In Table 1, these numbers are given for each completion. Next, we determined the mean difference (d) in RT′ values (Control 1) and RT″ values (Control 2) on RS and RL for Sets 1 to 9 of Experiment 3; that is, dRT′ = RT′(RS) − RT′(RL) and dRT″ = RT″(RS) − RT″(RL), respectively. We used the data of Experiment 3, because, as argued before, this experiment most strongly induced an initial disambiguation of the 0° view. Moreover, only in this experiment were the object views of Sets 7 to 9 used. In Figure 14A, for all objects, dRT′ and dRT″ have been plotted against the difference between the numbers of planes of symmetry for the RS completion and the RL completion: dS = S(RS) − S(RL). Pearson's correlation coefficient (r) for dS × dRT′ was −.89 ($N = 9$, $p < .01$), and the coefficient for dS × dRT″ was −.80 ($N = 9$, $p < .01$). Thus, although symmetry alone cannot account for the preferences as such, there is a clear tendency toward more symmetrical objects.

Table 1
Quantifications of Object Regularities

Set	S (RS)	S (RL)	S* (RS)	S* (RL)	I (RS)	I (RL)	I* (RS)	I* (RL)
1	1	3	1	2	15	8	15	8
2	0	2	0	1	17	9	17	9
3	2	1	2	1	13	15	13	15
4	3	1	1	1	21	15	21	15
5	2	0	1	0	18	18	18	18
6	2	0	0	0	13	17	24	17
7	1	5	1	4	16	7	16	7
8	4	1	4	1	12	27	12	27
9	9	2	4	1	12	27	12	27

Note. For each completion short rear indentation (RS) and long rear indentation (RL) of sets (1–9), various quantifications of regularities are given: S = number of planes of symmetry; S* = number of planes of symmetry compatible with the axes of symmetry of the top surface; I = SIT information load according to a decomposition in which the superstructure could be any surface (depending on the lowest overall complexity); I* = SIT information load according to a decomposition in which the superstructure could only be the top surface. SIT = structural information theory.

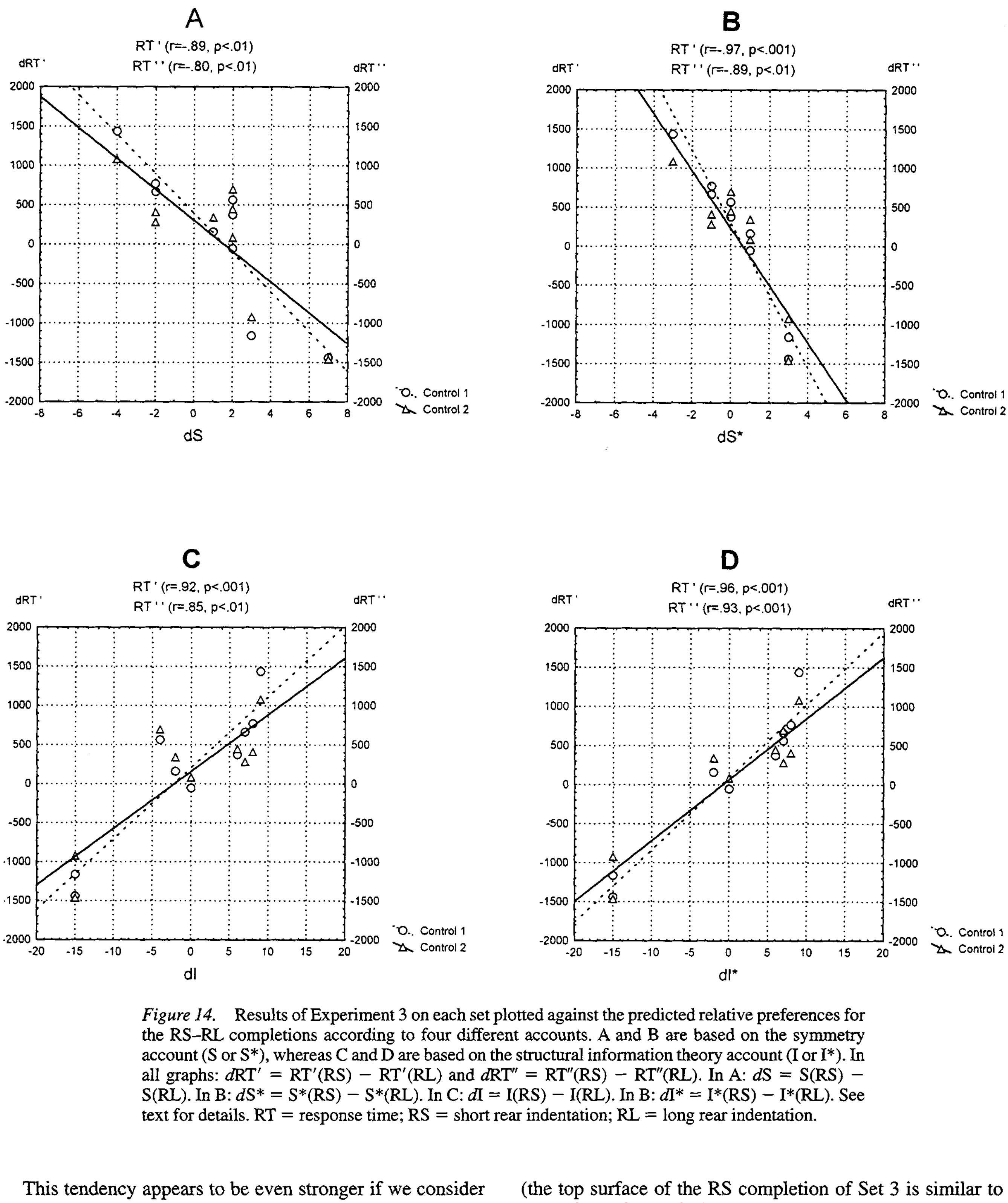

Figure 14. Results of Experiment 3 on each set plotted against the predicted relative preferences for the RS–RL completions according to four different accounts. A and B are based on the symmetry account (S or S*), whereas C and D are based on the structural information theory account (I or I*). In all graphs: $dRT' = RT'(RS) - RT'(RL)$ and $dRT'' = RT''(RS) - RT''(RL)$. In A: $dS = S(RS) - S(RL)$. In B: $dS^* = S^*(RS) - S^*(RL)$. In C: $dI = I(RS) - I(RL)$. In B: $dI^* = I^*(RS) - I^*(RL)$. See text for details. RT = response time; RS = short rear indentation; RL = long rear indentation.

This tendency appears to be even stronger if we consider just the top surface of each object. Consider, for example, Set 6, for which the planes of symmetry of the two completions are shown in Figure 13B. The RS completion of Set 6 actually resulted in the same object as the RS completion of Set 3 (Figure 13A) but oriented differently (the top surface of the RS completion of Set 3 is similar to the left surface of the RS completion of Set 6). Yet, according to Experiment 3, the RS completion of Set 6 seems to be much less preferred than the RS completion of Set 3. We therefore performed the same correlational analysis on the number of planes of symmetries that were compatible with the symmetry axes of the top surface. Note that, within the 2D image itself, these are actually axes of skewed symmetry. Theoretical considerations (Biederman, 1987), as well as empirical research (Wagemans, 1993), have supported the notion that the visual system interprets skewed symmetry as a nonaccidental property signaling bilateral symmetry viewed from oblique orientations. In Table 1, the number of planes of symmetry compatible with the top surface symmetry (S*) is given for all RS and RL completions. In Figure 14B, for all objects, dRT' and dRT'' are plotted against the dS^* values, $dS^* = S(RS) - S(RL)$. Pearson's correlation coefficient for $dS^* \times dRT'$ was $-.97$ ($N = 9, p < .001$), and the coefficient for $dS^* \times dRT''$ was $-.89$ ($N = 9, p < .01$).

A structural information account. The observed tendency toward object symmetry might indicate an overall tendency toward regular or simple shapes akin to the Gestalt notion of *Prägnanz* (e.g., Koffka, 1935). An elaborate theory that incorporates the visual system's tendency toward simplicity is the structural information theory (SIT) initiated by Leeuwenberg (1969, 1971). SIT has proved its value with respect to the description of 2D surface completion (Buffart et al., 1981; Van Lier, Van der Helm, & Leeuwenberg, 1994, 1995). A fundamental principle of SIT is the global minimum principle (Hatfield & Epstein, 1985; Hochberg & McAlister, 1953), according to which the interpretation with the simplest description is selected by the visual system. A detailed discussion of SIT would lead far beyond the scope of this article. However, we explain SIT into just enough detail to apply the theory as an operational "tool" by means of which object complexities can be determined. Further elaborations and mathematical foundations of the theory can be found elsewhere (Van der Helm & Leeuwenberg 1991, 1996; Van der Helm, Van Lier, & Leeuwenberg, 1992).

Given the constraints of SIT, global and local regularities such as bilateral symmetries, rotational symmetries, iterations, and alternations in a visual pattern are maximally accounted for. SIT represents visual patterns by symbol series, such that equal lines and angles have equal symbols. By means of coding rules, the symbol series is reduced to a so-called minimum code. Roughly stated, the number of descriptive parameters in a minimal code reflects the complexity of the code and, with that, the complexity of the visual structure it represents. This complexity is generally expressed in units of structural information (I). The SIT coding rules and determination of information loads are illustrated in the Appendix.

The complexity calculation, as used here, reflects only the regularities within each object. With respect to 2D surface completion, Van Lier, Van der Helm, and Leeuwenberg (1994, 1995) have shown that other factors, such as the degree of occlusion or the relative positions of surfaces, can be captured by the same measure of complexity. Operationalizations of such aspects for 3D object completions, however, would be quite elaborate and lie outside the focus of the present article.

Within SIT, objects can often be described by means of a decomposition in hierarchically related components (e.g., Leeuwenberg, 1971; Leeuwenberg & Van der Helm, 1991; Leeuwenberg, Van der Helm, & Van Lier, 1994; Van Lier, Leeuwenberg, & Van der Helm, 1997). The components at the highest descriptive level have been referred to as superstructures, whereas the components at the lower levels have been referred to as subordinate structures. The complexity of an object depends on the specific decomposition of that object. In the Appendix, the decomposition into superstructures and subordinate structures and the complexity calculations are explained further. In analogy with the previous analysis on mirror symmetry, the objects were decomposed in two ways. First, any object surface could be the superstructure as long as it was globally simplest. Second, only the top surface of the object could be the superstructure.

In Table 1, for each completion, the information loads according to these different procedures are given (referred to as I and I*, respectively). Note that only in one case (i.e., the RS completion of Set 6) is there a difference between I and I*. In all other instances, the first procedure already assigned the top surface to be the superstructure, evidently causing no difference with respect to the second procedure. Next, we calculated the differences between the I values of the RS completion and the RL completion within each set: $dI = I(RS) - I(RL)$. The same was done for the I* values: $dI^* = I^*(RS) - I^*(RL)$. In Figure 14C, for all objects, dRT' and the dRT'' have been plotted against the I values. In Figure 14D, the same has been done for the I* values. Pearson's correlation coefficients (*r*s) were as follows: $dI \times dRT'$, .92 ($N = 9, p < .001$); $dI \times dRT''$, .85 ($N = 9, p < .01$); $dI^* \times dRT'$, .96 ($N = 9, p < .001$); and $dI^* \times dRT''$, .93 ($N = 9, p < .001$).

Discussion. Both accounts appear to predict the data reasonably well. This is not surprising because the (Pearson) intercorrelations between the predictive measures were considerable: $dS \times dI$, $-.85$ ($N = 9, p < .01$), and $dS^* \times dI^*$, $-.92$ ($N = 9, p < .001$). It can be seen that, for all analyses, the RT′ correlations were higher than the RT″ correlations. This agrees with the idea that Control 2 can be considered the more severe control for determining the influence of regularity on the disambiguation of the back of an object. It further appeared that, according to both approaches, the top surface seems to have a special role. Such a possible "top surface priority" might be read as the top surface being a major perceptual entry with respect to the disambiguation of the complete object. One may speculate whether visual attention is drawn to the top surface for a certain built-in a priori reason or simply because the ambiguous rear indentation in the 0° views is visible only in the top surface.

In addition, the analyses on symmetry support the notion that the visual system uses the axes of symmetry in the top surface to disambiguate the object. Note that object symmetries compatible with the axis of symmetry of the top surface always involve vertical planes of symmetry. Within the domain of occlusion, such a prevalence of vertical symmetries agrees with research of Sekuler (1994) and Boselie (1994), who found similar trends toward vertical symmetries in the case of 2D surface completion. More generally, this prevalence may reflect the fact that vertical symmetry in various 2D displays is detected faster and more accurately (e.g., Barlow & Reeves, 1979; Corballis & Roldan, 1975; Palmer & Hemenway, 1978; Wagemans, Van Gool, & d'Ydewalle, 1991, 1992). At this point, we can only speculate about the relative influence of different axes of symmetry in each of the visible object surfaces and their compatibility or incompatibility with the planes of symmetry in possible object interpretations. Moreover, effects of object symmetry may very well interact with the object's orientation in the environment (e.g., Pani, 1993, 1999; Pani, Jeffres, Shippey, & Schwartz, 1996; Pani, William, & Shippey, 1995). Future research will certainly face a challenge in attempting to disentangle the influence of different orientational influences on object completion.

With respect to the SIT encodings, it can be said that the "top surface superstructure" generally accounts for vertical planes of symmetry because these symmetries probably reduce both the complexity of the top surface superstructure and the relative positions of the subordinate components. For the simple reason that the rear indentations always affected the top surface, regularities due to different positions of the indentations could be described most efficiently with a top surface superstructure. Only in Set 6 is the RS completion described simplest with a side surface as superstructure (i.e., the left surface of the 0° view in Figure 13B) yet much better predicted with a top surface superstructure.

This divergence does not necessarily imply a top surface priority in SIT encodings. There is another influential factor that also distinguishes between both encodings and deals with the visibility of regularities. Note that, in Figure 13B, the left surface of the 0° view of Set 6 is completely occluded. Thus, for the specific image, there is very little visible evidence for the simplest encoding. Such influences of the visibility on perceived completions agree to a certain extent with previous research on 2D surface completions (Van Lier, Van der Helm, & Leeuwenberg, 1994, 1995). In those articles, it has been shown, for surface completions, that the tendency toward global completions can be overruled if large parts are occluded. As already indicated, a similar quantification of those effects on 3D object completion would not be straightforward. Note, for example, that with respect to the 2D-image–3D-object relation, the degree of occlusion is equal for all RS completions and for all RL completions, whereas at the level of the SIT structural descriptions, occlusion might differentially affect superstructures and subordinate structures. It is our preliminary guess that partial occlusion of the superstructure has a greater impact on the perceived completion.

Although the correlations between the predictive measures of the symmetry account and the SIT account are rather high, there are a few differences that deserve some further attention. Comparing, for example, the plots of Figure 14B and Figure 14D, it can be seen that the I and I* values are more widely spread than the S and S* values. The data for S* are much more centered around $dS^* = 0$ than are the data for I* around $dI^* = 0$. This reflects the fact that SIT accounts in a more differential way for different regularities than does a mere mirror-symmetry approach. Note further that theoretically ambiguous RS–RL completions for which $dI^* = 0$ appear to be much more ambiguous experimentally than theoretically ambiguous RS–RL completions for which $dS^* = 0$. These differences tentatively illustrate that an account of the data seems more successful if it includes, like SIT, various structural aspects. In future research, it would be a respectable goal to further investigate specific explanations that emerge from the two different accounts.

Finally, completion research on 3D object images may provide interesting findings for the broader domain of object recognition as well. For example, the tendency toward object symmetry and the orientational effects observed in our experiments may contribute to the debate on whether object recognition is determined by viewpoint-independent, object-intrinsic properties or by viewpoint-dependent mechanisms (e.g., see Biederman & Gerhardstein, 1993; Tarr, 1995). It is our belief that ultimately object completion will be considered an inextricable part of object interpretation (see also Van Lier, 1999) and that relevant issues on object completion also hold for object recognition (and vice versa).

Conclusion

It has been shown that matching two images of a depth-rotated object depends on the specific disambiguation of the back of an object. If two images reveal different surfaces, matching is generally slower than if parts of the same surfaces are visible in both images. In the former case, matching depends on global and local completion tendencies of the ambiguous object rear. In addition, the presence versus absence of within-object regularities plays an important role in the prevalence of a specific object completion but cannot account for all of the data.

References

Barlow, H. B., & Reeves, B. C. (1979). The versatility and absolute efficiency of detecting mirror symmetry in random dot displays. *Vision Research, 19,* 783–793.

Bauer, B., & Jolicœur, P. (1996). Stimulus dimensionality effects in mental rotation. *Journal of Experimental Psychology: Human Perception and Performance, 22,* 82–94.

Bethell-Fox, C. E., & Shepard, R. N. (1988). Mental rotation: Effects of stimulus complexity and familiarity. *Journal of Experimental Psychology: Human Perception and Performance, 14,* 12–23.

Biederman, I. (1987). Recognition by components: A theory of human image understanding. *Psychological Review, 94,* 115–147.

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.

Bruce, V., & Morgan, M. (1975). Violations of symmetry and repetitions in visual patterns. *Perception, 4,* 239–249.

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

Cooper, L., & Podgorny, P. (1976). Mental transformations and visual complexity processes: Effects of complexity and similarity. *Journal of Experimental Psychology: Human Perception and Performance, 2,* 503–514.

Corballis, M., & Roldan, C. (1974). On the perception of symmetrical and repeated patterns. *Perception & Psychophysics, 16,* 136–142.

Corballis, M., & Roldan, C. (1975). Detection of symmetry as a function of angular rotation. *Journal of Experimental Psychology: Human Perception and Performance, 1,* 221–230.

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

Folk, M. D., & Luce, R. D. (1987). Effects of stimulus complexity on mental rotation rate of polygons. *Journal of Experimental Psychology: Human Perception and Performance, 13,* 395–404.

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

Hatfield, G., & Epstein, W. (1985). The status of the minimum principle in the theoretical analysis of visual perception. *Psychological Bulletin, 97,* 155–186.

Hochberg, J., & McAlister, E. (1953). A quantitative approach to figural 'goodness.' *Journal of Experimental Psychology, 46,* 361–364.

Julesz, B. (1971). *Foundations of cyclopean perception.* Chicago: University of Chicago Press.

Kahn, J., & Foster, D. (1986). Horizontal-vertical structures in the comparison of rigidly transformed patterns. *Journal of Experimental Psychology: Human Perception and Performance, 12,* 422–433.

Kanizsa, G., & Gerbino, W. (1982). Amodal completion: Seeing or thinking? In J. Beck (Ed.), *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.

Koenderink, J. (1990). *Solid shape.* Cambridge, MA: MIT Press.

Koffka, K. (1935). *Principles of Gestalt psychology.* New York: Harcourt, Brace & World.

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.

Lowe, D. (1987). The viewpoint consistency constraint. *International Journal of Computer Vision, 1,* 57–72.

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

Palmer, S., & Hemenway, K. (1978). Orientation and symmetry: Effects of multiple, rotational, and near symmetries. *Journal of Experimental Psychology: Human Perception and Performance, 4,* 691–702.

Pani, J. (1993). Limits on the comprehension of rotational motion: Mental imagery of rotations with oblique components. *Perception, 22,* 785–808.

Pani, J. R. (1999). Descriptions of orientation and structure in perception and physical reasoning. In E. Winograd, R. Fivush, & W. Hirst (Eds.), *Ecological approaches to cognition: Essays in honor of Ulric Neisser* (pp. 59–95). Mahwah, NJ: Erlbaum.

Pani, J. R., Jeffres, J. A., Shippey, G. T., & Schwartz, K. J. (1996). Imagining projective transformations: Aligned orientations in spatial organization. *Cognitive Psychology, 31,* 125–167.

Pani, J., William, C., & Shippey, G. (1995). Determinants of the perception of rotational motion: Orientation of the motion to the object and to the environment. *Journal of Experimental Psychology: Human Perception and Performance, 21,* 1441–1456.

Parsons, L. (1995). Inability to reason about an object's orientation using an axis and angle of rotation. *Journal of Experimental Psychology: Human Perception and Performance, 21,* 1259–1277.

Rock, I., & DiVita, J. (1987). A case of viewer-centered object perception. *Cognitive Psychology, 19,* 280–293.

Rock, I., Wheeler, D., & Tudor, L. (1989). Can we imagine how objects look like from other viewpoints? *Cognitive Psychology, 21,* 185–210.

Royer, F. (1981). Detection of symmetry. *Journal of Experimental Psychology: Human Perception and Performance, 7,* 1186–1210.

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.

Shepard, R., & Metzler, J. (1971). Mental rotation of three-dimensional objects. *Science, 171,* 701–703.

Shepard, S., & Metzler, D. (1988). Mental rotation: Effects of dimensionality of objects and type of task. *Journal of Experimental Psychology: Human Perception and Performance, 14,* 3–11.

Shiffrar, M., & Shepard, R. (1991). Comparison of cube rotations around axes inclined relative to the environment of the cube. *Journal of Experimental Psychology: Human Perception and Performance, 17,* 44–54.

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.

Takeichi, H., Murakami, I., Nakazawa, H., & Shimojo, S. (1995). The theory of the curvature constraint line for amodal completion. *Perception, 24,* 373–389.

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 & Review, 2,* 55–82.

Van der Helm, P. (1988). *Accessibility and simplicity of visual structures.* Unpublished doctoral dissertation, University of Nijmegen, Nijmegen, the Netherlands.
Van der Helm, P., & Leeuwenberg, E. (1986). Avoiding explosive search in automatic selection of simplest pattern codes. *Pattern Recognition, 19,* 181–191.
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. (1999). Investigating global effects in visual occlusion: From a partly occluded square to the back of a tree-trunk. *Acta Psychologica. 102,* 203–220.
Van Lier, R., Leeuwenberg, E., & Van der Helm, P. (1995). 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., 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. (1995). Competing global and local completions in visual occlusion. *Journal of Experimental Psychology: Human Perception and Performance, 21,* 571–583.
Vetter, T., & Poggio, T. (1994). Symmetric 3D objects are an easy case for 2D object recognition. *Spatial Vision, 9,* 443–453.
Wagemans, J. (1993). Skewed symmetry: A nonaccidental property used to perceive visual forms. *Journal of Experimental Psychology: Human Perception and Performance, 19,* 364–380.
Wagemans, J. (1995). Detection of visual symmetries. *Spatial Vision, 9,* 9–32.
Wagemans, J. (1997). Characteristics and models of human symmetry detection. *Trends in Cognitive Sciences, 1,* 346–352.
Wagemans, J., Van Gool, L., & d'Ydewalle, G. (1991). Detection of symmetry in tachistoscopically presented dot patterns: Effects of multiple axes and skewing. *Perception & Psychophysics, 50,* 413–427.
Wagemans, J., Van Gool, L., & d'Ydewalle, G. (1992). Orientational effects and component processes in symmetry detection. *Quarterly Journal of Experimental Psychology, 44A,* 475–508.
Wagemans, J., Van Gool, L., Swinnen, V., & Van Horebeek, J. (1993). Higher-order structure in regularity detection. *Vision Research, 33,* 1067–1088.
Wouterlood, D., & Boselie, F. (1992). A good-continuation model of some occlusion phenomena. *Psychological Research, 54,* 267–277.
Yuille, J., & Steiger, J. (1982). Nonholistic processing in mental rotation: Some suggestive evidence. *Perception & Psychophysics, 31,* 201–209.

Appendix

Structural Information Theory (SIT): Coding Rules, Information Loads, and Object Complexity

SIT encoding starts with a symbol series and accounts for a maximum of regularity within the symbol series, resulting in a minimum code. Three types of regularity are specified within SIT: iteration, symmetry, and alternation. In Table A1, the coding rules that describe these regularities are given. Within the minimum code, the number of parameters at all hierarchical levels determines the information load (I) and reflects the amount of irregularity in the series (see Van der Helm et al., 1992). For example, the minimum encoding of the series *abab* is given by 2*(*ab*). The I load of this code is 3 because of the symbols *a* and *b* (parameters at the lowest level) and the group *ab* (parameter at the highest level). The encoding procedure, from a symbol series to its minimum code, has been implemented in a computer algorithm called PISA (Van der Helm, 1988; Van der Helm & Leeuwenberg, 1986).

The RL completion of Set 1 (Figure A1) can be described by two components: a "double-diamond" shape (i.e., the top surface of the object) and a straight line. The description can be visualized by moving the straight line along the double-diamond shape, which would mimic, or reconstruct, the object's contours. In the visualized code in Panel A of Figure A1, the two components are shown. The relative positions of the components in that code indicate their super-subordinate relationship (for this object, the relationship could, in principle, be reversed, but this possibility is left out of consideration). The symbol α represents the angular connection between the components. After this decomposition, its information load (I) can be determined. First, all lines and angles are labeled, such that equal lines and angles have equal symbols. In this encoding, the superstructure and subordinate structure are kept separate. Next, the sequence of symbols is encoded into a parametric code by means of the computer program PISA (Van der Helm & Leeuwenberg, 1986), following the procedure described by Van der Helm and Leeuwenberg (1991) and Van der Helm et al. (1992). The number of descriptive parameters in the code gives the complexity of the object in terms of structural information (for this completion, I = 8).

In Panel B of Figure A1, the same has been done for the RS completion of Set 1. This time the double-diamond superstructure is interrupted because there are different subordinate components. The larger part of the superstructure has the same straight-line subordinate structure as earlier, whereas a smaller part has a

Table A1
SIT Coding Rules

Regularity	Symbol series	Code	Information load
Iteration	*aa*	2*(*a*)	1
Symmetry	*abcba*	S[(*a*)(*b*), (*c*)]	3
Alternation	*abac*	⟨(*a*)⟩/⟨(*b*)(*c*)⟩	3

Note. The three types of regularity used within structural information theory (SIT) are shown. The encoding of a symbol series proceeds by extraction of regularities from the series. The information load is determined by the number of parameters in the code.

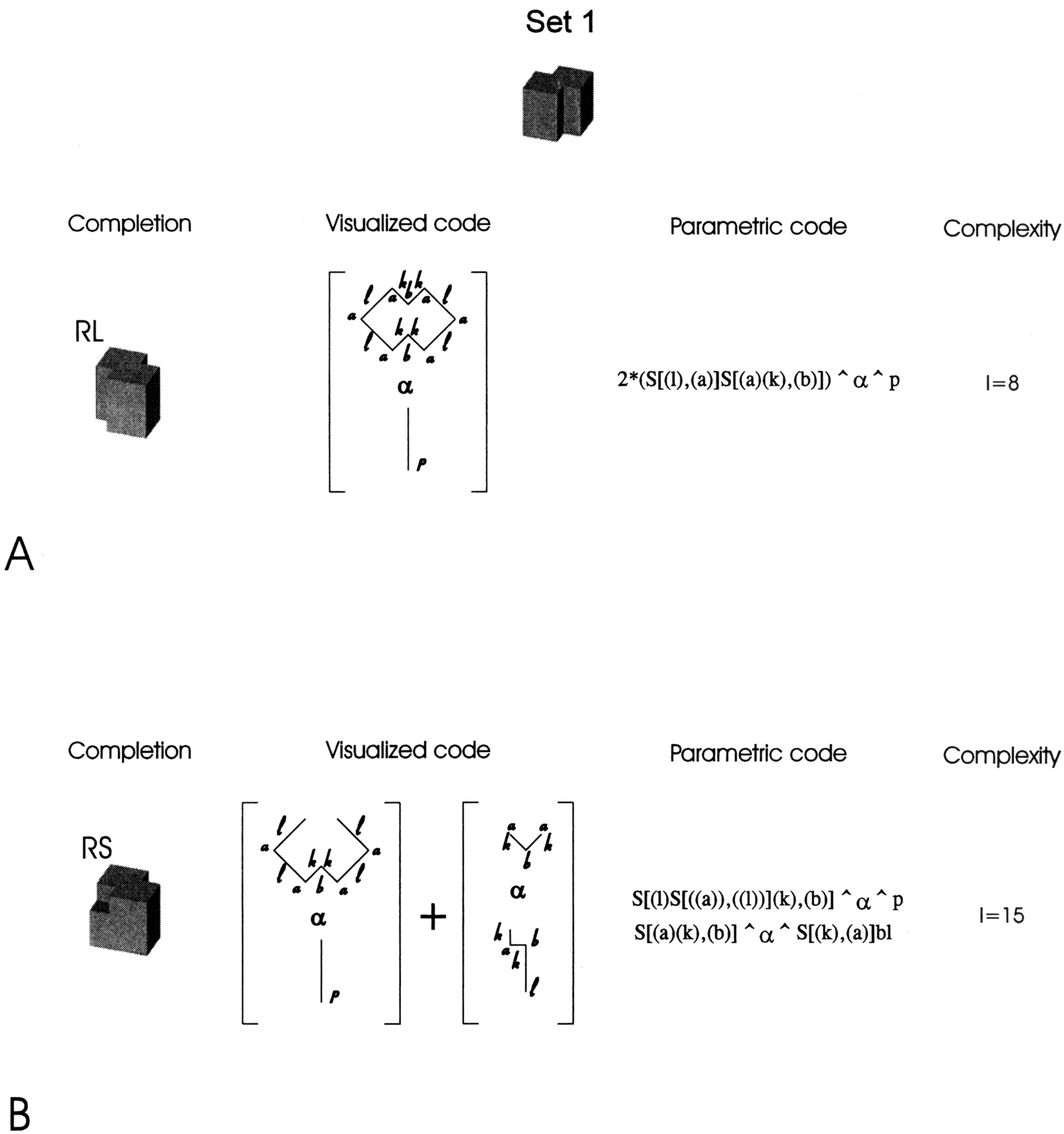

Figure A1. The structural information theory-based visualized codes, parametric codes, and complexities for the RL completion (A) and RS completion (B) of Set 1. RL = long rear indentation; RS = short rear indentation.

hooklike subordinate structure. The encoding procedure itself is similar to the one described earlier. The complexity in terms of structural information for this completion is I = 15. Because the RL completion has a lower complexity than the RS completion, the RL completion is predicted to be preferred to the RS completion. Similar encodings and calculations have been applied to obtain the I values (and I* values) for all other completions, as given in Table 1.

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