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Differentiating Global and Local Contour Completion Using a Dot Localization Paradigm

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Competing theories of partially occluded object perception (amodal completion) emphasize either relatively local contour relationships or global factors such as symmetry. These disparate theories may reflect 2 separate processes: a low-level contour interpolation process and a higher-order global recognition process. The 2 could be distinguished experimentally if only the former produces precise representations of occluded object boundaries. Using a dot localization paradigm, we measured the precision and accuracy of perceived object boundaries for participants instructed to complete occluded objects with divergent local and global interpretations. On each trial, a small red dot was flashed on top of an occluder. Participants reported whether the dot fell inside or outside the occluded object's boundaries. Interleaved, 2-up, 1-down staircases estimated points on the psychometric function where the probability was .707 that the dot would be seen as either outside or inside the occluded object's boundaries. The results reveal that local contour interpolation produces precise and accurate representations of occluded contours, and consistency across observers, but completion according to global symmetry does not. These results support a distinction between local, automatic contour interpolation processes and global processes based on recognition from partial information.

Keywords: amodal completion, contour interpolation, occlusion, relatability, symmetry

Even a single glance at an ordinary scene yields the experience of separate objects and surfaces. These outputs of seeing conceal the less complete and more chaotic inputs to vision—scattered patches of color, partially visible surfaces of objects, and pervasive occlusion of object parts and surfaces by other objects. Unlike the color patches, the complete, coherent objects, extended surfaces, and their arrangements in space are meaningful ecological descriptions, crucial to effective thought and action.

Visual interpolation processes convert the fragmentary input at the eyes into the experience of complete, coherent objects. Visual interpolation or completion has been studied for over half a century, and scientists have made important contributions to understanding the processes and mechanisms involved. However, some complicated problems remain. Here, we address several fundamental issues: whether there is one basic visual completion process or two, and whether modular perceptual processes can be distinguished from more open-ended recognition processes. These issues arise in considering global and local influences in visual interpolation. Does visual completion depend on processes that use relatively local geometric relations of edges and junctions, or does it also depend on processes that use global symmetry, simplicity, or familiarity?

These are old questions. Gestalt psychologists in the early 20th century may be seen as the source of both global and local theories. Although they did not focus much on visual completion per se, they described principles of simplicity and regularity that were held to apply to perception generally, as in the Gestalt Law of Prägnanz, stating that psychological processes will tend to achieve "the most regular, ordered, stable, balanced state possible" (Koffka, 1935; Wertheimer, 1923/1938). More local contour relations were also seen as important, expressed in the principle of "good curve" or good continuation (Wertheimer, 1923/1938).

Global Influences in Completion

That perceptual outcomes tend to be simple or symmetric implies sensitivity to global shape in completion. Gestalt principles were applied to partly occluded objects most explicitly by Michotte, Thinès, and Crabbé (1964/1991). *Good form* in an occlusion context predicts that one will tend to see the covered part as being whatever is needed to make the whole object as simple (e.g., regular, symmetric) as possible. Later efforts formalized these

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notions in coding theory (e.g., Buffart, Leeuwenberg, & Restle, 1981; Leeuwenberg & van der Helm, 2013), which has since been elaborated to account for some local effects as well (van Lier & Gerbino, 2015).

Familiarity is another possible global influence on completion. Visible regions of an occluded object may be sufficient to activate stored representations of that object or type. Early theories in experimental psychology and the philosophy of perception emphasized the influence of familiarity by holding that all meaningful perception derives from associative learning (Brunswik, 1956; Helmholtz, 1867/1962). This tradition has important contemporary advocates in the form of Bayesian approaches to perception (e.g., Knill & Richards, 1996). In contrast, the Gestalt psychologists argued for both theoretical and empirical reasons, that familiarity was not a major determinant of perceptual organization. Empirically, studies attempting to change perceptual segmentation and grouping (Gottschaldt, 1926/1938) or visual completion (Michotte et al., 1964/1991) through learning provided some evidence against such effects.

Local Contour Relationships in Completion

Michotte et al. (1964/1991) invoked the Gestalt principle of good continuation as a determinant of visual completion, first described by Wertheimer as the principle of “good curve” or “good continuation” (Wertheimer, 1923/1938). Wertheimer’s treatment focused on contour continuation in segmenting fully visible displays (continuous, branching lines), but relatively local contour relationships have been shown to be important in understanding visual completion.

The geometric relations supporting contour interpolation have been formally characterized in recent years (Kellman, Garrigan, & Shipley, 2005; Kellman & Shipley, 1991). Candidates for interpolation are contour segments ending in points of tangent discontinuity (i.e., junctions or corners), most commonly produced by partial occlusion, but also by ‘L’ junctions in illusory contour displays (Kellman & Shipley, 1991; Rubin, 2001; Shipley & Kellman, 1990). Pairs of such edges produce contour connections across gaps if they are *relatable*; that is, if they can be connected by a smooth, monotonic curve (see below). It has been proposed that all such connections are made in an intermediate representation; other constraints determine whether or how they appear in final scene representations (Kalar et al., 2010; Kellman, Garrigan, & Shipley, 2005; Kellman, Guttman, & Wickens, 2001). In this “promiscuous interpolation” view (Kellman, Guttman, & Wickens, 2001), the intermediate representation forms the substrate for final scene appearance of interpolated contours as partly occluded or illusory contours and surfaces. In some cases, competition among interpolations, or issues of border ownership, surface continuity, or closure may lead to weak or absent contour connections in the final scene representation (for discussion, see Kellman, Garrigan, & Shipley, 2005). For example, in the “path detection” paradigm of Field, Hayes, and Hess (1993), relatable Gabor elements group and appear to pop-out, yet no continuous, illusory contour connections are seen.

Interpolated edges match the orientation of inducing edges at points of tangent discontinuity (Kellman & Shipley, 1991). A pair of input edges is relatable if they can be connected by a smooth, monotonic curve bending no more than 90 degrees (for a more formal treatment, see Kalar et al., 2010). This criterion specifies the approximate boundary between edge fragments that do or do not connect, often the most important outcome for object perception. Within the category of relatable edges, strength of interpolation depends both on the support ratio (Banton & Levi, 1992; Shipley & Kellman, 1992) and relative angle (Singh & Hoffman, 1999). Subjective report and objective priming methods tend to find some evidence for weak interpolation effects somewhat beyond the 90 degree criterion (Fulvio, Singh, & Maloney, 2009; Guttman, Sekuler, & Kellman, 2003), whereas objective performance methods tend not to show interpolation effects beyond 90 degrees (e.g., Field, Hayes, & Hess, 1993).

This account is consistent with a wealth of empirical results (Field, Hayes, & Hess, 1993; Fulvio, Singh, & Maloney, 2008; Geisler & Perry, 2009; Kellman & Shipley, 1991; McDermott, Weiss, & Adelson, 2001; Saidpour, Braunstein, & Hoffman, 1994; Shipley & Kellman, 1992), and generalizations of relatability have been shown to account for objective performance data in three-dimensional (3D) contour interpolation (Kellman, Garrigan, & Shipley, 2005), 3D surface interpolation (Fantoni, Hilger, Gerbino, & Kellman, 2008; Saidpour, Braunstein, & Hoffman, 1994), and spatiotemporal interpolation (Keane, Lu, & Kellman, 2007; Palmer, Kellman, & Shipley, 2006).

What Is the Relationship Between Global and Local Influences in Completion?

As research has progressed toward more precise models, principles from the Gestalt school and empiricist traditions need to be better specified and reconciled. Traditional treatments often described an idea and gave a display to demonstrate it. This has heuristic value but leaves questions about how things work when more than one principle is involved and whether there is one overall process or multiple processes in visual interpolation. This question is our focus.

Figure 1 shows an example that may involve multiple influences in visual completion. There is a clear perception of occlusion, and

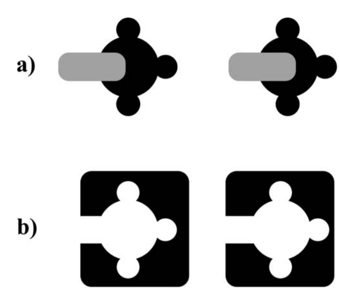

Figure 1. Figure with multiple influences in visual completion. The depth relations are reversed in (a) and (b). Both displays are stereo pairs that can be free-fused by crossing the eyes. Stereoscopic viewing enhances the effects but is not necessary. (a) Occluded display that has been claimed to support a global completion process based on symmetry. The symmetric interpretation of the occluded figure involves perceiving a fourth articulated lobe behind the occluder, as in Figure 5b. (b) Illusory contour version of (a). Here, the completed figure appears in front of the white background (the gray “occluder” region in a) against which it lacks contrast. While (a) has been claimed to support a symmetric global completion, such a claim is never made about illusory figures such as (b).

it is also clear that most of the black figure is unoccluded. What shape does the occluded portion have? From a global symmetry perspective, one would predict a fourth articulated lobe of the figure behind the occluder. Results from priming paradigms have found support for such global completion (Sekuler, Palmer, & Flynn, 1994), while results from drawing tasks and simultaneous matching tasks have found support for both local and global interpretations (Takashima, Fujii, & Shiina, 2009; van Lier, van der Helm, & Leeuwenberg, 1995).

Kanizsa (1979) was perhaps the first to explore in detail displays with global and local completion predictions that were placed in conflict. Figure 2 shows two such displays from Kanizsa (1979). The reader may confirm Kanizsa's observation that local continuity dominates any global influence on completion in these displays.

As we have considered, other demonstrations and data support both global and local factors in visual object completion. It is clear from studies of local contour linking processes that they can operate without supporting global influences (Field, Hayes, & Hess, 1993; Kellman et al., 2010). Global completion theories would involve completion of hidden areas in accord with overall symmetry or familiarity, which would sometimes result in contour completions inconsistent with local interpolations. Are global and local theories in conflict? How can the importance of local and global influences be reconciled?

One interpretation of Kanizsa's demonstrations is that both local and global influences are factors in completion, but local continuity is more powerful. A different idea is suggested by priming studies indicating that ambiguous displays can prime both global and local completions (van Lier et al., 1995). Although these issues have been discussed for decades, there is no clear model or data that indicates whether global and local factors contribute to the same perceptual representations, produce separate parallel representations, sometimes combine, and at other times coexist, or what rules might govern what happens when.

Here we propose and investigate a different hypothesis: The apparently different effects of global and local factors may be explained by the existence of two separable processes in the formation of object representations. The first is a modular, bottom-up perceptual process that completes contours based on local geometry. The output of this process is a precise perceptual representation of the locations of interpolated contours. The second process is a higher-order, top-down, more cognitive process that uses global cues such as symmetry and regularity, and/or past experience, to suggest the most likely shape of a partially occluded object. We have previously raised this possibility and labeled it *recognition from partial information* or RPI (Kellman, 2001; Kellman, 2003; Kellman, Garrigan, & Shipley, 2005; Kellman, Garrigan, Shipley, & Keane, 2007). It seems likely that this second process is not "perceptual" in the same way as the first. It consists of the activation of representations that may be consistent with a partly hidden object, but it does not create precise interpolated contours. The outcome of this second process would consist at least of a hypothesis or decision regarding the likely symmetry or familiarity of the object, *but would not include a perceptual representation with precise borders*. Figure 3 contrasts these two ideas about completion of partly occluded objects.

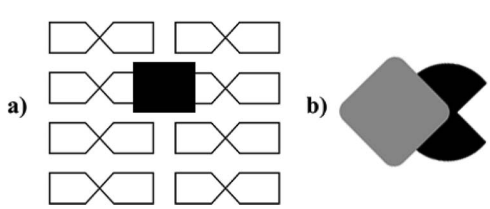

Figure 2. Occluded displays that support local completion (after Kanizsa, 1979). (a) The regularity of the pattern suggests that behind the occluder are the ends of two pentagons separated by a gap. Nevertheless, the disconnected contours appear connected with straight lines. (b) The occluded portion of the figure appears completed with a smooth curved edge, even though bilateral symmetry relative to a vertical axis suggests otherwise.

Although seeing the cat's head and tail, or even just the tail, is sufficient to create an impression of a cat behind the occluder, this activation of a representation does not appear to include filling-in of particular contours in precise positions connecting the visible regions behind the occluder.

Evidence from illusory figures supports the idea of two separate processes. Many studies indicate commonalities in the processes that generate partly occluded contours (amodal completion) and those that generate illusory contours (modal completion). According to the *identity hypothesis*, an identical contour linking process underlies contour interpolation in occluded and illusory figures (Kellman & Shipley, 1991; Kellman, Yin, & Shipley, 1998; Ringach & Shapley, 1996; Shipley & Kellman, 1992). Although similarities or small differences in psychophysical data in comparable occluded and illusory displays cannot conclusively confirm or refute the identity hypothesis (see Kellman, Yin, & Shipley, 1998; Zhou, Tjan, Zhou, & Liu, 2008), many studies using objective performance methods show highly similar patterns for comparable illusory and occluded displays (Guttman & Kellman, 2004; Kellman, Yin, & Shipley, 1998; Palmer, Kellman, & Shipley, 2006). Perceptual phenomena involving crossing interpolations, such as the Petter Effect, have been argued to *logically imply* the identity hypothesis (Kellman, Garrigan, & Shipley, 2005; Kellman, Garrigan, Shipley, & Keane, 2007; Kellman, Yin, & Shipley, 1998). Recent electrophysiological data on contour interpolation in occluded and illusory displays has strongly supported the identity hypothesis (Murray, Foxe, Javitt, & Foxe, 2004; Shpaner, Murray, & Foxe, 2009).

What does the identity hypothesis have to do with the possibility of separable local and global processes in amodal completion? Global completion ideas draw from general theories of simplicity, regularity, or familiarity in perception, ideas that have been invoked to explain both amodal and modal completion. Curiously, however, there appear to be no phenomena in illusory contour perception in which visual completion creates symmetrical parts. For example, the fourth articulated lobe predicted by global completion in Figure 1a has no counterpart in any claims made about illusory figure displays. One simply does not see such completions. Figure 1b shows an illusory contour version of the shape shown in Figure 1a. The visible contours for this shape and the gaps between visible contours are identical to those shown in Figure 1a. However, there is no tendency for observers to perceive a fourth lobe of a symmetric figure. The situation is similar for familiarity. To our knowledge, there are no reports of illusory contour perception based on familiarity as assessed by objective performance methods or subjective methods with care taken to

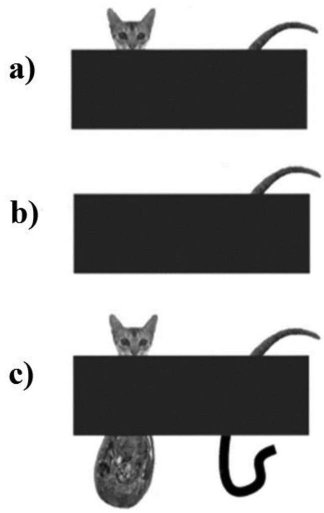

Figure 3. Examples of recognition from partial information and contour-interpolation processes. (a) When presented with this display, observers readily report a cat behind the occluder whose head and tail form a connected object. (b) Even the tail alone may be sufficient to evoke reports or beliefs about a cat behind the occluder. (c) Contour-interpolation processes connect the cat's head to the vase and its tail to the curved line; they do not connect the cat's head and tail, although an observer may still believe in or report such a connection. From Kellman, Garrigan, and Shipley, *Psychological Review*, 2005; reprinted by permission.

minimize response bias. Kanizsa (1979) produced numerous demonstrations pitting familiarity or physical possibility against autonomous completion processes based on contour relations. His demonstrations seem compelling in showing that familiarity and plausibility have little or no role in inducing completion.

Global influences have been claimed to produce symmetric or familiar figures in amodal completion but not in modal completion. Modal and amodal completion appear to share an identical underlying contour linking process. If both of these ideas are correct, the simplest reconciliation is that there are two kinds of processes at work in amodal completion, one of which does not operate in modal completion. The contour interpolation process underlying both modal and amodal completion fills in contours across gaps in the input with equally precise detail about contour locations (Guttman & Kellman, 2004). Under occlusion, however, in addition to this perceptual completion process, RPI may suggest what might lie behind an occluder. To give an extreme example, one may know what lies behind the opaque doors of a cabinet in one's kitchen, yet this is not a perceptual interpolation process. Prior knowledge, sensitivity to potential familiarity of objects from visible color or object parts, or sensitivity to the possibility of a symmetric object may all allow expectations about partly hidden areas of our perceived world. RPI does not apply in modal completion, because perceptually completed areas appear in front, unoccluded. Guesses, memories, recognition of potential symmetry of what might be behind an occluder do not occur when there is no occluder. This idea could explain the lack of symmetry and familiarity based completions in illusory contours and figures.

Michotte et al. (1964/1991) explicitly contrasted such knowledge with the automated process of amodal completion. He showed a triangle, like that in Figure 4a, that was occluded across its middle, and which appeared to be a simple, complete (partially occluded) triangle. However, when the occluder was removed, it was revealed that the lines of the triangle crossed in the area covered up by the occluder. Even given this knowledge about the complete form of the drawing, when the occluder was replaced, participants continued to experience the compelling perception of a simple triangle lying behind the occluder. He argued that there was a difference between perceptual processes that complete the contours of the triangle in collinear fashion and knowledge-based processes that would allow the subject to remember the more complex figure behind the occluder.

To summarize the hypothesis of separable processes: A basic, low-level, bottom-up, perceptual contour completion process outputs a crisp, precise perceptual representation of interpolated contours in occluded and illusory objects. When occlusion is present, a second, higher-order, top-down, cognitive process comes into play. This RPI may suggest a likely shape of the object. Here, the viewer arrives at a decision regarding the likely shape of the object, but they do not have a crisp, precise, perceptual representation of the occluded contours.

Experimental Approach

In the experiments reported here, we attempted to distinguish these putative dual processes experimentally. If there are two processes that lead to reports of completion under occlusion, they may have different properties, and these may be accessible through certain kinds of experimental tasks. Contour interpolation should give rise to precise boundary representations, whereas RPI should only provide a vague idea of where contours and surfaces are actually positioned behind an occluder. In the case of symmetric completions, this would be an interesting empirical finding, as there is nothing inherent in the conceptual idea of global symmetry that would preclude it from specifying the exact positions of hidden parts. Not only can mathematical computations using symmetry and the visible parts produce an exact result in such cases, but in other contexts, humans have been shown to have high sensitivity to symmetry across large regions of the visual field (Tyler & Hardage, 1996; Wenderoth, 1995). Mirror symmetry effects in other perceptual tasks (e.g., detecting perfect or partial

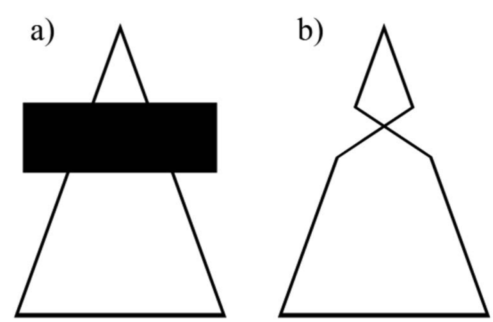

Figure 4. Michotte's triangle (redrawn from Michotte et al., 1964/1991). (a) Observers report the perception of a triangle lying behind the occluder. (b) The occluder is removed, and it is revealed that the lines cross. Despite this information, when the occluder is replaced, participants continue to perceive a regular triangle lying behind the occluder.

symmetry in mirror-symmetric dot patterns) show a high degree of precision, with estimates in the 4–12′ range for localization of individual elements (Barlow & Reeves, 1979; Jenkins, 1985). Accordingly, if a truly perceptual symmetry-based process operates in amodal completion, we might expect global completion of this sort to produce accurate and precise boundary representations, consistent across observers.

The following experiments utilized stimuli for which the global interpretation exhibits mirror symmetry about a vertical axis, as many studies have shown that reflection about a vertical axis is more salient than other types of symmetry, and is detected rapidly and spontaneously (Corballis & Roldan, 1974, 1975; Goldmeier, 1937/1972; Mach, 1897; Rock & Leaman, 1963; Palmer & Hemenway, 1978; Wagemans, Van Gool, & d'Ydewalle, 1992; Wenderoth, 1994).

To test these possibilities, we used a dot localization method developed by Guttman & Kellman (2004; see also Pomerantz, Goldberg, Golder, & Tetewsky, 1981); this method has been shown to be a sensitive indicator of contour interpolation in a number of studies (Guttman & Kellman, 2004; Maertens & Shapley, 2008; Stanley & Rubin, 2003). The dot localization task was used here in three experiments. Experiment 1 focused on displays having visible parts consistent with the possibility of both bilateral and rotational symmetry, both of which would imply an articulated part behind the occluder. These displays were partly occluded in such a way that two relatable edges could give rise to a local, smooth contour completion that would produce an asymmetric overall object. The two displays, with divergent local and global completions, are shown in Figure 5. They are similar to stimuli used in match-to-sample priming tasks that found support for dominant global processes in perceptual completion (Sekuler, Palmer, & Flynn, 1994). As we will see, Experiment 1 showed that local contour interpolation produces precise, accurate representations of interpolated contours that are consistent across participants, while global contour interpolation does not. Issues unaddressed by Experiment 1 and other related issues are the focus of Experiments 2a, 2b, and 3.

Participants completed either a local or global contour interpolation in a dot localization task. They were presented with an occluded display, and then a red probe dot was briefly flashed somewhere on the occluder. Participants were tasked with reporting whether the probe dot fell inside or outside of the occluded object's boundaries. Two adaptive staircases were used to estimate the distance, in terms of pixels away from the boundary, where the

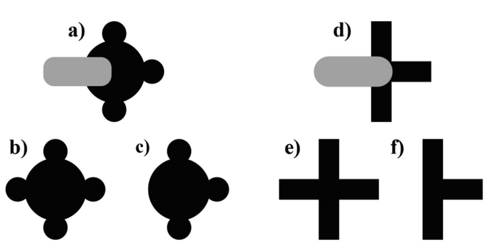

Figure 5. Displays used in Experiment 1. (a) Occluded version of the Bumps display, along with the (b) global and (c) local completions. (d) Occluded version of the Cross display, along with the (e) global and (f) local completions. Bumps and Cross are similar to figures that have been used in previous experiments that found support for global completion.

probability was .707 that the dot would be seen as inside and outside the boundary.

The primary measure we examined was *imprecision*, which was operationalized as the distance between the outer and inner thresholds. We hypothesized that local contour interpolation processes produce representations with precise boundary locations, while global completion processes produce imprecise boundary locations. Thus, we expected to find that participants in the global group would have greater imprecision than participants in the local group.

We also examined two other dependent measures. The first is *location*, which was measured as the distance of the mean of the outer and inner thresholds from the theoretical location of the occluded object boundary. Because the measures are averaged across participants within a group, average group location reveals the overall tendency within a group to see the boundary as left or right of where it truly lies. This measure is worth examining because it is possible that our best predictions of the location for local interpolations, based on the geometry, are not quite perfect. The results of a previous study suggest that local interpolation may give us flatter completions than the relatability geometry would predict (Guttman & Kellman, 2004). It would be interesting (and would invite follow-up studies) if we found that local participants consistently tend toward flatter completions. In addition, finding that participants in the local group tend toward flatter completions while participants in the global group do not would provide further evidence for the separation of these two processes.

We also examined *location error*, which was measured as the mean of the absolute value of location. This differs from the location measure in that it averages across participants the unsigned deviation from the theoretical location, rather than the signed deviation. For the location data, two participants with opposite and equal deviations of 5 pixels would average to 0 error, whereas for the location error variable, their average would be 5. The location error measure captures the inaccuracy that participants within a group exhibit overall, without respect to the direction (left or right of the true boundary) of the error in location. It would be interesting if, in addition to producing *imprecise* boundary locations, global displays also showed large average deviations across participants from the theoretical boundary location.

As we will see, the results provide strong evidence of two complementary amodal completion processes. One is clearly perceptual in that it produces, behind occluders, precise representations of object boundaries. The other seems to be better characterized as global activation of a more conceptual representation. Unlike perception of contours and objects in other contexts, this more conceptual process does not seem to produce either accurate or precise representations of hidden boundaries.

Experiment 1

Method

Participants. A sample of 35 participants (22 women) completed the experiment. Three were excluded for failing an objective measure of task compliance (described below), leaving 32 participants in the final sample, with 16 participants in each group. All participants provided informed consent, were students attending the University of California, Los Angeles, reported having normal or corrected-to-normal vision, and normal color vision (no colorblindness). Participants received partial course credit for their participation.

Displays. The experiment utilized two occluded displays, with divergent local and global completions, similar to those used in priming match-to-sample tasks (Sekuler, Palmer, & Flynn, 1994). The "Bumps" display subtended 17.03° × 14.10° of visual angle in total; the occluder subtended 9.68° × 4.10°, and the visible regions subtended 10.97° × 14.1°. The "Cross" display subtended 16.56° × 14.10° of visual angle in total; the occluder subtended 11.16° × 4.29°, and the visible regions subtended 8.53° × 14.10°.

Task instructions. Participants were randomly assigned to one of two groups, global or local, and received different instructions depending on their group assignment. Those in the local group were told that the object was not symmetrical, and that the hidden edge lying behind the occluder was a simple, monotonic, curved or straight continuation of the two visible edges. Participants in the global group were told that the object was symmetrical, and that the hidden edge lying behind the occluder completed the object symmetrically.

Before beginning the computer portion of the experiment, a research assistant presented participants with black cardstock cutouts of the stimulus objects partially covered by gray cardstock cut-outs of the occluders. The participants were then asked to describe the hidden edge of each occluded object. The occluder was then removed, and the cut-out object was revealed. The set of cut-out objects for each condition matched the completion the participants were expected to use in the computer portion of the experiment. Participants did not proceed with the computer portion of the task until they demonstrated that they understood what the hidden edge of the object looked like.

As an additional check that the participant understood the instructions, each participant was required to complete a drawing test, in which they drew, on top of the gray occluder, the boundary of the black object that fell behind the occluder. All participants passed this test.

Apparatus. All displays were created and displayed using the MATLAB programming language and the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997). Stimuli were presented on a ViewSonic G220fb CRT monitor with a 1,024 × 768 resolution, powered by a Power Macintosh computer with a 2 GHz Dual-Core PowerPC G5 processor and an nVidia Quadro FX 4500 graphics card. Participants sat with their head 60 cm away from the screen, ensured by an adjustable chin rest. Participants completed the experiment alone in a dark room, while wearing noise-cancelling headphones. The 'z' and '/' keys were marked with glow-in-the-dark tape so that they could be easily located in the dark.

Procedure. Participants provided informed consent, received task instructions, and were seated at the computer in the chinrest. At the beginning of each trial, a focus rectangle was presented on-screen for a duration of 500 ms and was jittered from trial to trial by up to 1.0° from the center of the screen. Next, the stimulus was presented for 400 ms with a red dot (6.71 × 6.71 arcmin) displayed for the last 50 ms along the X axis at a given coordinate while the Y coordinate remained unchanged from trial to trial. A mask consisting of randomly arranged grayscale ellipses then filled the screen for 400 ms. The participant then responded whether the red dot had appeared inside or outside of the occluded boundary of the object by pressing the 'z' key for 'outside' and the '/' key for 'inside.'

Two interleaved, adaptive staircases estimated the distance, in terms of pixels away from the boundary, where the probability was .707 that the dot would be seen as falling outside the boundary (outer threshold) or inside the boundary (inner threshold) for each object (four staircases total). Each staircase had a step size of 10 pixels for two reversals, 5 pixels for two reversals, and then 1 pixel for eight reversals. The last eight reversals were averaged to estimate the threshold for each staircase. The entire experiment took less than half an hour (roughly 400 trials).

To ensure that participants did not change their percept midway through the experiment, participants were required to complete a second drawing test identical to the first after completing the computer task. All participants passed this test.

Dependent measures and data analyses. The experiment followed a 2 × 2 mixed factorial design, with one between-subjects variable (Condition: local vs. global), and one within-subjects variable (Stimulus: Bumps and Cross). We hypothesized that local contour interpolation processes produce representations with precise boundary locations, while global completion processes produce imprecise boundary locations. Thus, the primary measure we examined was *imprecision* (measured as the distance between the outer and inner thresholds). We also examined *location* (measured as the distance, from zero, of the mean of the outer and inner thresholds). Because the measures are averaged across participants within a group, differences in average group location may reveal different tendencies within the groups to see the boundary as lying left or right of where it truly falls. Finally, we examined *location error* (defined as the mean of the absolute value of each participant's location). Location error provides an indication of how far away from the true boundary participants within a group perceive the boundary to be, on average.

Exclusion criteria. To identify participants not making an honest effort to complete the task, catch trials were randomly inserted with a 1/50 chance at the end of each trial. Catch trials were similar to normal trials except that the stimulus and red dot were not presented. Instead, the fixation rectangle was presented twice, followed by the mask, and the participant was instructed either, "Press 'z' if you are paying attention. Press '/' if you are not paying attention." or vice versa. Each catch trial had an equal chance of being a 'z correct' or '/ correct' trial. Participants with worse than 70% correct were thus eliminated from the analysis. This resulted in the elimination of three participants who had achieved only 38, 50, and 60% correct.

Post-experiment drawings were examined to determine if any participants should be excluded for not following task instructions, as evidenced by drawing an incorrect boundary for any stimulus. Three independent raters examined and rated the drawings using a pass/fail criterion. Interrater reliability was 100%. All participants passed all drawing tests. After completing the final drawing test, participants were debriefed and asked whether they found the experiment confusing in any way, and if there was anything they wanted the experimenter to know. No subjects reported any confusions or misbehavior that would result in exclusion from the analysis.

Results

Imprecision. Imprecision scores, shown in Figure 6, reveal substantial differences between the global and local participants. Local group participants were more precise on average and highly

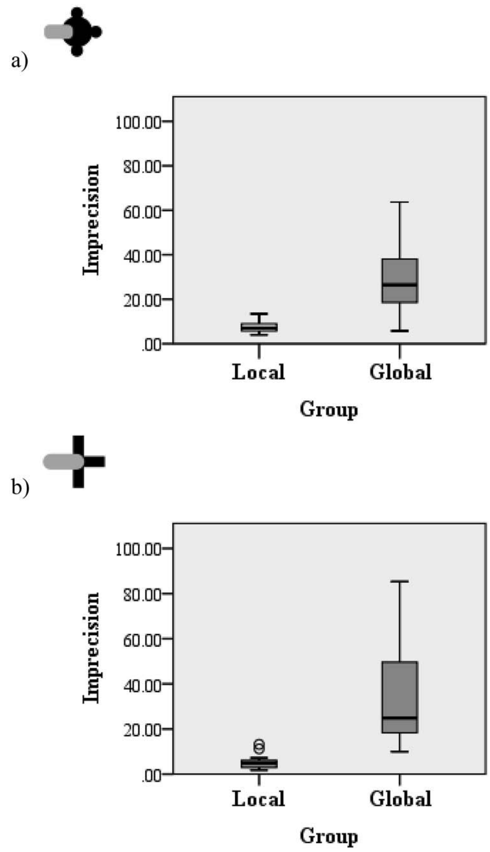

Figure 6. Imprecision Data from Experiment 1. Higher imprecision indicates less precise localization. Boxplots show the distributions of imprecision scores, in arcminutes, for the local and global participant groups for the (a) Bumps and (b) Cross stimuli. The dark line in the middle of the box represents the median imprecision score. The bottom of the box indicates the 25th percentile. The top of the box represents the 75th percentile. The whiskers extend to the most extreme value within 1.5 times the interquartile range. The dots represent outliers.

consistent with each other (i.e., less variable) whereas global participants were both less precise and more variable in their imprecision. Statistical tests confirmed these differences.

Levene's test. Levene's test for equality of variances confirmed the difference in variances evident in Figure 6 (Bumps: $F(1, 30) = 16.82$, $p < .001$, Cross: $F(1, 30) = 25.02$, $p < .001$), indicating that participants in the local group (Bumps: local variance = 8.64, Cross local variance = 9.95) were less variable than participants in the global group (Bumps global variance = 257.45, Cross global variance = 528.63).

Because of both decidedly heterogeneous variances and nonnormality in some cases, two separate analyses were performed. For the first analysis, the data were ranked, and a two-way repeated-measures analysis of variance (ANOVA) was performed on the ranks (Conover & Iman, 1981), followed by individual t tests on the differences between local and global mean ranks. In addition, we report nonparametric bootstrapped confidence intervals (CIs; 95% CI), with identical results.

Rank transformation. The ANOVA on ranks confirmed the differences between groups, $F(1, 30) = 99.63$, $p < .001$. Independent-samples t tests on the differences between the local and global mean ranks found a significant difference for each stimulus (Bumps: $t(30) = -6.96$, $p < .001$, 95% CI [−18.76, −10.24]; Cross: $t(30) = -8.46$, $p < .001$, 95% CI [−19.24, −11.76]), indicating that local participants were more precise (Bumps: $M = 9.25$, $SD = 5.08$; Cross: $M = 8.75$, $SD = 5.18$) than global participants (Bumps: $M = 23.75$, $SD = 6.61$; Cross: $M = 24.25$, $SD = 5.18$). The reported means and *SD*s are the means and *SD*s of the ranks.

A Cohen's d effect size was calculated using the means and *SD*s of the ranks (Bumps: $d = 2.46$; Cross: $d = 2.99$); in each case, the effect size exceeds Cohen's convention for a large effect ($d = .80$).

Bootstrapped CIs. Using Matlab version R2015a, 5,000 bootstrapped samples with 32 observations were drawn, with replacement, from the combined original untransformed local and global samples. Sixteen observations from each bootstrapped sample were randomly assigned to each group (local and global), and a mean difference score was calculated for each pair of bootstrapped local and global samples. A CI on the difference between means was computed (Bumps: $M^* = -0.08$, 95% CI [−10.00, 11.20]; Cross: $M^* = 0.01$, 95% CI [−15.36, 14.92]). For both stimuli, the real-life difference between sample means (Bumps: $M = 22.25$ arcmin; Cross: $M = 29.40$ arcmin) falls far outside of the bootstrapped CI.

Location. Examination of the distributions of location scores shown in Figure 7 reveals that, while local participants were consistent in their perceived location of the interpolated contour, global participants were much more variable. In addition, there may be a tendency for global participants to see the boundary as left of where it truly lies (corresponding to a negative location value) while local participants tend to see the boundary as right of where it truly lies (positive location).

Levene's test. Levene's test for equality of variances confirmed the difference in variances (Bumps: $F(1, 30) = 14.64$, $p = .001$, Cross: $F(1, 30) = 33.37$, $p < .001$), indicating that participants in the local group (Bumps: local variance = 23.44, Cross local variance = 16.55) were less variable than participants in the global group (Bumps global variance = 1,732.56, Cross global variance = 2,135.19).

Rank transformation. A rank transformation was applied to the data. A two-way repeated-measures ANOVA on the ranks found a Significant Stimulus × Group Interaction, $F(1, 30) = 4.69$, $p = .038$. Independent-samples t tests on the differences between the local and global mean ranks found a significant difference for the Bumps stimulus (Bumps: $t(22.64) = 2.92$, $p = .008$, 95% CI [2.53, 14.85]; Cross: $t(21.15) = .635$, $p = .533$, 95% CI [−4.84, 9.09]), suggesting that, for that stimulus, the local and global groups differed in their perceived location. As shown in Figure 7, local participants tended to see the Bumps interpolated contour to be more right of its true location (Bumps: $M = 20.84$, $SD = 5.52$; Cross: $M = 17.56$, $SD = 5.63$), while global participants tended to see the contour as more left of its true location (Bumps: $M = 12.16$, $SD = 10.54$; Cross: $M = 15.44$, $SD = 12.15$). The reported means and *SD*s are the means and *SD*s of the ranks. Degrees of freedom were adjusted to correct for heterogeneous variances. A Cohen's d effect size for the Bumps stimulus, calculated using the means and *SD*s of the ranks, reveals a large effect (Bumps: $d = 1.03$, Cookie: $d = .23$).

Bootstrapped CIs. Bootstrapped 95% CIs were computed using the same procedure described previously. The results suggest

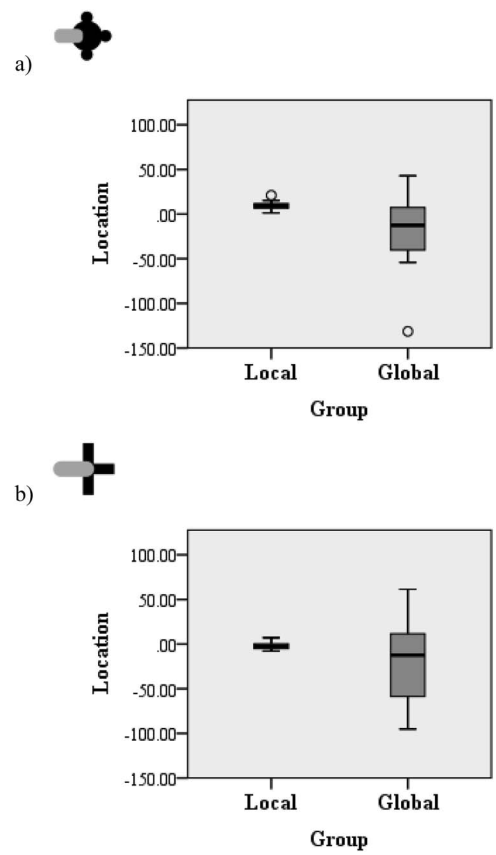

Figure 7. Location Data from Experiment 1. Positive scores indicate a tendency for participants within a group to see the boundary as right of where it truly lies. Negative scores indicate a tendency for participants within a group to see the boundary as left of where it truly lies. Boxplots show the distributions of location scores, in arcminutes, for the local and global participant groups for the (a) Bumps and (b) Cross stimuli. The dark line in the middle of the box represents the median location score. The bottom of the box indicates the 25th percentile. The top of the box represents the 75th percentile. The whiskers extend to the most extreme value within 1.5 times the interquartile range. The dots represent outliers.

the same conclusions as the tests performed on the rank transformed data. For the Bumps stimulus but not for the Cross stimulus, the real-life sample difference between group means (Bumps: $M = -27.22$ arcmin; Cross: $M = -16.97$) falls outside of the bootstrapped CI (Bumps: $M^* = -0.003$, 95% CI [−22.55, 21.81]; Cross: $M^* = 0.01$, 95% CI [−22.26, 22.72]).

Flattening effect. We were also interested in replicating results obtained by Guttman and Kellman (2004), which suggested that local interpolation may yield flatter completions than the relatability geometry predicts. To examine this question, the local group means were tested against zero using a one-sample t test. There was a significant difference for the Bumps stimulus, but not the Cross stimulus, in the expected direction (Bumps: $t(15) = 7.70$, $p < .001$, 95% CI [6.74, 11.90]; Cross: $t(15) = -1.981$, $p = .07$, 95% CI [−4.18, 0.15]). In contrast, there was no significant difference from the theoretical boundary location for the global group for either stimulus (Bumps: $t(15) = -1.72$, $p = .106$, 95% CI [−40.08, 4.28]; Cross: $t(15) = -1.64$, $p = .121$, 95% CI −43.61, 5.64]). In a control experiment, this result was replicated, and a reversed version of the Bumps stimulus (with the occluder on the left side rather than the right) produced similar results.[1]

Location error. As can be seen in Figure 8, local participants had markedly smaller location error and were far more consistent with each other than global participants.

Levene's test. Levene's test for equality of variances confirmed the difference in variances (Bumps: $F(1, 30) = 8.79$, $p = .006$, Cross: $F(1, 30) = 47.63$, $p < .001$), indicating that participants in the local group (Bumps: local variance = 23.44, Cross local variance = 6.32) were less variable than participants in the global group (Bumps global variance = 962.12, Cross global variance = 913.59).

Rank transformation. A two-way repeated-measures ANOVA on the rank transformed data with a Greenhouse-Geisser correction for violations of sphericity found a significant main effect of group, $F(1, 30) = 34.17$, $p < .001$. Independent-samples t tests on the differences between the local and global mean ranks found a significant difference for both stimuli (Bumps: $t(30) = -3.29$, $p = .003$, 95% CI [−15.40, −3.60]; Cross: $t(30) = -5.99$, $p < .001$, 95% CI [−18.27, −8.98]), indicating that global participants were more inaccurate (Bumps: $M = 21.25$, $SD = 9.48$; Cross: $M = 23.31$, $SD = 7.17$) than local participants (Bumps: $M = 11.75$, $SD = 6.62$; Cross: $M = 9.69$, $SD = 5.60$). The reported means and *SD*s are the means and *SD*s of the ranks. A Cohen's d effect size, calculated using the means and *SD*s of the ranks, revealed a large effect for both stimuli (Bumps: $d = 1.16$; Cross: $d = 2.12$).

Bootstrapped CIs. Bootstrapped 95% CIs were computed using the same procedure described previously. The results suggest the same conclusions as the tests performed on the rank transformed data. For both stimuli, the real-life sample difference between group means (Bumps: $M = 22.97$ arcmin; Cross: $M = 35.11$) falls far outside of the bootstrapped CI (Bumps: $M^* = -0.05$, 95% CI [−17.24, 17.64]; Cross: $M^* = 0.01$, 95% CI [−18.88, 19.08]).

Discussion

The results of Experiment 1 were consistent with the hypothesis that local contour interpolation processes produce representations with precise boundary locations, while displays designed to engage possible global completion processes produce neither consistent

[1] To determine whether the flattening effect was because of a simple left/right bias, a control experiment was conducted utilizing both the original version of the Bumps stimulus (occluder on left side) as well as a reversed version of the Bumps stimulus (the right side of the figure was occluded rather than the left). This new figure had circular lobes on the top, left, and bottom. For both stimuli, the local completion required interpolation of a smooth curve in the occluded region. The method was otherwise similar to Experiment 1. Thirty-eight subjects participated in this experiment; 4 were excluded for failing a drawing test (2 participants) or pressing the same key consecutively for more than 25 trials (2 participants). The results suggest a significant flattening for both the occluder-on-left stimulus ($M = 4.77$, $SD = 9.92$, $t(33) = 2.805$, $p = .008$, 95% CI [1.31 8.24]) and the occluder-on-right stimulus ($M = -8.60$, $SD = 6.73$, $t(33) = -7.45$, $p < .001$, 95% CI [−10.95, −6.25]). Note that a negative location indicates a more leftward percept while a positive location indicates a more rightward percept, thus, for the occluder-on-left stimulus, a positive location indicates a flattened percept, while for the occluder-on-right stimulus, a negative location indicates a flattened percept.

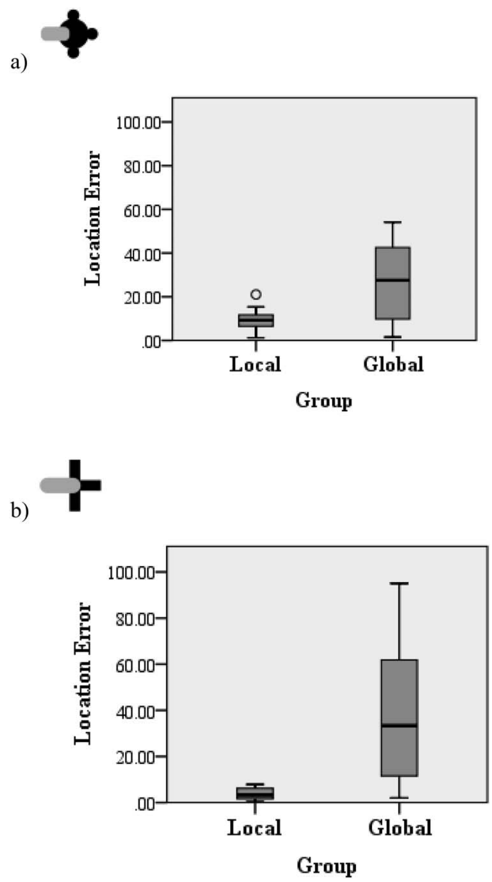

Figure 8. Location Error Data from Experiment 1. Higher location error scores indicate that participants perceived the boundary to be farther away from its true location. In other words, participants were more inaccurate in their estimate of the location of the boundary. Boxplots show the distributions of location error scores, in arcminutes, for the local and global participant groups for the (a) Bumps and (b) Cross stimuli. The dark line in the middle of the box represents the median location error score. The bottom of the box indicates the 25th percentile. The top of the box represents the 75th percentile. The whiskers extend to the most extreme value within 1.5 times the interquartile range. The dots represent outliers.

nor precise boundary locations. These findings were evident in all three dependent measures assessed here.

Consistent with other work, local completion produced small differences between the inner and outer thresholds (Guttman & Kellman, 2004), on the order of 6 to 9 arcmin. This kind of precision, and the consistency across participants in the local condition, is unlikely to arise through guessing or cognitive strategies. It is consistent with the idea that local interpolation processes produce precise representations of object edges behind occluders. Both the much larger differences in inner and outer thresholds and the markedly higher variation among participants for the global displays argues against the operation of a perceptual process that establishes precise boundary representations based on global symmetry.

The same pattern appeared for the location data. Participants in the local condition were very consistent with each other and produced estimated positions of the interpolated contours that were close to the theoretically predicted locations. The Bumps display indicated a perceived location somewhat inward from a constant curvature completion; this slight flattening was consistent across participants and has been observed for curved completions in some other work (Guttman & Kellman, 2004). The location error data also showed relatively small absolute errors. Note that small constant error in location shown by local participants exerts an effect on location error; the data suggest that perception is somewhat nonveridical, but consistent.

Very different patterns were observed in the global condition. Perceived boundaries as shown by the average location data were not far from the true boundary location, but participants were highly variable, with variances that were orders of magnitude more than the local participants. Moreover, the location error data revealed that even while the aggregate mean location did not fall far away from the predicted location, individual participants' estimates did, averaging almost half a degree of visual angle away from the theoretical location.

In summary, Experiment 1 indicated that displays that might plausibly have either local or global symmetry-based completions revealed evidence of precise and accurate perceived contours only in the local case. We note that precision and consistency across participants are often hallmarks of modular perceptual processes, whereas the large variability and interobserver inconsistency we observed in global participants seem more consistent with cognitive strategies or guessing.

Experiment 2a

Experiment 1 provided data on the precision and accuracy of boundary perception where local or global factors were available, but it raises other questions. The displays used in Experiment 1 required formation of a fourth articulated part in the occluded region, compatible with mirror and rotational symmetry. These displays were drawn from the literature on amodal completion and are representative of displays that have been claimed to produce global completion based on symmetry (e.g., Sekuler, Palmer, & Flynn, 1994).

It could be argued, however, that completion in the global cases required construction of parts that fell farther from the ends of nearby visible edges than in the local cases. One could also argue that the contour to be interpolated, in global cases, is more complex in some sense. Of course, these issues are somewhat intrinsic to any theory that postulates completion based on global symmetry. Moreover, a question of the importance of distance from local edge endpoints seems to reference local interpolation theories that depend on such variables, rather than global theories, which do not necessarily. Based on the precision of symmetry processing in other (noncompletion) tasks, a symmetry-based completion process might be expected to yield spatially precise and accurate boundary representations. Alternatively, such a process might be influenced by distance and complexity. It would thus be interesting to investigate global and local completion in a situation in which the local and global contours to be interpolated were equated as much as possible, and for which the distance of the completed contours from the local inducing contours was similar.

The goal of the Cookie stimulus used in Experiment 2 was to make the local and global completions as comparable as possible (e.g., in terms of distance from nearby edges, etc.) That was done by making them, as much as was possible, mirror reflections of each other. Both groups, for that stimulus, are interpolating smooth curves—a convex curve in the local case and a concave curve in the global case. A perfect mirror reflection of the entire occluded region was not used, as the occluder had to be offset slightly from the intersection of the local and global interpretations to avoid the Gerbino illusion (Fantoni, Gerbino, & Kellman, 2008; Gerbino, 1978).

Another goal of Experiment 2a was to consider a simpler display in which global completion may be predicted, yet does not require creation of a fourth articulated part. We used a partly occluded triangle. It is interesting to note that the formal account of relatability restricts interpolated contours to bending through no more than 90 degrees. This means that linear edges that disappear behind an occluder and whose linear extensions would meet to form an acute angle are not relatable and should not support local interpolation (Kellman & Shipley, 1991). That account also constrains interpolations to be smooth (i.e., interpolation does not create corners). These constraints have been supported by considerable experimental evidence (Field, Hayes, & Hess, 1993; Guttman, Sekuler, & Kellman, 2003; Kellman, Garrigan, & Shipley, 2005; Kellman & Shipley, 1991). Thus, a potential triangle whose linearly extended edges meet at an acute angle behind an occluder might be predicted to produce a clear vertex behind the occluder based on global symmetry, but not from local interpolation processes.

In Experiment 2a, we used a partially occluded isosceles triangle to examine constraints on locally interpolated contours (see Figure 9d). A partially occluded triangle display has been suggested as a counterexample to local contour relatability as determining when interpolation does and does not occur (Boselie & Wouterlood, 1992). This is an excellent example for the general point of the current investigation, because the evidence given for this assertion consisted of presenting the display and observing that it seems obvious that a triangle lies behind the occluder. This kind of report, however, is consistent with the idea of RPI described earlier, and more exacting measures are needed to determine whether such "completion" produces precise or accurate representations of the boundaries of objects. We hypothesized that local contour completion does not occur in such cases, and that if participants report a triangle behind the occluder, they are not using a local contour completion process, but rather, are using a higher-order, top-down, cognitive reasoning process to arrive at a decision about the likely familiarity of the occluded figure.

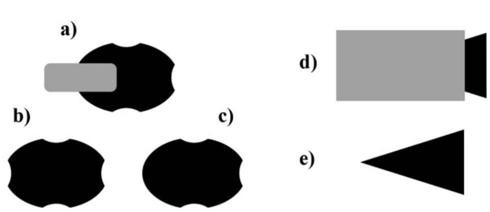

Figure 9. Occluded displays used in Experiment 2a. (a) Occluded version of the Cookie display, along with the (b) global and (c) local completions. Cookie was designed to equate the local and global completions as much as possible. (d) Occluded version of the Triangle display, along with the (e) unoccluded version. The Triangle stimulus is similar to that in Boselie and Woutlerlood (1992), and was designed to test the argument, put forth in that article, that figures with edges oriented at significantly less than 90 degrees can give rise to locally interpolated contours, and thus, that local theories of contour completion need to account for such cases.

Method

The methods were identical to those used in Experiment 1, with two exceptions. First, two new stimuli, illustrated in Figure 9, were used for the experiment. Second, participants in both groups received identical instructions for the Triangle stimulus.

Participants. Thirty-five participants (22 women) completed this experiment. Three were excluded for failing an objective measure of task compliance (described below), leaving 32 participants in the final sample, with 16 participants in each group. In addition, one participant was excluded from the Triangle analyses for failing a drawing test (described below) for that stimulus. Thus, the Triangle analyses included a total of only 31 participants. All participants provided informed consent, were students attending the University of California, Los Angeles, reported having normal or corrected-to-normal vision, and normal color vision (no colorblindness). Participants were offered partial course credit for their involvement.

Displays. The experiment utilized two occluded displays. The Cookie display, shown in Figure 9a, had divergent local and global completions that were equated as much as possible. The Triangle display, shown in Figure 9d, had an identical completion for both groups. The Cookie display subtended 17.69° × 9.42° of visual angle in total; the occluder subtended 9.86° × 3.92°, and the visible regions subtended 13.07° × 9.42°. The Triangle display subtended 20.66° × 9.68° of visual angle in total; the occluder subtended 17.43° × 9.68°, and the visible regions subtended 3.32° × 8.93°.

Dependent measures and data analysis. We used the same dependent measures as in Experiment 1: (imprecision, location, and location error). The two stimuli required different analyses. For each dependent variable, independent samples t tests were used to test the difference between the local and global groups for the Cookie stimulus. For the Triangle display, there was no local instruction group. A one-sample t test was used to test the difference between the mean of all participants' Triangle scores and the largest mean value obtained by local participants for any of the Bumps, Cross, or Cookie displays.

Exclusion criteria. The same exclusion criteria were used as in Experiment 1. One participant failed the postexperiment drawing for the Triangle stimulus. Three participants were excluded for failing to achieve 70% correct catch trial performance (achieving only 38, 50, and 60% correct). During debriefing, no participants reported any confusions or misbehavior that would result in exclusion from the analysis. However, a few global participants spontaneously mentioned that, for the Cookie stimulus, they were perceiving the edge to be rounded, and then keeping in mind that there was a bite or chunk taken out of it, so that the symmetric edge was just slightly right of the rounded edge. In other words, global subjects may have used the local interpolation as a guide, because of the local and global interpretations being so near to each other. We consider the impact of this possible strategy in the discussion.

Results

Imprecision–Cookie stimulus. Figure 10 shows imprecision data for the local and global participants. The results of Experiment 1 were generally replicated. The local participants appear to be both more precise and less variable, though the difference in variability appears smaller than observed in Experiment 1.

Levene's test. Levene's test for equality of variances confirmed the difference in variances ($F(1, 30) = 10.45$, $p = .003$, indicating that participants in the local group (variance = 13.98) were less variable than participants in the global group (variance = 49.86).

Rank transformation. An independent-samples t test on the difference between the local and global mean ranks confirmed the differences in the distributions of the two groups, $t(30) = -2.51$, $p = .018$, 95% CI [−13.95, −1.43], indicating that local participants were more precise ($M = 12.66$, $SD = 7.08$) than global participants ($M = 20.34$, $SD = 10.01$). The reported means and *SD*s are the means and *SD*s of the ranks. A Cohen's d effect size, which was calculated using the means and *SD*s of the ranks ($d = .89$), exceeds Cohen's convention for a large effect ($d = .80$).

Bootstrapped CIs. A bootstrapped 95% CI was computed using the same procedure described previously. The results suggest the same conclusion as the test performed on the rank transformed data. The real-life sample difference between group means ($M = 5.97$ arcmin) falls outside of the bootstrapped CI: 95% CI [−4.37, 4.38].

Imprecision–Triangle stimulus. The Triangle stimulus was designed to test whether figures with input edges that violate the 90 degree constraint of contour relatability can give rise to locally interpolated contours (e.g., Boselie & Wouterlood, 1992). Theoretical accounts of local contour completion (e.g., Kellman & Shipley, 1991) would predict that completion does not occur in such cases, and that when participants report they perceive a triangle lying behind the occluder, they are not using a local contour completion process, but rather are using a higher-order, more cognitive or reasoning process to produce reports of the possibility of a familiar or simple figure. Because the alternative hypothesis is that participants are using a local contour completion process, we compared participants' performance on the Triangle stimulus to performance of participants in the local group on the Bumps, Cookie, and Cross stimuli. Thus, the means of the local participants' scores for the Bumps, Cross, and Cookie stimuli were used as a guideline as to what amount of imprecision could reasonably be expected if the alternative hypothesis was true. The local mean imprecision scores (in arcminutes) for the three stimuli were: Bumps: 7.78, Cookie: 8.42, Cross: 5.27. To be conservative, Triangle imprecision scores were tested against the largest local mean imprecision found for any stimulus, which was 8.42 arcmin, for the Cookie stimulus.

Imprecision was large for the triangle display. The mean was more than a degree of visual angle (61.10 arcmin). As can be seen in Figure 10, many participants produced imprecision values far above this value. A one-sample t test on the difference was highly significant, $t(30) = 7.80$, $p < .001$, 95% CI [38.88, 66.48]. The effect size ($d = 1.40$) indicates a very large difference between the imprecision scores for the Triangle ($M = 61.10$, $SD = 37.62$) and locally completed contours for the other three stimuli.

Location–Cookie stimulus. The results were consistent with those of Experiment 1. Global participants were more variable in their perceived location of the interpolated contour. In addition, we again see the tendency for local participants to perceive a flatter contour than was predicted by the local geometry (positive location).

Levene's test. Levene's test for equality of variances confirmed a reliable difference in variances, $F(1, 30) = 11.50$, $p = .002$, indicating that participants in the local group (variance = 25.58) were less variable in perceived location than participants in the global group (variance = 294.47).

Rank transformation. A rank transformation was applied to the data. Independent-samples t tests on the differences between the local and global mean ranks found a significant difference, $t(30) = 2.29$, $p = .029$, 95% CI [.77, 13.48], suggesting that the local and global groups differed in their perceived location. As shown in Figure 11a, local participants tended to flatten the interpolated contour and see the boundary as right of the location predicted by the local geometry ($M = 20.06$, $SD = 7.21$), while

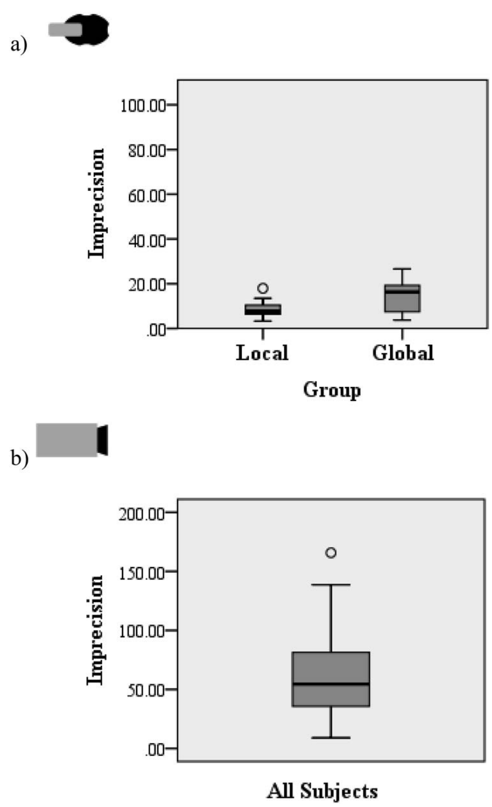

Figure 10. Imprecision Data from Experiment 2a. Higher imprecision indicates less precise localization. Boxplots show distributions of imprecision scores, in arcminutes. The dark line in the middle of the box represents the median imprecision score. The bottom of the box indicates the 25th percentile. The top of the box represents the 75th percentile. The whiskers extend to the most extreme value within 1.5 times the interquartile range. The dots represent outliers. (a) Distributions of imprecision scores for the local and global participant groups for the Cookie stimulus. For easy comparison to results of Experiment 1, imprecision scale runs from 0 to 100 arcmin. (b) Distributions of imprecision scores for all participants for the Triangle stimulus. Note the scale runs from 0 to 200 arcmin.

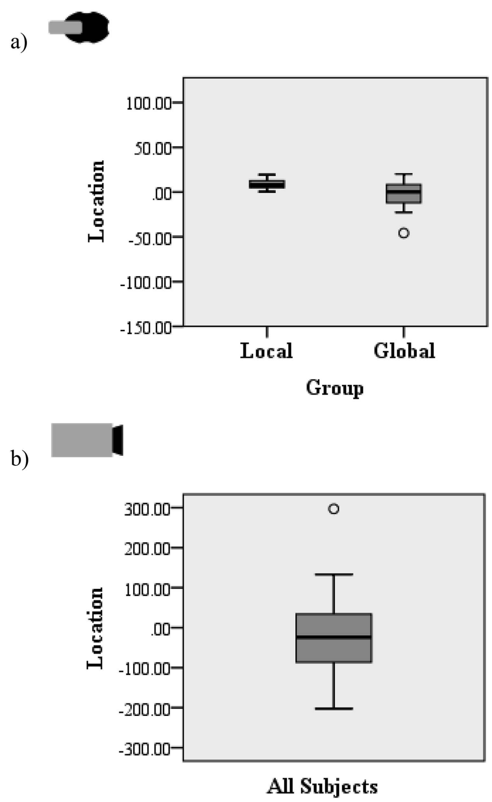

Figure 11. Location Data from Experiment 2a. (a) Distributions of location scores for the local and global participant groups for the Cookie stimulus. For easy comparison to results of Experiment 1, the scale runs from −150 to 100 arcmin. (b) Distributions of location scores for all participants for the Triangle stimulus. Note the scale runs from −300 to 300 arcmin. Higher location scores indicate an overall tendency for participants within a group to see the boundary as to the right of where it truly lies. Lower location scores indicate an overall tendency for participants within a group to see the boundary as to the left of where it truly lies. Boxplots show distributions of location scores, in arcminutes. The dark line in the middle of the box represents the median location score. The bottom of the box indicates the 25th percentile. The top of the box represents the 75th percentile. The whiskers extend to the most extreme value within 1.5 times the interquartile range. The dots represent outliers.

global participants were less inclined to flatten the contour (M = 12.94, SD = 10.13). The reported means and SDs are the means and SDs of the ranks. A Cohen's d effect size, calculated using the means and SDs of the ranks (d = .81), again reveals a large effect.

Bootstrapped CIs. A bootstrapped 95% CI was computed using the same procedure described previously. The results suggest the same conclusion as the test performed on the rank transformed data. The real-life sample difference between group means (M = −11.53 arcmin) falls outside of the bootstrapped CI: 95% CI [−9.59, 9.38].

Flattening effect. We were also interested in replicating the results obtained by Guttman and Kellman (2004) and Experiment 1, which suggest that, for convex stimuli, local interpolation results in flatter completions than the geometry predict. To examine this question, the local group mean was tested against zero using a one-sample t test. There was a significant difference in the expected direction, $t(15) = 6.80$, $p < .001$, 95% CI [5.90, 11.29]. In contrast, there was no significant difference from the theoretical boundary location for the global group, $t(15) = -0.68$, $p = .505$, 95% CI [−12.08, 6.21].

Location–Triangle stimulus. Location scores for the triangle display, shown in Figure 11b, suggest that participants are, on average, elongating the triangle to make it pointier than extension of the visible contours would produce. Inspection of the data also suggest that one participant, who located the vertex of the triangle approximately 5 degrees of visual angle away from its predicted location, may be having a disproportionate effect on the mean and SD. The analysis was thus conducted both with and without that outlier.

Outlier included. A one-sample t test on the difference between mean location (M = −25.39, SD = 106.71) and zero was not significant, $t(30) = -1.33$, $p = .195$, 95% CI [−64.53, 13.75]. The effect size (d = .24) suggests a small effect.

Outlier excluded. A one-sample t test on the difference between mean location (M = −36.14, SD = 89.85) and zero was significant, $t(29) = -2.20$, $p = .036$, 95% CI [−69.70, −2.59]. The effect size (d = .40 suggests a small to medium effect.

Location error–Cookie stimulus. The distributions of location error scores, shown in Figure 12, do not suggest a difference in means between the two groups. Levene's test for equality of variances was marginally reliable, $F(1, 30) = 3.89$, $p = .058$, suggesting that participants in the global group (variance = 117.37) were somewhat more variable than participants in the local group (variance = 25.58).

A rank transformation was applied to the data. An independent-samples t test on the difference between the local and global mean ranks did not find a significant difference, $t(30) = -0.94$, p = .354, 95% CI [−9.91, 3.66], suggesting that global participants were not more inaccurate (M = 18.06, SD = 9.79) than local participants (M = 14.94, SD = 8.99). The reported means and SDs are the means and SDs of the ranks.

Bootstrapped CIs. A bootstrapped 95% CI was computed using the same procedure described previously. The results suggest the same conclusion as the test performed on the rank transformed data. The real-life sample difference between group means (M = 4.62 arcmin) falls inside of the bootstrapped CI: 95% CI [−5.80, 5.96].

Location error–Triangle stimulus. Participants' performance on the Triangle stimulus was again compared to performance of participants in the local group for the Bumps, Cookie, and Cross stimuli. The local location error scores (in arcminutes) for the three stimuli were: Bumps: 9.32, Cookie: 8.59, Cross: 3.69). To be conservative, the Triangle location error scores were tested against the largest local mean location error observed for any of the other stimuli, which was 9.32 arcmin, for the Bumps stimulus.

The distribution of location error scores, shown in Figure 12, suggests that participants are high above that value, and also, that one outlier may be having a disproportionate effect on the mean. One-sample t tests were conducted both with and without that outlier.

Outlier included. A one-sample t test on the difference between mean location error (M = 84.90, SD = 67.85) and the largest location error exhibited by local participants for any of the

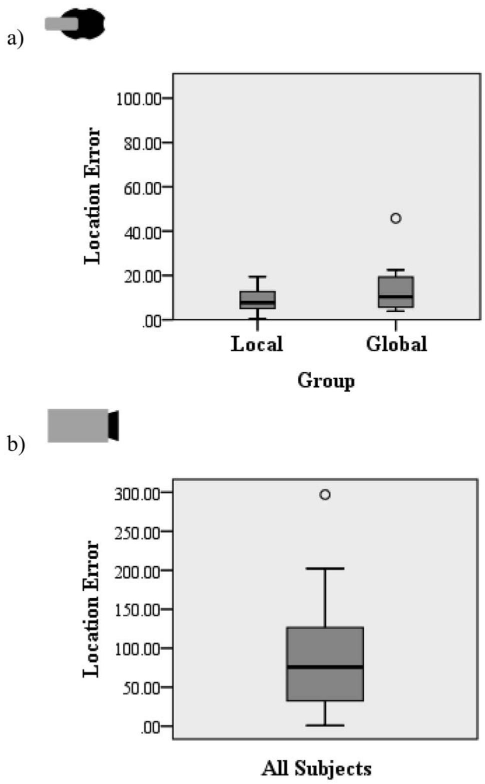

Figure 12. Location Error Data from Experiment 2a. (a) Distributions of location error scores for the local and global participant groups for the Cookie stimulus. For easy comparison to results of Experiment 1, location scale runs from 0 to 100 arcmin. (b) Distributions of location error scores for all participants for the 'Triangle' stimulus. Note the scale runs from 0 to 300 arcmin. Higher location error scores indicate that participants perceived the boundary to be farther away from its true location. In other words, participants were more inaccurate in their estimate of the location of the boundary. Boxplots show the distributions of location error scores, in arcminutes. The dark line in the middle of the box represents the median location error score. The bottom of the box indicates the 25th percentile. The top of the box represents the 75th percentile. The whiskers extend to the most extreme value within 1.5 times the interquartile range. The dots represent outliers.

other three stimuli was significant, $t(30) = 6.20$, $p < .001$, 95% CI [50.70, 100.47]. The effect size ($d = 1.11$) suggests a large effect.

Outlier excluded. A one-sample t test on the difference between mean location error ($M = 77.83$, $SD = 56.20$) and the largest location error exhibited by local participants for any of the other three stimuli was significant, $t(29) = 6.68$, $p < .001$, 95% CI [47.53, 89.50]. The effect size ($d = 1.22$) suggests a large effect.

Experiment 2b

Experiment 2b served as a control for Experiment 2a. Because the triangle stimulus used in Experiment 2a had a low support ratio, we ran 49 new participants in the dot localization task with a new version of the triangle stimulus, shown in Figure 13. For this new stimulus, the same triangle and occluder were used as in Experiment 2a; however, the occluder was offset so that a larger portion of the triangle was revealed, increasing the support ratio.

Method

The method was identical to that used in experiment 2a, but the 'New Triangle' stimulus alone was used.

Participants. Forty-nine participants (37 women) completed the experiment. Two participants were excluded for having catch-trial performance below 75%. Thus, 47 participants were included in the analysis. All participants provided informed consent, were students attending the University of California, Los Angeles, reported having normal or corrected-to-normal vision, and normal color vision (no colorblindness). Participants received partial course credit for their participation.

Results

Imprecision. Imprecision scores, shown in Figure 14a, suggest that participants were quite imprecise at localizing the occluded boundary. In addition, one participant may have had a disproportionate effect on the mean. The analysis was thus conducted both with and without that participant. Performance was tested against the largest local mean imprecision found for any of the Bumps, Cookie, or Cross stimuli, which was 8.42 arcmin, for the Cookie stimulus.

Outlier included. A one-sample t test on the difference was significant, $t(46) = 8.87$, $p < .001$, 95% CI [30.80, 48.88]. The effect size ($d = 1.30$) indicates a very large difference between the imprecision scores for the New Triangle ($M = 48.26$, $SD = 30.76$) and locally completed contours for the other three stimuli.

Outlier excluded. A one-sample t test on the difference between mean imprecision score ($M = 45.54$, $SD = 24.74$) and the worst local mean imprecision for any previous stimulus (8.42 arcmin) was significant, $t(45) = 10.17$, $p < .001$, 95% CI [29.77, 44.46]. The effect size ($d = 1.50$) indicates a very large effect.

Location. Location scores for the triangle display, shown in Figure 14b, again suggest that participants are, on average, elongating the triangle to make it pointier than extension of the visible contours would produce. In addition, two outliers, with location scores of 365.06 and 406.09 arcmin, may be having a disproportionate effect on the mean. The analysis was conducted both with and without those subjects.

Outliers included. A one-sample t test on the difference between mean location ($M = 90.00$, $SD = 87.66$) and zero was significant, $t(47) = 7.03$, $p < .001$, 95% CI [64.18, 115.66]. The effect size ($d = 1.32$) suggests a large effect.

Outliers excluded. A one-sample t test on the difference between mean location ($M = 76.78$, $SD = 62.16$) and zero was significant, $t(44) = 8.29$, $p < .001$, 95% CI [58.10, 95.45]. The effect size ($d = 1.24$ suggests a large effect.

Figure 13. New Triangle stimulus used in Experiment 2b. The same triangle was used as in the original Triangle stimulus from Experiment 2a, but the position of the occluder was set such that a larger portion of the triangle was revealed.

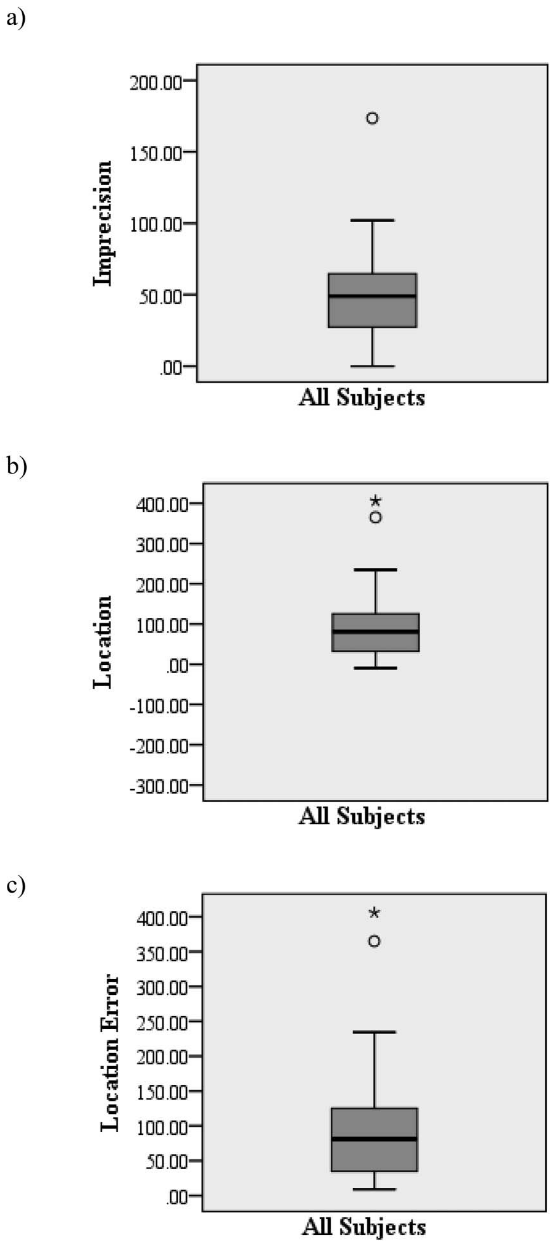

Figure 14. Data from Experiment 2b. Boxplots show the distributions of (a) imprecision, (b) location, and (c) location error scores, in arcminutes. The dark line in the middle of the box represents the median score. The bottom of the box indicates the 25th percentile. The top of the box represents the 75th percentile. The whiskers extend to the most extreme value within 1.5 times the interquartile range. The dots represent outliers.

Location error. The distribution of location error scores, shown in Figure 14c, suggests both large amounts of error, and great variability between subjects. In addition, two outliers, with location error scores of 365.06 and 406.09, may be having a disproportionate effect on the mean. The analysis was thus conducted both with and without those subjects. Performance was tested against the largest local mean location error observed for any of the Bumps, Cookie, or Cross stimuli, which was 9.32 arcmin, for the Bumps stimulus.

Outliers included. A one-sample t test on the difference between mean location error (M = 94.18, SD = 83.59) and the largest location error exhibited by local participants for any of the other three stimuli (9.32 arcmin) was significant, $t(46) = 6.96$, $p < .001$, 95% CI [60.32, 109.40]. The effect size (d = 1.02) suggests a large effect.

Outliers excluded. A one-sample t test on the difference between mean location error (M = 81.23, SD = 57.05) and the largest location error exhibited by local participants for any of the other three stimuli (9.32 arcmin) was significant, $t(44) = 8.46$, $p < .001$, 95% CI [54.77, 89.05]. The effect size (d = 1.26) suggests a large effect.

Experiment 3

Experiment 3 was designed to test the possibility that poor performance in the global conditions of the previous experiments was due to interference from the local process. Experiment 3 utilized the displays shown in Figure 15. Both displays contain occluded, potentially symmetric objects with no possible local completion, as the edges leading into the occluder are not relatable.

Method

The method was identical to the preceding experiments, except that there was only one condition (global), and the occluded stimuli were designed to have a symmetric completion and no possible local completion. For the Vase stimulus, the dot moved along the horizontal axis (negative location values correspond to leftward/within the object). For the Candy stimulus, the dot moved along the vertical axis (negative location values correspond to downward/within the object). These dot trajectories are marked in Figure 15.

Participants. Thirty-eight subjects participated in this experiment. Two subjects were excluded for failing the drawing tests, and two subjects were excluded for pressing the same key consecutively for more than 25 trials. Thus, 34 participants were included in the analysis. All participants were students attending the University of California, Los Angeles. Normal or corrected-to-normal vision was a prerequisite for participation, as was normal color vision (no colorblindness). Participants were offered partial course credit for their participation.

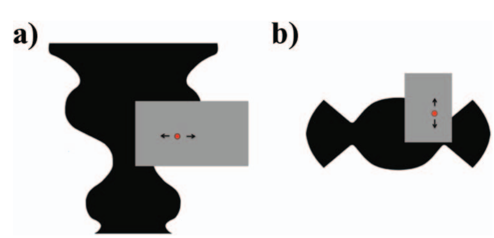

Figure 15. Stimuli used in Experiment 3. (a) Vase and (b) Candy. On top of the stimuli, the dot trajectory used in the experiment is illustrated. Both stimuli have an obvious symmetric completion, but, because the edges leading into the occluder are not relatable, no local completion is possible. See the online article for the color version of this figure.

Displays. The experiment utilized two occluded displays. Both displays had an obvious global symmetric completion, but no possible local completion. The Vase display subtended 13.90° × 13.07° of visual angle in total; the occluder subtended 7.89° × 4.54°, and the visible regions subtended 11.76° × 13.17°. The Candy display subtended 12.83° × 6.57° of visual angle in total; the occluder subtended 3.32° × 4.81°, and the visible regions subtended 12.83° × 4.71°.

Results

Imprecision. Imprecision scores, shown in Figure 16, suggest that imprecision is still quite large, even without local interference. In addition, for the Candy stimulus, one outlier, with an imprecision of 60.81 arcmin, may be having a disproportionate effect on the mean. The analysis was thus conducted both with and without that participant. Performance was compared with the worst local mean imprecision found for any of the Bumps, Cookie, or Cross stimuli, which was 8.42 arcmin, for the Cookie stimulus.

Outlier included. A one-sample t test on the difference between the sample mean imprecision and the worst local mean imprecision for any previous stimulus was significant for both the Vase and Candy stimuli (Vase: M = 22.54, SD = 14.53, $t(35)$ = 5.83, $p < .001$, 95% CI [9.20, 19.04]; Candy: M = 16.60, SD = 10.66, $t(35)$ = 4.60, $p < .001$, 95% CI [4.57, 11.78]). The effect sizes (Vase: d = .97, Candy: d = .77) suggest a large effect.

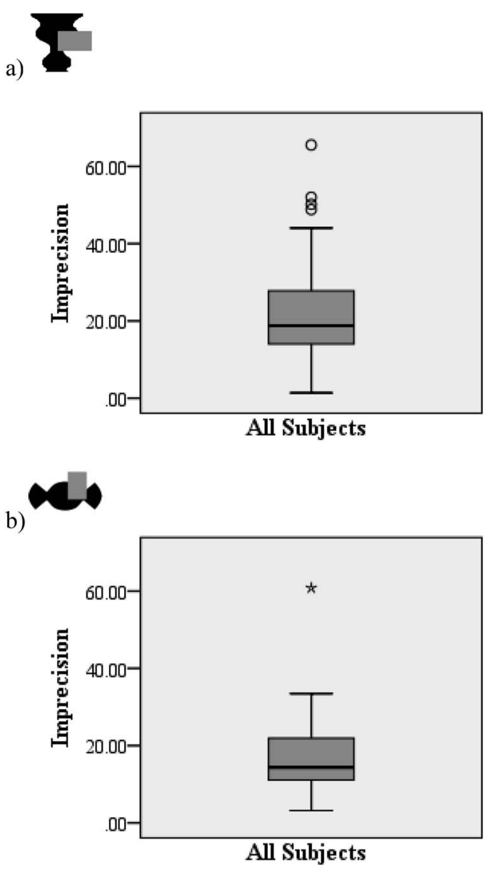

Figure 16. Imprecision data from Experiment 3. Boxplots show the distributions of imprecision scores for the (a) Vase, and (b) Candy stimuli in arcminutes. The dark line in the middle of the box represents the median imprecision score. The bottom of the box indicates the 25th percentile. The top of the box represents the 75th percentile. The whiskers extend to the most extreme value within 1.5 times the interquartile range. The dots represent outliers.

Outlier excluded. The distribution of Candy imprecision scores, shown in Figure 16b, suggests that one outlier, with an imprecision of 60.81 arcmin, may be having a disproportionate effect on the mean. Excluding that subject from the analysis, the effect remains highly significant (M: 15.33, SD: 7.60, $t(34)$ = 4.68, $p < .001$, 95% CI [3.40, 8.63]).

Location. Figure 17 shows the location scores, in arcminutes, for the Vase and Candy stimuli. One-sample t tests on the difference between the sample location and zero were significant for the Vase stimulus but not the Candy stimulus, suggesting the participants exhibited a tendency to perceive the boundary for the Vase as more inward (Vase: M = −12.42, SD = 15.35, $t(35)$ = −4.86, $p < .001$, 95% CI [−17.61, −7.23]; Candy: M = −5.03, SD = 16.20, $t(35)$ = −1.86, p = .071, 95% CI [−10.51, 0.46]). The effect size for the Vase stimulus suggests a large effect (d = .81).

Location error. Figure 18 shows the location error scores, in arcminutes, for the Vase and Candy stimuli. It appears that, even without local interference, the location error scores are larger than those found for local stimuli. Performance was tested against the largest local mean location error for any of the stimuli from previous experiments, which was 9.32 arcmin, for the Bumps stimulus. One-sample t tests on the difference between the sample mean location error and the largest local location error were significant (Vase: M = 18.98, SD = 10.26, $t(35)$ = 5.65, $p < .001$, 95% CI: [6.19, 13.13]; Candy: M = 15.70, SD = 9.54, $t(35)$ = 4.02, $p < .001$, 95% CI: [3.16, 9.61]). The effect sizes suggest a large and medium effect for the Vase and Candy stimuli, respectively (Vase: d = .94, Candy: d = .67).

General Discussion

We hypothesized that local contour interpolation processes produce representations with precise boundary locations, whereas global processes do not. This hypothesis was supported by the results. Experiment 1 showed that precision of boundary locations was robustly greater for local as compared with global conditions (Bumps and Cross) that had different completions according to local and global theories. The Bumps and Cross displays were selected because they are representative of stimuli that have been claimed to produce global completion based on symmetry (Sekuler, Palmer, & Flynn, 1994). However, it could be argued that in Experiment 1, the globally predicted interpolated boundary fell further away from the inducing edges, or was more complex than the locally interpolated segment, making the task more difficult in the global case. The Cookie display used in Experiment 2 was designed to address these concerns by making the local and global completions as comparable as possible in terms of their distance from the endpoints of visible edges, and complexity of the interpolated segment. That was done by making them, as much as was possible, mirror reflections of each other. The local subjects interpolated a smooth convex curve while the global subjects interpolated a smooth concave curve. The results showed reliably greater precision for local interpolation in this display. Differences in precision showed large effect sizes in favor of the local inter-

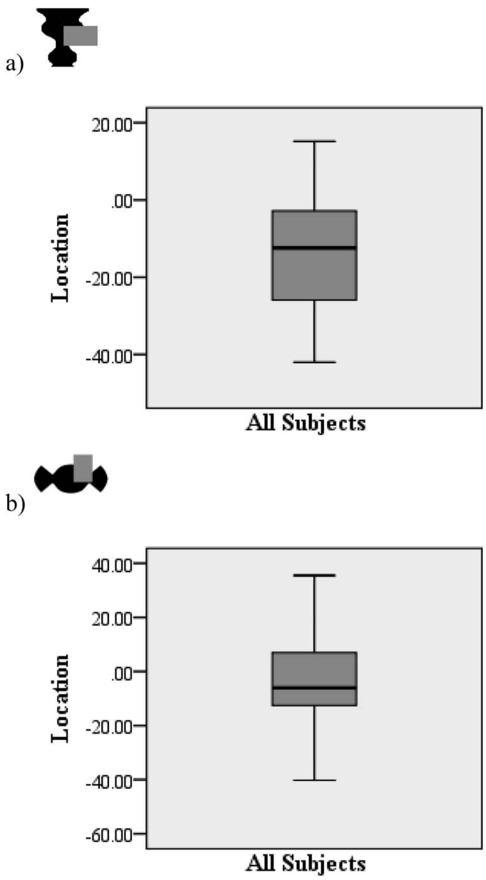

Figure 17. Location data from Experiment 3. Boxplots show the distributions of location scores for the (a) Vase, and (b) Candy stimuli in arcminutes. The dark line in the middle of the box represents the median location score. The bottom of the box indicates the 25th percentile. The top of the box represents the 75th percentile. The whiskers extend to the most extreme value within 1.5 times the interquartile range. The dots represent outliers.

polation condition, and response variability was reliably less among local participants than global participants. Experiment 3 showed that high imprecision and location error in the global condition does not result from interference with the local process. Imprecision and location error were high and comparable with global condition results in earlier studies.

Equally informative as the condition differences in imprecision, global completion conditions produced much more variability in imprecision across participants. Local participants, across all three measures, were highly consistent with each other. Their range of scores was very narrow relative to the range of scores for global participants. These results support a great deal of earlier research suggesting that local contour interpolation is an automatic process that operates in a relatively invariant way across participants and is rooted in basic visual mechanisms (Heitger, von der Heydt, Peterhans, Rosenthaler, & Kübler, 1998; Kalar et al., 2010; Kanizsa, 1979; Kellman & Shipley, 1991). Local interpolation seems unlikely to be based on open-ended inference processes (cf., Fodor, 1983), reasoning, or imagination, as these might be expected to vary substantially across observers. In contrast, the present results indicate that for attempts to complete globally, individual participants have poorly localized boundary representations, give location estimates that are on average far from the predicted location, and respond inconsistently with one another. The results suggest that processes based on recognition of potential global symmetry lead to vague, variable responses about the location of objects' bounding contours.

Differences in location and location error provide additional support for the idea of separable local and global processes. Local participants exhibited a small but consistent (approximately 6–9 arcmin) tendency to flatten interpolated contours. This flattening effect was replicated for stimuli with an occluder placed on either the left or right side. Thus, this effect is not due to a simple left/right bias. Global participants did not exhibit a tendency to flatten the interpolated contour. The flattening we observed resembles but slightly exceeds that reported in earlier amodal completion work (Guttman & Kellman, 2004). It may suggest an unexplained aspect of the shape of interpolated contours, and suggests the dot location method may be used to study proposals about the exact form of interpolated contours (Kellman & Shipley, 1991; Ullman, 1979; Fulvio, Singh, & Maloney, 2006; Fantoni & Gerbino, 2003).

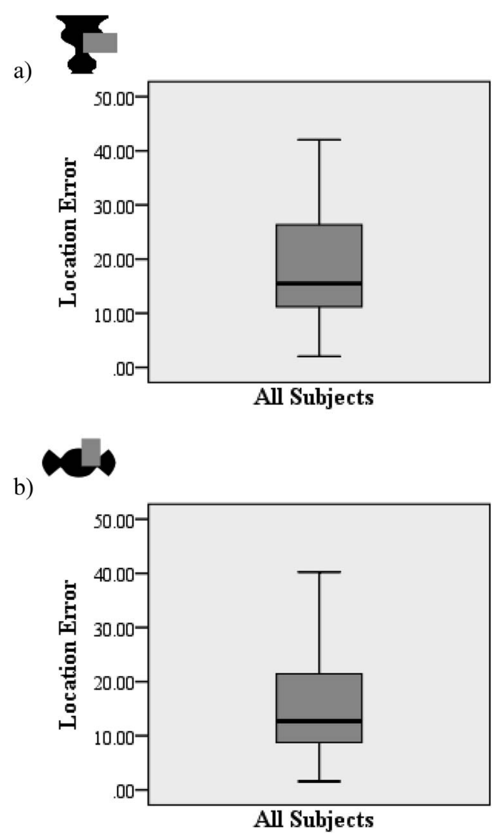

Figure 18. Location error data from Experiment 3. Boxplots show the distributions of location error scores for the (a) Vase, and (b) Candy stimuli, in arcminutes. The dark line in the middle of the box represents the median location error score. The bottom of the box indicates the 25th percentile. The top of the box represents the 75th percentile. The whiskers extend to the most extreme value within 1.5 times the interquartile range. The dots represent outliers.

For present purposes, the consistency across local participants of this deviation from geometric predictions coheres with the idea that local interpolation rests on basic mechanisms that operate according to fixed rules.

Finally, in addition to being less precise, global completions appear to also be less accurate in the sense that their interpolated boundaries fall, on average, farther away from the true boundary (location error). This pattern of differences in location scores held for all displays except the Cookie stimulus in Experiment 2; however, because the local and global interpretations were so near to each other (the global boundary was slightly to the right of the local boundary), global participants reported that the locally interpolated contour could be used as a guide. In addition, although perceived location was consistent and precise for local participants, the small but consistent deviation from the theorized boundary location for perceptually flattened stimuli contributed to higher location error scores for those participants and stimuli.

Taken together, the results strongly suggest two separate processes involved in contour completion. The first is a low-level process that completes contours based on the local geometry of contour relatability, and results in a relatively precise perceptual representation of interpolated contours that is consistent across participants. The second is a higher-order process that uses global cues, and/or past experience, to suggest the most likely shape of a partially occluded object. This higher-order process results in at least a decision or idea regarding the likely symmetry or familiarity of the object, but *does not give rise to a perceptual representation with precise borders*. Distinguishing these processes opens the door to significant theoretical progress, both for understanding the workings of each process and for beginning to understand how these different aspects of object perception interact.

Experiments 2a and 2b also provide illuminating evidence about the limiting conditions for local contour interpolation processes. Kellman and Shipley (1991) proposed the notion of *relatability* (see also Kellman, Garrigan, & Shipley, 2005) as a formal account of the geometry governing visual interpolation. According to relatability, contour segments ending in points of tangent discontinuity can produce contour connections across gaps if they can be connected by a smooth, monotonic curve that bends by no more than 90 degrees. Boselie and Wouterlood (1992) argued against the 90 degree constraint with a partly occluded display similar to the triangle displays used in Experiments 2a and 2b. They claimed that simple visual inspection was sufficient to see that this display contained a partly occluded triangle, and that this observation therefore refuted Kellman & Shipley's theory. This claim would be correct if such a triangle display produced actual perceptual completion of boundaries. Perception of a "triangle" in such a display would also deviate from the predictions of local interpolation theories in that interpolation typically creates smooth boundaries, not vertices. The results of Experiments 2a and 2b clearly suggest that local contour completion, whose hallmark is clear, spatially precise representations of perceived boundaries, does not occur in such cases. In Experiment 2a, the imprecision and location error results of participants for the Triangle stimulus were more than an order of magnitude greater than in any cases where local interpolation theories predict contour completion. Experiment 2b demonstrated poor performance for a similar stimulus with a higher support ratio. The results suggest that, in contrast to the subjective observation of Boselie and Wouterlood (1992), experimental data indicate that participants do not perceptually complete the triangle in ways that result in precise local edge representations, nor do they perceive a vertex located anywhere near the point at which the linear extensions of visible edges would meet behind an occluder.

This example makes clear how the present results and their interpretation might resolve certain theoretical logjams. When participants report that they perceive a triangle lying behind the occluder, they are using a higher-order, knowledge-based process that is leading them to a decision about the likely familiarity or simplicity of an object that is partly out of sight. The process that participants are using is clearly not giving rise to a perceptual representation with precise or accurate boundaries. Thus, the two-process account makes clear why Boselie and Wouterlood (1992) were correct in saying people report a triangle when one vertex is occluded; yet such observations should nonetheless not be used to modify local interpolation theories.

This study invites a number of follow-up studies. It would be worthwhile, for example, to examine differences between local and global participants using familiar, rather than symmetric, stimuli, as other global completion theories have suggested a role for familiarity as well as symmetry or simplicity. There are also other kinds of global regularities, such as continuation of spatially oscillating contours, for which local and global completion theories sometimes make differing predictions. Additional research may further elaborate the distinction proposed here between local mechanisms of interpolation in human vision and processes that produce reports about partly occluded objects based on recognition from partial information.

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