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Is interpolation cognitively encapsulated? Measuring the effects of belief on Kanizsa shape discrimination and illusory contour formation

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ABSTRACT

Contour interpolation is a perceptual process that fills-in missing edges on the basis of how surrounding edges (inducers) are spatiotemporally related. Cognitive encapsulation refers to the degree to which perceptual mechanisms act in isolation from beliefs, expectations, and utilities (Pylyshyn, 1999). Is interpolation encapsulated from belief? We addressed this question by having subjects discriminate briefly-presented, partially-visible fat and thin shapes, the edges of which either induced or did not induce illusory contours (relatable and non-relatable conditions, respectively). Half the trials in each condition incorporated task-irrelevant distractor lines, known to disrupt the filling-in of contours. Half of the observers were told that the visible parts of the shape belonged to a single thing (group strategy); the other half were told that the visible parts were disconnected (ungroup strategy). It was found that distractor lines strongly impaired performance in the relatable condition, but minimally in the non-relatable condition; that strategy did not alter the effects of the distractor lines for either the relatable or non-relatable stimuli; and that cognitively grouping relatable fragments improved performance whereas cognitively grouping non-relatable fragments did not. These results suggest that (1) filling-in effects during illusory contour formation cannot be easily removed via strategy; (2) filling-in effects cannot be easily manufactured from stimuli that fail to elicit interpolation; and (3) actively grouping fragments can readily improve discrimination performance, but only when those fragments form interpolated contours. Taken together, these findings indicate that discriminating filled-in shapes depends on strategy but the filling-in process itself may be encapsulated from belief.

1. Introduction

Cognitive encapsulation refers to the degree to which a perceptual process operates independently of beliefs, expectations, and other "higher-level" cognitive states[1] (Fodor, 1983; Pylyshyn, 1999). Contour interpolation is a perceptual process that fills-in missing contours on the basis of how surrounding (visible) edges are spatiotemporally related. Is contour interpolation cognitively encapsulated?

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[1] Some use "cognitive" to refer to any mental state, while others use it to refer to those that are post-perceptual. We use the term in the latter sense. That is, cognitive states are typically: instantiated outside of the primary sensory cortices, subject to voluntary control, and manifested as beliefs, expectations, desires, and utilities. This definition is (perhaps necessarily) imprecise, but should be sufficient for interpreting the present data.

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We focus specifically on interpolation because it is *prima facie* a likely candidate for encapsulation. It is phylogenetically primitive (Nieder, 2002), ontogenetically precocious (Kellman & Spelke, 1983; Valenza, Leo, Gava, & Simion, 2006), and (at least in part) physiologically early (Peterhans, von der Heydt, & Baumgartner, 1984; Seghier & Vuilleumier, 2006; Sugita, 1999), all of which imply a limited role for cognitive input. Moreover, while other studies have examined whether attention can alter interpolation (Marcus & van Essen, 2002), or whether interpolation can occur despite the wishes of the observer (Davis & Driver, 2003; Keane, Mettler, Tsoi, & Kellman, 2011), none have examined whether *beliefs or expectations* can extinguish interpolation when it normally occurs or induce interpolation when it normally does not. Addressing this question will be valuable, first, because it will bear on a long-standing debate as to whether the mechanisms of perception operate independently of cognition (Fodor, 1983; Pylyshyn, 1999); and second, because it can inform current models of object perception, in terms of what types of inputs can feed into the process (e.g., Grossberg & Mingolla, 1985; Grossberg & Raizada, 2000; Kalar, Garrigan, Wickens, Hilger, & Kellman, 2010; Seghier & Vuilleumier, 2006).

1.1. Evidence regarding cognitive encapsulation

Studies thus far have yielded only indirect evidence regarding the encapsulation of interpolation. In visual search and multiple object tracking experiments, the attempt to ignore interpolated contours failed to block interpolation effects (Davis, 2003; He & Nakayama, 1992; Keane et al., 2011). In a contour linking study, pictures of complete shapes before a trial did not improve subjects' ability to integrate fragments into a single moving shape (Lorenceau & Alais, 2001). In attentional cuing experiments, the attentional guidance offered by occluded contours could not be removed via pictorial cues that biased observers to interpret edges as disconnected (Pratt & Sekuler, 2001). By contrast, in a subsequent cuing study (Lee & Vecera, 2005), a visual short-term memory task destroyed the attentional guidance afforded by interpolated (but not real) contours. This latter effect does not by itself imply reduced interpolation, however.[2]

Subjective reports also provide clues. Interpolation can create shapes that would be contextually unexpected or semantically nonsensical, suggesting a limited role of cognition (see Fig. 1; Kanizsa, 1985; Kellman, Garrigan, Shipley, & Keane, 2007). At the same time, observers can vacillate between modal and amodal representations or invoke object knowledge to represent the approximate shape edges (Gellatly, 1982; Kellman et al., 2007; see also, Lesher, 1995, esp. pp. 295–296).[3] These subjective reports—although intriguing and worthy of further study—should be regarded with caution, since they may result from the construction or manipulation of representations at relatively late (post-interpolation) stages in visual processing (Kellman, Garrigan, & Shipley, 2005).

Paradigms most relevant to the current study are those that examine the *filling-in*, and not just grouping, of interpolated contours, where 'filling-in' refers to the tendency to represent and rely upon the regions corresponding to the missing contours.[4] In one such study, "fat" and "thin" Kanizsa squares were harder to differentiate when distractor lines appeared near the illusory boundaries (Ringach & Shapley, 1996). This occurred even though subjects knew that the lines were task-irrelevant and even though the lines were well-separated from the inducing edges of the squares. No such impairment was found in a control condition that lacked filled-in contours. In a separate study, when subjects were explicitly and repeatedly told to ignore distractor lines, the discrimination of illusory (but not fragmented) shapes strongly depended on those lines (Keane, Lu, Papathomas, Silverstein, & Kellman, submitted for publication). Others have found a reliance on filling-in regions with standard Kanizsa shapes, noise-corrupted Kanizsa shapes, and spatiotemporal illusory shapes (Gold, Murray, Bennett, & Sekuler, 2000; Gold & Shubel, 2006; Keane et al., 2007; Sekuler & Murray, 2001; Zhou, Tjan, Zhou, & Liu, 2008). A few studies demonstrated attentional modulation of contour filling-in but in all of these cases the integrated elements did not strongly group either because of narrowband spatial frequency composition (Freeman, Sagi, & Driver, 2001), misaligned edges (McMains & Kastner, 2011) or inadequate junction structure (Li, Piëch, & Gilbert, 2008; Rubin, 2001).

The foregoing studies, while not monolithic in agreement, converge on several conclusions: interpolation can proceed even when observers attempt to stop it; attention can modulate interpolation, at least for weakly-grouped elements; and processes subsequent to (or otherwise separate from) interpolation may be relevant for interpreting first-hand reports and psychophysical data, especially when the stimuli are observed for extended durations. What is still unknown, and what we now address, is whether the *strength or existence* of filling-in can be modulated via cognitive expectation.

1.2. Methodology, hypotheses, and rationale

A description of our approach must be prefaced by several clarifications. First, encapsulation is not the same as

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[2] The color memory task may have served not to weaken interpolation, but to strengthen the representation of the fragmented array in which the color patches appeared. This memorized configuration essentially may have "out competed" the amodal contours in guiding attention. Such an explanation is rendered more plausible by the facts that observers could not respond until 600 ms after inducer onset, and that interpolation strength may rapidly rise and fall within 200 ms of inducer onset (Keane, Lu, & Kellman, 2007; Lee & Nguyen, 2001). Others have also argued that recently stored stimulus representations can trump the attentional guidance afforded by (currently visible) real and interpolated contours (Zemel, Behrmann, Mozer, & Bavelier, 2002).

[3] Kanizsa (1985) termed post-perceptual representations of non-visible objects "mental integration", and, more recently, Kellman and colleagues (2007) called it "representing on partial information (RPI)". Both authors were referring to processes that were at least partly cognitive in nature.

[4] Grouping and filling-in are not the same. Grouping involves specifying whether disparate elements belong together; filling-in also involves delineating the specific shape that those elements form and using information that appears near the delineated edge. As an example, four similarly oriented "pac-men" may be grouped but they will not cause the visual system to represent and use regions that are between the pac-men (Ringach & Shapley, 1996).

automaticity. In our view, an automatic mechanism produces an output without requiring certain beliefs or expectations while an encapsulated mechanism produces an output even when *contrary* to belief or expectation. So all encapsulated processes are automatic but not the other way around. Here, we see if cognition can veto a process that would otherwise occur. Second, the aim is not to see whether interpolation can proceed against observers' desires since such a result has already been shown multiple times before (Davis, 2003; Keane et al., 2011). The goal instead is to examine whether contour filling-in depends on how a subject cognitively *regards* the image, which is an important, virtually untested aspect of interpolation. Third, our investigation centers on whether belief can alter perceptual representations of contours, not whether belief can generate its own contour representations. An observer may—upon seeing only the head of a cat— cognitively represent the entire outline of a cat by applying knowledge of how such animals typically appear (see Fig. 1F). But, again, this accomplishment is not of primary interest. The present aim is to use a metric for illusory contour formation that has been used repeatedly in the perception literature (see below) to examine whether cognition can change perception itself; whether illusory contours can be generated or diminished on the basis of belief alone. Fourth, the present inquiry will not consider whether cognition can change the 2D path or perceived depth of a contour (e.g., from being modal to amodal, see Fig. 1). While such an investigation is relevant to the encapsulation debate, the focus is on whether contour strength is amplified when subjects are given good reason to believe that a contour is present, or weakened when given good reason to believe that it is not.

In two experiments, the question of encapsulation was explored with a variation of Ringach and Shapley's well-validated fat/thin task (Gold et al., 2000; Guttman & Kellman, 2004; Maertens, Pollman, Hanke, Mildner, & Moller, 2008; Murray, Imber, Javitt, & Foxe, 2006; Pillow & Rubin, 2002; Ringach & Shapley, 1996; Spehar, 2000; Stanley & Rubin, 2003; Yin, Kellman, & Shipley, 1997). In all trials, the middle portions of discriminated shapes were camouflaged by an identically colored (gray) background, so that only four corners were physically visible (see Fig. 2). Half of the trials involved fragments that were positioned to initiate interpolation (relatable condition); the remaining trials involved fragments that were misaligned to prevent interpolation (non-relatable condition). Half of the relatable and non-relatable trials involved distractor lines. As in Ringach and Shapley (1996), these added segments were objectively information-less in that they always appeared along a path that fell exactly between the fat and thin shape alternatives. The distractor lines occupied only 2/3rds of the camouflaged edge and thus were always clearly separated from the task-relevant contours. Filling-in was measured by the performance decrement caused by the distractor lines: *the more that performance decreased as a result of the lines, the more that filling-in could be said to occur*. Others have also measured filling-in as a tendency to rely on irrelevant information (Dillenburger & Roe, 2010; Gold & Shubel, 2006; Gold et al., 2000; Keane et al., 2007; Ramachandran, Ruskin, Cobb, Rogers-Ramachandran, & Tyler, 1994; Ringach & Shapley, 1996; Zhou et al., 2008). Collinear facilitation studies have also assumed that linking between Gabor elements happens only if information in or near the

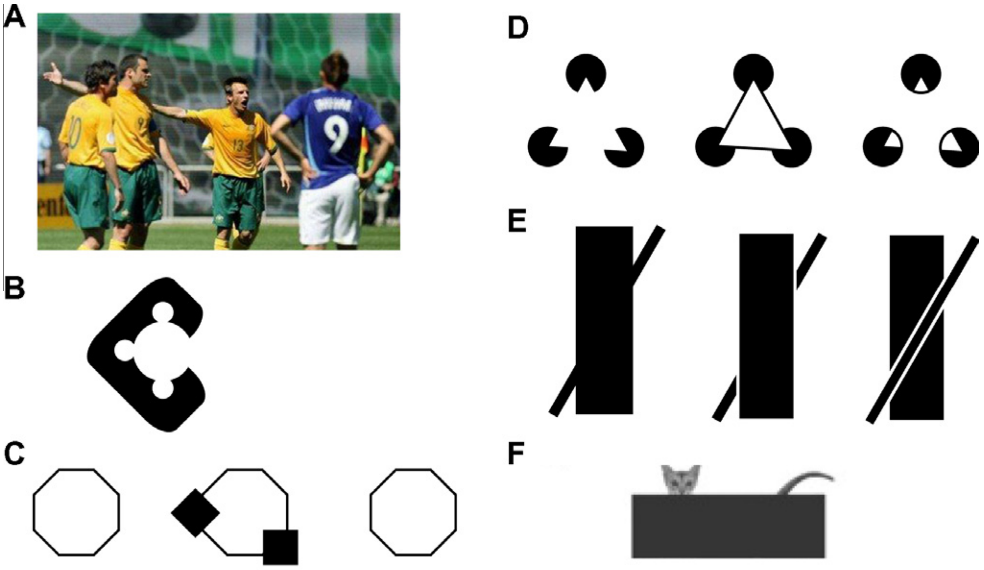

Fig. 1. *Stimuli relevant to the possible encapsulation of interpolation*. (A–C) Interpolation binds parts into forms that violate what one would expect on the basis of context or background knowledge, indicating that cognition may be ineffectual for altering interpolation (part B was adapted from Kellman et al., 2007, pp. 603–604; part C was adapted from Pylyshyn, 1999, p. 345, and originated in Kanizsa, 1985). (D–E) On the other hand, the left triangle and the left *vertical* rectangle are most naturally viewed as being in front (center) even though they can—with effort—be viewed as occluded, as shown on the right (Fig. 1D from Papathomas, 1999). (F) When perception does not represent a well-defined shape, observers can use their knowledge of how an object typically looks to roughly represent the occluded parts (Fig. 19A from Kellman, Garrigan, & Shipley, 2005, p. 604). These last three cases indicate that cognition may be relevant to contour interpolation after all.

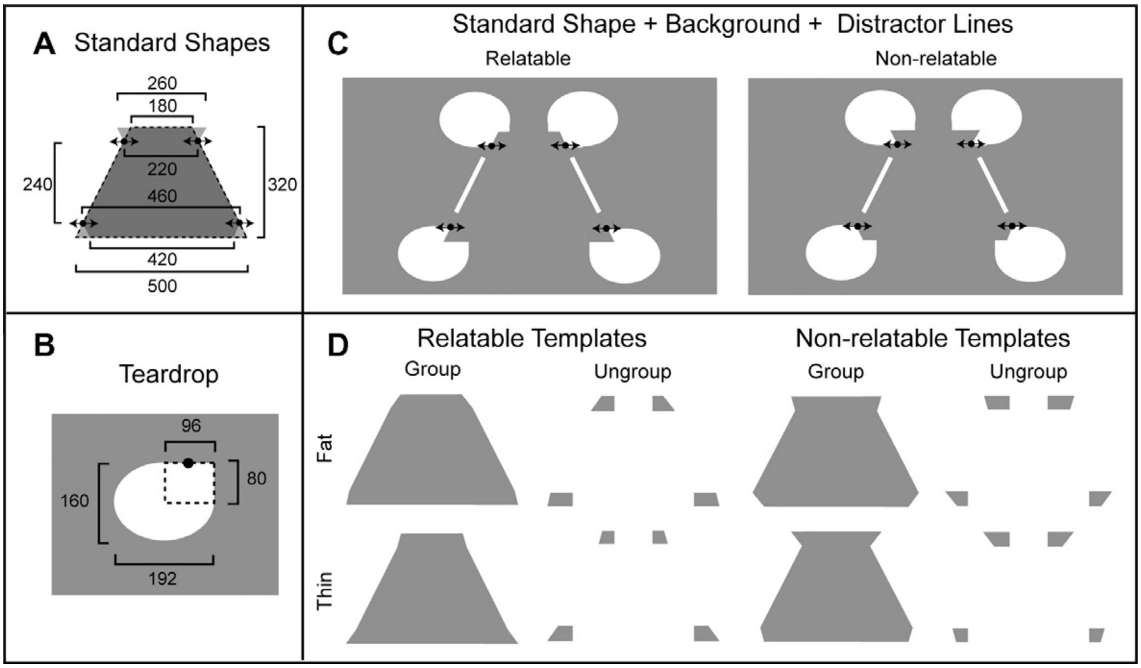

Fig. 2. *Stimuli for both experiments.* (A) Relatable and non-relatable standard shapes are shown superimposed for comparison (with the relatable shape bordered by a dotted line). Dimensions are provided in pixels, where 1 pixel ≈ 1.4 arcmin. Both standard shapes shared four "anchor points", depicted above as black dots with two-sided arrows. Fat and thin shapes were produced by shifting anchor points peripherally and centrally, respectively. (B) White teardrop elements appeared behind each visible corner of a target shape. Anchor points of a standard shape were horizontally centered in the rectangle portion of the teardrop (marked by the black point). (C) Standard shapes are shown with the distractor lines and teardrop background. (D) Group and ungroup templates were shown to encourage subjects to treat visible edges as belonging to one thing or several. The ungroup template corresponded exactly to those regions of the group template that were physically visible during a trial. Thus both the group and ungroup templates would appear identical when placed over the teardrop background.

filled-in region is differentially processed (Freeman et al., 2001; Polat & Sagi, 1993, 2007).

A strategy was encouraged by giving subjects response template pictures and verbal instructions at the beginning of the experiment, and also at the beginning of each block of trials (described below). A strategy was further encouraged by giving participants pictures of the templates during the response phase of each trial. The purpose of repeatedly showing the templates in this way was to increase the chances that a strategy would be consistently applied throughout an experiment. There were two strategy conditions. One was to group the visible fragments together into an object (the "group" strategy) and the other was to treat the four visible fragments as distinct entities ("ungroup" strategy, see Fig. 2). Consequently, some subjects were informed that the fragments were distinct even though the geometric relation of the edges would (on certain trials) encourage interpolation; other subjects were informed that the fragments belonged together, even though those fragments (on certain trials) did not have a relatable geometry. Importantly, both sets of instructions were *the same* in regards to which regions contained visible edge information and how these edges differed for fat and thin. Both groups were encouraged as much as possible to attend to the same four visible edge regions. The instructions differed only in how subjects were asked to *regard* the connectedness of the visible edges so that any behavioral differences resulting from the instructions could be attributed to this belief difference.[5] The reason why ungroup subjects might not use the distractor line regions in the relatable condition is because they were explicitly and repeatedly told that those regions do not contain the boundary of the discriminated target. Conversely, group subjects might use the distractor lines in the non-relatable condition because they were explicitly and repeatedly told that those regions are traversed by the figure boundary and it might be natural to examine these regions in the discrimination. Others have also suggested that cognitive templates are relevant as to whether subjects rely upon filled-in regions in fat/thin tasks (Anderson, 2007; Gold & Shubel, 2006; Gosselin & Schyns, 2003).

The primary aim of this study was to examine whether illusory contour formation is encapsulated from belief. If the distractor lines strongly deteriorate performance in the relatable condition and minimally impair performance in the non-relatable condition, and if such outcomes occur regardless of strategy, then filling-in may be considered cognitively impenetrable. If distractor line influence does hinge on strategy, then belief—or attentional strategies

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[5] There are different ways to induce the belief (or disbelief) that fragments are connected. For example, in Fig. 1A, knowledge that people do not have 8 foot arms causes the belief that the two parts of the arm are separated, whereas in the present paper, instructions and pictures produced a similar expectation. For present purposes, it is not important *how* subjects come to have a belief about connectedness but only *that* they have the belief.

that result from belief—alter illusory contour formation. A secondary goal was to examine the effect of cognitive grouping on overall shape discrimination, since no other study seems to have explored this directly. If discrimination ability in the relatable and non-relatable conditions is the same regardless of an observer's grouping template, then that would constitute important evidence for the cognitive impenetrability of illusory shape perception.

The fat/thin paradigm, as we employed it, has advantages over paradigms of previous studies: (1) unlike object tracking, attentional cuing, contour linking, and visual search studies, our task examines the filling-in and not just grouping of illusory contours; (2) unlike studies that ask participants to rate contour strength, the fat/thin paradigm provides an *objective* measure of strategy on the interpolation process, which is appropriate given that interpolation can proceed without subjects even knowing it (Keane et al., 2011; Vuilleumier, Valenza, & Landis, 2001); (3) unlike all tasks to date, ours is the first that directly explores whether illusory contours can be weakened or strengthened on the basis of beliefs about contour connectedness.

2. Experiment 1

2.1. Participants

Twenty-two participants completed the grouping condition (mean age = 23; 4 males), and the same number completed the ungrouping condition (mean age = 23; 8 males). Two participants from each condition were excluded for chance performance (<51%). All had normal or corrected-to-normal visual acuity, were naïve to the purposes of the task, and received course credit or monetary compensation.

2.2. Apparatus

The displays were presented on a Viewsonic CRT monitor with a resolution of 1024 × 768 pixels and a refresh rate of 60 Hz. Observers were seated with a chinrest about 95 cm from the screen so that the display subtended 24 × 18 deg (pixel = 0.0239° or 1.4 arcmin). Except for the red fixation point, stimuli were always one of two achromatic colors: gray (59 cd/m^2) or white (76 cd/m^2). Displays were programmed in MATLAB using Psychophysics Toolbox (Brainard, 1997; Pelli, 1997).

2.3. Stimuli

Participants discriminated fat and thin shapes that were created by altering a "standard shape". Four vertices of the standard shape were designated "anchor points" in that they were the same for both the relatable and non-relatable shapes (see Fig. 2). To create a thin shape, the anchor points were horizontally moved inward (centrally) from where they would be on the standard shape. To create a fat shape, these anchor points were moved outward peripherally. The magnitudes by which these anchor points moved defined the five levels of discrimination difficulty: ±2, 3, 4, 5, or 6 pixels. Each of these difficulty levels occurred for the two kinds of shapes—relatable or non-relatable. Visible edges in the relatable trials were arranged so that they satisfied geometric relations required for interpolation (Kellman & Shipley, 1991); edges in the non-relatable trials were severely misaligned to disrupt interpolation (Fulvio, Singh, & Maloney, 2006, 2008; Kellman & Shipley, 1991). Target shapes appeared on four white teardrop elements, which themselves appeared on a background that was the same color as the target. Each teardrop was composed of a rectangle and oval, as shown in Fig. 2B. The ovals were added because other studies of interpolation typically use notched, curved elements and because the discontinuities in these elements may be important for creating illusory contours (Hoffman, 2000). Anchor points for a standard shape were centered along the innermost horizontal edge of the teardrop rectangles (see figure for details). Implied is that the teardrop elements (and their relative arrangement) were identical for the relatable and non-relatable trials. An advantage to the teardrop background (rather than notched circles) is that the visible portions of shapes corresponded to four trapezoids that could be fat or thin. This made the group and ungroup conditions more comparable (since both involved making judgments about the width of polygons), and also simplified the task instructions in the ungroup condition (see below). Distractor lines had the same Weber contrast as the teardrops (30%), and occupied 2/3 of the length of the oblique camouflaged edge of the standard shapes. These lines were centered between the anchor points of the standard shape, and had a horizontal thickness of 9 pixels (0.22 deg).

The dimensions of the relatable and non-relatable standard shapes are shown in Fig. 2A. The support ratio, which is the visible edge length divided by the total edge length (Shipley & Kellman, 1992) was 0.25 for the oblique contours of the standard shapes. A modest support ratio was chosen to increase the chances of finding cognitive effects on interpolation, since contours of lower salience may be more susceptible to high-level influence (McMains & Kastner, 2011).

As can be gleaned from Fig. 2, the relatable and unrelatable shapes were controlled along most dimensions, and may be better controlled than any previous version of the fat/thin task. The total area visible and the total area camouflaged was the same for the relatable and non-relatable shapes. The slopes, positions, and lengths of the invisible oblique edges were the same. The distractor lines, when they appeared, were also the same. Also, each corner of a discriminated alternative involved only one visible orientation on one side, and the opposite orientation on the alternate side. For a given fat/thin shape difference (e.g., 4 pixels), the difference in visible surface areas for fat and thin shapes was the same for the relatable and non-relatable.

While both relatable and non-relatable shapes had greater support ratio for the upper than lower horizontal illusory contours, the difference in these two support ratios was greater for the non-relatable shapes. It was unclear whether this structural difference would matter. Just in case it did, the stimulus was randomly inverted on half the trials, as described below. Therefore, if subjects have a bias to attend to the part of the figure with the more strongly interpolating horizontal contours (for example), our set-up would make it difficult to act on that bias. It is worth noting that this structural difference is probably inconsequential since the difference concerns only the *horizontal* illusory contours, and since these contours were neither discriminated nor did they involve distractor line disruption nor did they provide information about the true shape identity. By contrast, the oblique contours were discriminated, were corrupted with distractor lines, and did provide information about the true target identity. The camouflaged portion of those oblique contours *was* identical for the relatable and non-relatable configurations. Moreover, although we tried to control the relatable and non-relatable among most dimensions and although this yields some interesting comparisons, assessing cognitive effects on filling-in does not require comparing the two kinds of stimuli. Assessing encapsulation requires only examining whether distractor line effects change as a function of strategy in each case (relatable/non-relatable).

2.4. Procedure

There were four blocks corresponding to whether a shape was relatable or non-relatable, and whether distractor lines were present or absent. Blocks were counterbalanced across observers with the rule that half of the experiment incorporated only relatable trials and the other half incorporated only non-relatable. Distractor line trials were blocked in order to minimize noise and attentional distraction, which might occur when trials with and without lines are intermixed (Hodsdoll, Mevorach, & Humphreys, 2009; Kristjánsson & Driver, 2008; Theeuwes & Burger, 1998). Other studies of the fat/thin task have also primarily used blocking (Gold et al., 2000; Pillow & Rubin, 2002; Ringach & Shapley, 1996; Zhou et al., 2008). Each of the four blocks involved 240 trials, and there were 48 trials for each of the five discrimination difficulty levels in each block. Half of those 48 trials were thin trials and the remaining were fat. For each of these groups of 24 trials, half were inverted about the central horizontal axis. Thus, fat, thin, inverted and upright stimuli at each difficulty level were presented quasi-randomly within a block.

The phases of a trial for Experiment 1 are outlined in Fig. 3. The target presentation, blank screen, and background element intervals were the same in duration as in Ringach and Shapley (1996) and were similar to various other studies that have used the paradigm (Murray et al., 2006; Stanley & Rubin, 2003; Zhou et al., 2008). The background element interval was intended to minimize lingering visible persistence of the target (Sperling, 1960), and gave subjects only a limited amount of time to view the target. During the response phase, the two extreme response templates (±6 pixel difference from the standard) were shown to encourage either a group or ungroup strategy. The thin template was always shown on the left; the fat, on the right. For inverted trials, the response templates were also shown as inverted. The purpose of these templates was to reinforce the instructions and to ensure that subjects were maintaining the same cognitive expectation throughout a block of trials.

For all participants, each half of an experiment began with 100 trials of practice, which took about 5 min to complete. These trials involved the same kind of shape (relatable/non-relatable) as the first test block. The practice block always involved the easiest difficulty level (±6 pixels), and never included distractor lines. Half of the stimuli in the practice trials were inverted (chosen quasi-randomly).

Task instructions were presented in the following way. For the group instructions, at the beginning of each block (including the practice block), participants were told that they would discriminate complete shapes, the middle portions of which would blend in perfectly with the background. They were provided with the two extreme shape templates side-by-side (differing from the standard by ±6 pixels), and were asked to scrutinize the difference between the two. The two shapes were then presented at the same location in alternation (period = 1 s) for 30 s. Participants were then told that on some trials the shapes may appear inverted, and were given pictures of fat and thin inverted shapes side-by-side. Participants were further told that on some trials, distractor lines would appear near the border of the shape and that, regardless of the lines, they should try their best to judge whether the shape is fat or thin. Observers were told that at the end of each trial, they would be given examples of the two discriminated shapes. The instructions encouraged inspection of the fat/thin templates during the response phase of a trial, if that was found to be helpful.

For the ungroup instructions, at the beginning of each block (including the practice block) participants were told that they would discriminate two sets of four trapezoids, certain portions of which would blend in perfectly with the background. They were provided with the two extreme sets of trapezoids side-by-side, and were asked to scrutinize the difference between the two. They then were shown the fat and thin sets of trapezoids in serial succession (at the same spatial location) for 30 s (period = 1 s). Participants were also told that, on some trials, the target set of trapezoids would appear inverted and were shown the two extreme fat/thin inverted trapezoid sets, side-by-side. Participants were further told that on some trials, distractor lines would appear between the different trapezoids, and that regardless of the lines, they should try their best to judge whether the trapezoids were all thin or all fat. As already noted, we further motivated an ungrouping strategy by giving the subjects templates of fat and thin trapezoid sets during the response phase of each trial. As before, observers were encouraged to inspect the response phase templates, if that was found to be helpful.

For both sets of instructions, we minimized variability across trials and between participants by reminding observers at the beginning of each block to maintain fixation. Half way through each block, observers were instructed to take a break, if desired.

Each subject received only one set of instructions (either group or ungroup) throughout an experiment primarily because subjects would doubtfully be able (or at least willing) to switch from a group strategy to an

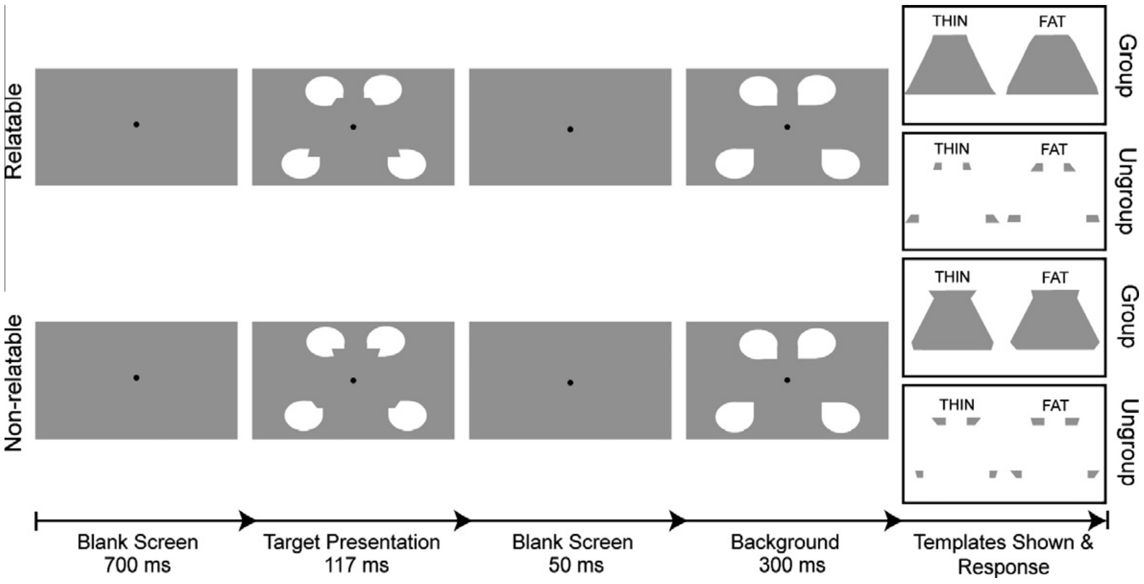

Fig. 3. *Schematic illustration of a relatable or non-relatable trial for both grouping conditions in Experiment 1*. The target shape blended in with the gray background and became visible only by overlapping with the teardrop elements. On half of the blocks, distractor lines (not shown) also appeared along with the target. The visible fragments of the target could be either relatable or non-relatable, and either fat (as shown) or thin (not shown). To encourage a specific grouping strategy, subjects were shown the two extreme thin and fat templates during the response phase. When a target was shown as inverted, all other aspects of the display were also inverted (including the templates).

ungroup strategy, especially if the former made the task easier. As others have pointed out, once an observer knows how to interpret a highly fragmented cow picture, a cow is experienced in all subsequent viewings of that picture (Dallenbach, 1951). Others have also noted out that manipulating strategy is best done on a between-subject basis, at least for some types of cognitive tasks (Kahneman & Frederick, 2005, p. 280). Most importantly, the goal of the current investigation is not to test how or whether subjects can switch from one strategy to another but only whether differences in belief about connectedness can lead to differences in filling-in.

2.5. Analyses

Sensitivity (d') was calculated for each subject and condition. These values were subsequently analyzed via a 2 (grouping instructions) $\times$ 2 (relatability) $\times$ 2 (distractor lines) $\times$ 2 (inversion) $\times$ 5 (difficulty) mixed-design ANOVA. To compare strategy effects on filling-in for shape perception, we then performed an ANOVA on just the relatable trials and also on just the non-relatable trials. Prior to the analyses, proportion values of 1 and 0 were corrected to prevent undefined d' (MacMillan & Creelman, 1991). More specifically, for each kind of trial, proportions equal to 0 were assigned a value of $1/(2N)$, and proportions equal to 1 were equated to $1 - 1/(2N)$, where N denotes the number of trials in a discrimination category ($N = 12$).

2.6. Results and discussion

Results are shown in Fig. 4. The ANOVA indicated several expected results. Increasing the fat/thin shape difference made the task easier ($F(4, 152) = 62.5$, $p < .001$, $\eta_p^2 = .622$). The relatable condition produced better performance than the non-relatable condition ($F(1,38) = 10.4$, $p = .003$, $\eta_p^2 = .216$). There was an interaction between distractor lines and relatability, such that the lines hurt performance when near illusory contours but very little otherwise, $F(1,38) = 9.3$, $p = .004$, $\eta_p^2 = .197$. This two-way interaction did not depend at all on the grouping strategy, $F(1,38) = .188$, $p = .667$, $\eta_p^2 = .005$.

The grouping instructions were relevant in other ways. Subjects who grouped overall did better than those who did not, $F(1,38) = 7.9$, $p = .008$, $\eta_p^2 = .173$. This main effect interacted with relatability ($F(1,38) = 13.7$, $p = .001$, $\eta_p^2 = .265$) such that grouping helped performance when edges were relatable, but not otherwise. The benefit of grouping also interacted with the inversion variable ($F(1,38) = 5.4$, $p = .026$, $\eta_p^2 = .125$) such that inverting the stimulus hurt performance more when subjects attempted to see the stimulus as being a single object. Finally, there was a significant interaction between inversion and relatability ($F(1,38)=$, $p = .03$, $\eta_p^2 = .125$) in that inversion hurt performance more for the relatable than non-relatable shapes. (See Supplementary material for graphs of the inversion effects). These last two interactions suggest that when a shape is seen as a single thing—either because of relatability or because of cognitive strategy—inverting that shape will make discrimination harder. The reason for the inversion effect is unclear, but one possibility is that top-heavy (inverted) objects are less familiar and hence harder to discern than upright shapes. Alternatively, there may be a familiarity advantage for upward-tapering shapes, since objects commonly recede in depth as they protrude further from the lower visual field (Reichel & Todd, 1990). The relevance of inversion to shape discrimination will be discussed further in the "General discussion".

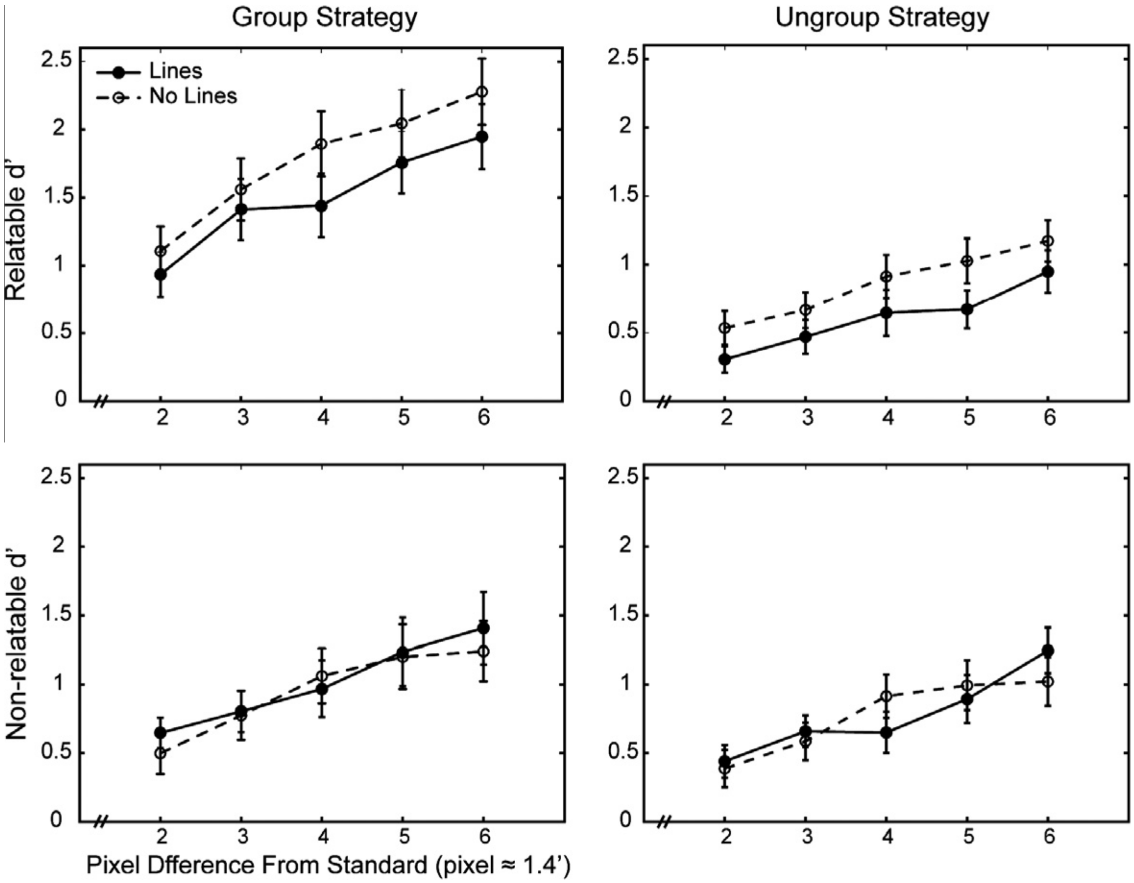

Fig. 4. *Shape discrimination sensitivity in Experiment 1 as a function of pixel difference from the standard shape.* Data from the grouping strategy (left column) and ungrouping strategy (right column) are shown for the relatable (top row) and non-relatable (bottom row) conditions. Graphs show performance with and without distractor lines (solid and dashed lines, respectively) for the five difficulty levels, each of which was defined in terms of how much the standard shape was altered to create the fat and thin alternatives (see Fig. 2). Error bars show ±1 SEM.

To examine more fully the role of strategy on filling-in during illusory contour formation, we examined just the relatable trials across strategy instructions. As expected, performance was markedly worse with distractor lines, $F(1,38) = 15.5$, $p < .001$, $\eta_p^2 = 0.289$. Importantly, the distractor line effect did not depend on strategy, $F(1,38) = 0.03$, $p = .86$, $\eta_p^2 = 0.001$. This means that simply believing that connecting contours are absent or present fails to inhibit or enhance filling-in, respectively. No other factor or combination of factors (e.g., inversion, difficulty, etc.) altered the effect of the lines (all *ps* > .4). Yet grouping was still relevant: When relatable edges were treated as a single entity, sensitivity was much higher ($F(1,38) = 15.3$, $p < .001$, $\eta_p^2 = 0.287$) and sensitivity improved more dramatically as shape differences increased, $F(4, 152) = 3.9$, $p = .005$, $\eta_p^2 = 0.093$. These results are consistent with the finding that a grouping strategy (provided via priming) can boost discrimination sensitivity when less salient interpolated contours bind visible edges together (Kellman et al., 2007, pp. 504–505). More generally, grouping effects that we uncovered fit with other data that show that conceptual categorization (or attentional strategies resulting from categorization—see General discussion) can alter perceptual discrimination and object recognition (Bravo & Farid, 2003; Gauthier, James, Curby, & Tarr, 2003; Goldstone, 1994).

Next the non-relatable trial data were examined. The most important outcome was that the distractor lines, overall, had no effect on overall performance, $F(1,38) = 0.116$, $p = .76$, = 0.003, which held true regardless of observer strategy, $F(1,38) = 0.12$, $p = .74$, $\eta_p^2 = 0.003$. The effect of the lines did modestly depend on difficulty level ($F(4, 152) = 2.8$, $p = .03$, $\eta_p^2 = .068$), but follow-up comparisons showed that the line and no-line trials were the same for each difficulty level (all *ps* > .10). No other factors altered the effects of the lines. Therefore, regardless of whether subjects thought that the non-relatable edges were connected, the distractor lines continued to be irrelevant, and filling-in did not occur. In contrast to the relatable trials, grouping into a single object did *not* produce an overall benefit, $F(1,38) = 1.0$, $p = .33$, $\eta_p^2 = 0.026$; nor did it alter the effect of the difficulty variable, $F(4, 152) = 0.219$, $p = .93$, = 0.006. Thus, when fragments were non-relatable, grouping could neither induce filling-in, nor alter overall accuracy, nor modify the effects of task difficulty on shape discrimination.

3. Experiment 2

The previous experiment suggests that cognitively grouping a stimulus improves the discrimination of relatable (but not non-relatable) shapes, makes upright stimuli easier to distinguish, and fails to alter contour filling-in. An objection to the foregoing is that there was no independent measure to ensure that subjects followed the directions. For example, perhaps the ungroup subjects employed a non-optimal strategy that did not actually involve believing that the figures were fragmented. Similarly, the instructions may have altered not subjects' beliefs but the manner in which subjects examined and utilized the response templates. Finally, there lingers a possibility that subjects deployed different strategies on blocks with and without distractor lines. In this experiment, we address all of these concerns by: (i) asking subjects at the end of each half of an experiment how they regarded the stimuli; (ii) showing the response templates only on 5% of the trials; and (iii) randomizing the distractor line trials within the relatable and non-relatable blocks. If the results turn out to be highly similar, and if subjects report using the instructions in the way expected, then the results of the first experiment will be confirmed.

3.1. Method

3.1.1. Participants

Twenty-six participants were assigned the grouping instructions (mean age = 19; 3 males) and 28 were assigned the *un*grouping instructions (mean age = 20; 7 males). Three ungroup subjects and one group subject were excluded for chance performance (<51%). All had normal or corrected-to-normal visual acuity, were naïve to the purposes of the task, and received course credit or monetary compensation. The participants in Experiment 2 were different from those who participated in the first experiment.

3.1.2. Apparatus

The apparatus was the same as Experiment 1.

3.1.3. Stimuli

The stimuli were the same as before except that the fat/thin shapes differed from the standard shape by 4, 5, 6 or 7 pixels. Larger shape differences were utilized in order to boost the probability of experiment completion, which might be especially helpful for the lower-performing "ungroup" subjects.

3.1.4. Procedure

The procedure was similar to Experiment 1 with a few exceptions. First, response templates were shown immediately after a subject participated in 20 consecutive trials. During this period, the fat/thin upright templates were shown side-by-side for 3 s and the fat/thin inverted templates were shown for the same duration. The ordering of the upright and inverted templates was randomized and a key press enabled continuation in each case. Second, subjects answered a questionnaire at the end of each of the two blocks (relatable and non-relatable). The questionnaire required subjects to draw the fat and thin stimuli that they thought appeared over the teardrop elements and also asked subjects whether any additional strategies were used in the discrimination. Third, there were 4 (rather than 5) difficulty levels and therefore 20% fewer trials overall. This change may have slightly decreased the statistical power (which lead us to increase the number of subjects), but it provided subjects adequate time to complete the questionnaires. Finally, trials with and without distractor lines were randomized to further ensure that the same strategy was applied in each of the two cases.

3.2. Analyses

The ANOVA analyses for the psychophysical data were the same as before except that the difficulty variable had four (rather than five) levels. For the questionnaires, two raters judged each observer's strategy for each block (relatable and non-relatable). Raters were shown the two types of instructions (group and ungroup) and were told to use all of the questionnaire information (pictures and written response) to determine how subjects regarded the stimuli. Raters were told to use information about attentional strategies only if that helped identify a subject's beliefs. In the rare cases where there was inter-rater disagreement (see below), a third rater (BPK) served as a tie-breaker. None of the raters had any knowledge of a subject's true grouping strategy when examining the questionnaires.

To compare the two experiments, we collapsed data across difficulty and conducted a 2 (experiment) × 2 (grouping) × 2 (relatability) × 2 (distractor) × 2 (inversion) mixed model ANOVA. In this combined analysis, separate ANOVAs were also performed on the relatable trials only and on the non-relatable trials only.

3.3. Results and discussion

Across all trials, outcomes were similar to before (see Fig. 5). Increasing the shape differences made the task easier, $F(3,\ 144) = 17.7$, $p < .001$, $\eta_p^2 = .505$. Illusory shapes were easier to discriminate than fragmented shapes, $F(1,48) = 11.7$, $p = .001$, $\eta_p^2 = .197$. In contrast to Experiment 1, the distractor lines had a significant overall detrimental effect, $F(1,48) = 28.7$, $p < .001$, $\eta_p^2 = .374$. This effect may not be entirely surprising since other studies indicate (for example) that singleton distractors impair visual search performance more when they are randomized rather than blocked (Hodsdoll et al., 2009) and that distractors of the same type or location are more easily ignored when they occur over consecutive trials (Kristjánsson & Driver, 2008; see also, Theeuwes & Burger, 1998).

Similar to before, the distractors hurt performance much more when they appeared near illusory contours ($F(1,48) = 12.7$, $p = .001$, $\eta_p^2 = .209$) and this interaction did not depend on strategy, $F(1,48) = 0.3$, $p = .57$, $\eta_p^2 = .007$. In other words, the lines disrupted filling-in much more in the relatable than in the non-relatable condition, and the effect was not modulated on the basis of how subjects regarded the missing shape contours.

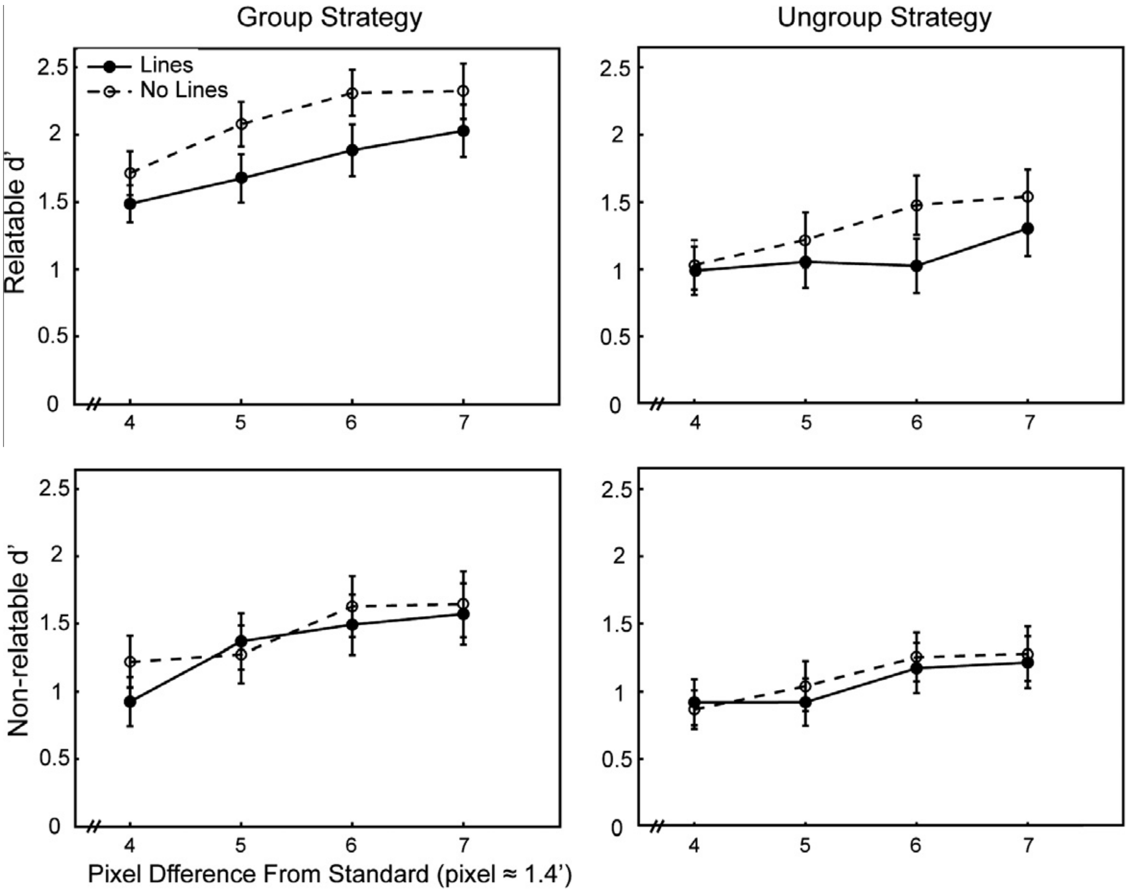

Fig. 5. *Shape discrimination sensitivity for Experiment 2 as a function of pixel difference from the standard shape*. Data from the grouping strategy (left column) and ungrouping strategy (right column) are shown for the relatable (top row) and non-relatable (bottom row) conditions. Graphs show performance with and without distractor lines (solid and dashed lines, respectively) for the four difficulty levels. Error bars show ±1 SEM.

As before, strategy was still highly relevant. Subjects overall did better when regarding the edges as parts of a single object, ($F(1,48) = 5.0$, $p = .03$, $\eta_p^2 = .094$), and this effect was stronger when the edges were relatable ($F(1,48) = 4.75$, $p = .03$, $\eta_p^2 = .09$). There was a grouping by inversion interaction ($F(1,38) = 5.4$, $p = .026$, $\eta_p^2 = .125$), such that—when there was cognitive grouping—inverted shapes were harder to discriminate than upright shapes. (See Supplementary material for graphs of inversion effects.) There was no longer a significant interaction between inversion and relatability ($F(1,38) = 2.34$, $p = .13$, $\eta_p^2 = .047$). We tentatively hypothesize that the interaction is real but the effect size is relatively small and requires a larger number of subjects to be detected more reliably. No other effects were significant on this ANOVA analysis.

Next, just the relatable trials were examined. The distractor lines impaired discrimination accuracy, $F(1,48) = 31.1$, $p < .001$, $\eta_p^2 = .393$, and this impairment did not change with strategy ($F(1,48) = 1.3$, $p = .26$, $\eta_p^2 = .026$) or any other factor in the analysis. Moreover, cognitive grouping lifted overall sensitivity, $F(1,48) = 9.1$, $p = .004$, $\eta_p^2 = .160$). These results once again indicate that discriminating illusory shapes, but not filling-in illusory contours, strongly depends on cognitive expectation.

In the non-relatable analysis, there was a modest effect of the distractor lines ($F(1,48) = 4.5$, $p = .04$, $\eta_p^2 = .085$) most likely because their random appearance made inhibition slightly more challenging, as noted (Hodsdoll et al., 2009; Kristjánsson & Driver, 2008; Theeuwes & Burger, 1998). Grouping the non-relatable stimuli into a single shape did not produce a discrimination advantage, $F(1,48) = 1.375$, $p = .25$, $\eta_p^2 = .028$. Most importantly, distractor line effects did not significantly depend on grouping strategy, $F(1,48) = 0.5$, $p = .50$, $\eta_p^2 = .009$) or any other factor in the analysis. Therefore, while the lines may have worsened performance due to attentional distraction, their influence did not at all depend on whether subjects actually believed the empty region to contain a shape contour.

3.3.1. Confirming subjects' beliefs

In order to confirm that subjects cognitively regarded the configurations in the appropriate way, questionnaires were examined from all 50 subjects for the relatable trials and the non-relatable trials. The two raters had the same assessment on 96 out of 100 questionnaires, indicating that the responses were straightforward to interpret. More importantly, 90% of the subjects were rated as having adopted the instructed templates on both blocks, suggesting that subjects by-and-large maintained the appropriate belief throughout. It is worth noting that the group and ungroup subjects differed marginally in their tendencies to conform to their given templates (Fisher's Exact Test, $p = .05$): all of the grouping subjects maintained their templates throughout the experiment whereas only 20 out of 25 of the ungroup subjects maintained their templates. Also of interest is that all strategy-switching subjects (hereafter, "aberrant" subjects) eventually saw the relatable stimuli as unitary, but only two did so for the non-relatable. Therefore, it seems that some subjects were capitalizing on the presence of illusory contours.

To verify that the psychophysical results for Experiment 2 did not depend on the aberrant subjects, we conducted the same ANOVA analyses as above (all trials, relatable only, non-relatable only) with those subjects removed. Each of the (61) ANOVA results was qualitatively the same as before, with two exceptions: the distractor line effect became non-significant in the non-relatable trials ($p = .04 \rightarrow p = .055$) and the grouping by inversion interaction became significant in the relatable trials ($p = .102 \rightarrow p = .048$). These new results, which mirror what was found in Experiment 1, do not impact the major claims of the study.

An objection to the questionnaire data is that subjects may have been parroting back the instructions rather than providing their true belief about contour connectedness. Although we cannot definitively rule out this possibility, there are several reasons to think otherwise. First, subjects were not explicitly told to try to see the stimuli in a particular way nor were they warned against using alternative strategies; subjects were simply told what the configurations were (e.g., "You will discriminate the two shapes below"). There was consequently little reason for subjects to feel reluctant to report helpful strategies. In addition, the between-subject design would make it difficult for subjects to guess whether strategy was relevant to the experiment or whether a strategy was implicit in the instructions. (The word "strategy" was not mentioned in the recruitment phase or in the experiment instructions). Lastly, the aberrant subjects all switched from the ungroup to the group template, which would be expected given if the former were more difficult. These considerations indicate that the questionnaires provide a reasonable measure of the cognitive expectations deployed in the experiment.

3.3.2. Comparing Experiments 1 and 2

To gain additional power and to test more sensitively for potential high-level influences on filling-in, we analyzed performance for all 90 subjects across the two experiments. Except for the expected higher performance in Experiment 2 ($F(1,86) = 5.6$, $p = .02$, $\eta_p^2 = .061$), the experiments were statistically undifferentiated on every measure for the relatable trials, for the non-relatable trials, and across all trials (all $ps > .24$). More importantly, there was a strong distractor by relatability interaction ($F(1,86) = 21.5$, $p < .0001$, $\eta_p^2 = .200$), which itself did not depend on strategy, $F(1,86) = 0.5$, $p = .49$, $\eta_p^2 = .006$). Strategy also did not alter the effect of the lines in the relatable trials alone ($F(1,86) = 0.7$, $p = .41$, $\eta_p^2 = .008$) or in the non-relatable trials alone, ($F(1,86) < 0.1$, $p = .951$, $\eta_p^2 < .001$), indicating once again that cognitive expectation does not exercise an appreciable influence on filling-in. Finally, a grouping strategy increased overall sensitivity in the relatable trials ($F(1,86) = 23.1$, $p < .0001$, $\eta_p^2 = .211$) but not in the non-relatable trials ($F(1,86) = 2.2$, $p = .14$, $\eta_p^2 = .025$) suggesting that cognitive grouping is most helpful when it allows subjects to notice and use contours pre-formed by the mechanisms of perception.

4. General discussion

Results produced by way of two experiments provide evidence for a cognitively encapsulated filling-in process during contour interpolation. Relatable displays produced strong filling-in effects that could not be diminished or enhanced by believing or disbelieving that the fragments were connected, respectively. Non-relatable displays created minimal filling-in effects, and these could not be modulated via cognitive expectation. However, believing that relatable edges were of a single shape strongly improved overall performance and made upright shapes easier to distinguish. The foregoing set of results were obtained at a variety of difficulty levels, when distractor lines were randomized or blocked, and when the templates were given on every trial or after every 20th trial. Strategy adoption was independently confirmed by simply asking subjects at the end of each half of the experiment how they regarded and discriminated the stimuli. These data, considered jointly, suggest that the discrimination of filled-in Kanizsa shapes depends on belief, but that the filling-in of contours does not. Below, we provide a tentative explanation for some of these results, discuss implications, and conclude with suggestions for research in this underexplored area of vision research.

4.1. Shape discrimination: A preliminary explanation

A number of models of illusory contour perception posit rather sophisticated interactions between early and late brain areas that eventuate in illusory object recognition (Grossberg & Raizada, 2000; Murray et al., 2006; Seghier & Vuilleumier, 2006). These models either imply or are at least consistent with the view that integration involves at least two sets of processes: one that detects and integrates local edge information, and one that recognizes the shape as falling into a specific category (e.g., as fat or thin). Such a sequence may offer a starting point from which to explain the current findings. In our view, as soon as relatable inducers are perceived, they will form interpolated connections, which in turn will be influenced by information near the interpolated path. Corrupting the stimulus representation compromises the template matching process, which in turn lowers discrimination accuracy. In a similar vein, the absence of strategy effects in the non-relatable condition may owe to the inability to unify fragments that lack inherent cues to grouping. In this case, a grouping strategy gives participants cognitive templates that apply to the entire stimulus, but only parts of the non-relatable stimulus can be matched to the templates, rendering little advantage for discrimination accuracy.

Why did strategy improve performance when edges were relatable? Since distractor lines hurt performance regardless of strategy, an interpolated shape likely arose in each strategy condition. The grouping strategy likely helped by offering a better cognitive template. To put it most simply, it is easier to match a stimulus shape representation with one of two shape templates than with one of two fragmented templates.

The reason why inversion hurt performance only when fragments were grouped is unclear, but may also have to do with cognitive templates. For example, when the shape was inverted, there was considerable mismatch between the resulting shape representation and the (upright) template, making the task harder. By contrast, when the stimulus was not inverted, the entire visual shape could be compared to the entire template, and judgments were facilitated. As noted above, the reason observers preferred the upright shape may have to do with the fact that ordinary objects tend to be larger on the bottom or that objects more often recede in depth as they rise further from the ground.

4.2. Implications for filling-in contours

Our result shows that filling-in contours happens automatically and that interpolation cannot easily be overruled by the beliefs that the observer has about the stimulus. In other words, not only does interpolation occur without thinking, it also occurs even when it is contrary to beliefs about connectedness. It is premature, however, to conclude that cognitive expectations are *always* irrelevant to interpolation. At the very least, intentional states may alter attention, which in turn may alter the filling-in process.[6] Just as modulating attention can affect the perception of motion coherence (Liu, Fuller, & Carrasco, 2006), contrast (Pestilli & Carrasco, 2005), and lightness (Tse, 2005), attention may also be able to modulate filling-in in at least some cases (e.g., when high spatial frequencies are lacking, Freeman et al., 2001). However, our results make it unlikely that these modulations would be substantial, especially when contours are salient (Marcus & van Essen, 2002; McMains & Kastner, 2011). Consistent with certain neural models of grouping (Grossberg & Raizada, 2000), our results also make it unlikely that strategy can produce filling-in effects when the process would normally not occur.

On a related note, we do not claim to have found the conditions for producing the strongest beliefs about contour connectedness. Our goal was more modest—to show that when grouping instructions are salient, clear, and frequently repeated and when subjects have the beliefs that we think they have (in regards to contour connectedness), belief does not play a major role in filling-in contours. To put it another way, we used a variation of a commonly used perception task with viewing conditions that are very similar to those used in prior studies to show that cognitive expectation does not appreciably modulate the strength of illusory contour formation.

The outcomes of the current experiments add to the growing literature regarding the viability of the modularity research program. As Fodor (1983) rightly pointed out, it would be extremely helpful methodologically if the information processing systems of the mind turn out to be independent of central cognitive processing. It would mean that we could examine particular aspects of the mind, without regard to the goings-on of the beliefs and desires of the subject. If central characteristics of contour interpolation turn out to be intact irrespective of intentional states, then that would greatly simplify the quest to build an all-encompassing theory of visual object perception. Here, we have provided evidence that filling-in during interpolation, at least, does not strongly depend on belief.

4.3. Implications for illusory shape discrimination

Some data suggest that explicitly notifying subjects about the presence of illusory contours improves performance relative to control conditions (Nagai, Bennett, & Sekuler, 2008, p. 5), but the current paper presents the first clear evidence for the effect. An objection might be that subjects performed worse in the ungroup condition only because the instructions were harder to understand. This is unlikely because—in the non-relatable trials—the ungroup subjects did no worse than the grouping subjects. Therefore, *there was nothing intrinsically harder about the ungroup directions*. More generally, the benefit of applying a unitary (rather than fragmented) shape template makes sense in light of the well-established "single-object advantage", according to which extracting distal information is easier when it derives from only one referent (Baylis & Driver, 1993; Duncan, 1984).

Our results further imply that filling-in illusory contours and discriminating illusory shapes depend on different mechanisms. The latter is partly conceptually mediated and depends on instructions; the former is much earlier and may be cognitively encapsulated. Indirect evidence for this dissociation has been adduced elsewhere. In a visual agnosia study, patient HJA normally integrated local elements to form contours, but poorly discriminated partly occluded shapes (Giersch, Humphreys, Boucart, & Kovács, 2000). In an electrophysiological study (Murray et al., 2006), when subjects discriminated relatable shapes from one another or non-relatable shapes from one another, the difference in VEP in these two cases (what was termed the "IC effect") occurred fast (124–186 ms) and regardless of whether subjects accurately discriminated the shape. It was also found that accuracy in a relatable condition correlated with neurophysiologic responses at 330–406 ms post-stimulus onset, which was well after the IC effect (see also Imber, Shapley, & Rubin, 2005). Boundary completion was concluded to be early, automatic and dissociable from a later shape categorization stage—a view that fits nicely with our findings.

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[6] The encapsulation view, as espoused by Pylyshyn (1999), acknowledges the relevance and import of attention for altering (the inputs of) perception. However, Pylyshyn's view prohibits expectation and utilities from altering perception independently of attention.

Results obtained thus far also address a recent challenge to the fat/thin shape discrimination paradigm. Anderson (2007) writes:

> [T]he fat/thin paradigm is highly sensitive to task strategies. Indeed, it shows that such strategies can completely obscure differences in perceived completion strength… [Therefore] performance on the fat–thin task is not modulated by the strength or occurrence of completion, at least not in any simple manner that allows it to be used as a diagnostic tool for measuring contour completion" (p. 522).

Our finding that strategy alters performance in the relatable conditions is in accord with Anderson's claim. The interaction between inversion and strategy further exhibits the relevance of grouping at least for modestly grouping stimuli. But Anderson's assertion that the presence of completion fails to explain discrimination accuracy is not supported by the current data. The occurrence of completion, but not strategy, determined whether distractor lines degraded performance. Furthermore, the influence of strategy on overall performance does not appear to invalidate previous results established with the paradigm (Kellman et al., 2005; Ringach & Shapley, 1996; Yin et al., 1997). When relatable fragments are grouped, they offer benefits that cannot be rivaled by non-relatable displays. There appears to be no better explanation of the benefit than the fact that interpolation unifies—and renders more accessible—the edge relations of spatially segregated fragments (Baylis & Driver, 1993; Duncan, 1984).[7]

This is not to say that the discovery of high-level effects is irrelevant to prior work; some fat/thin studies may need to be re-interpreted if strategy could vary between conditions, time-points or subject groups. For example, the fat/thin task has been used to study autism (Milne & Scope, 2008) and visual development (Hadad, Maurer, & Lewis, 2010). In these cases, group differences or similarities may not necessarily be reflective of differences or similarities in early perception. Adding a distractor line condition might be one way to tease out the contributions of lower and higher-level mechanisms to illusory shape perception.

4.4. Forming vs. noticing illusory contours

Another implication of our finding is that subjects can fail to consciously discover illusory contours formed in early perception. We found similar results in a multiple object tracking study wherein 94% of subjects exhibited behavior consistent with contour interpolation but only 62% reported seeing any such contours immediately after the experiment (Keane et al., 2011, Experiment 1). This was despite the fact that the contours appeared on 50% of the trials of each experimental block. A similar lack of insight can be found in the annals of history. As Purghé and Coren (1992) pointed out, 19th century scientists like Helmoholtz, Wundt, Ebbinghaus, Sanford, and Titchner all published figures with illusory contours, but never remarked upon their phenomenal existence. Not until the next century were interpolated figures formally "discovered" and investigated (Kanizsa, 1955; Schumann, 1904). It can be concluded that the acts of noticing and forming illusory contours are dissociable, and that phenomenology is an imperfect measure of the presence of interpolation.

4.5. Future directions

Evidence has converged on the view that long-range, horizontal (lateral) connections between simple cells of similar orientation tuning, in early visual cortex facilitate the integration of elements into global configurations (Lee & Nguyen, 2001; Seghier & Vuilleumier, 2006). Certain ventral and parietal structures (e.g., lateral occipital complex, caudal intraparietal sulcus) may also be important to the filling-in of contours (Kellman et al., 2005; Mendola, Dale, Fischl, Liu, & Tootell, 1999; Murray, Foxe, Javitt, & Foxe, 2004; Shpaner, Murray, & Foxe, 2009). But what parts of the brain mediate changes in cognitive strategy? Relevant regions likely include the orbital prefrontal cortex (OFC) and inferotemporal cortex. The former generates expectations or guesses about the viewed stimulus and aids qualitative visual discrimination (Bar, 2003; Bar et al., 2006); the latter (which receives feedback from the OFC) is activated primarily at moments when the stimulus is confronted, and encodes fine-grained and, at times, diagnostic feature information (Freedman, Riesenhuber, Poggio, & Miller, 2003; Sigala & Logothetis, 2002). It is worthwhile to use brain imaging techniques to see, first, what changes when subjects change their strategy on these sorts of tasks, and second, whether any earlier cortical mechanisms are responsive to changes in cognitive expectation.

Another question is how strategy effects vary with contour *salience*. We intentionally used a modest support ratio (25%) to increase the likelihood of finding high-level effects. If the support ratio were higher (Shipley & Kellman, 1992), if the contours were presented in stereoscopic depth or in motion (Lesher, 1995, p. 283; Ostrovsky, Meyers, Ganesh, Mathur, & Sinha, 2009; Palmer, Kellman, & Shipley, 2006), or if the inducing edge information were more distributed over space (Maertens & Shapley, 2008), then the "ungroup" subjects may automatically discover and use the optimal grouping strategy.

Also unexplored is whether cognition can modulate the *spatial path* of interpolation. As noted above, we focused on whether expectation can extinguish or invent filled-in contours. Fig. 1 provides informal evidence that the depth layering or the 2-D path can be altered, but it is unclear as to what level in processing this modulation occurs.

Lastly, our version of the fat/thin task can also be recruited to fruitfully explore clinical deficits in perceptual organization. For example, individuals who have disorders such as schizophrenia are hypothesized to be worse at extracting global structure from a visual stimulus (Silverstein & Keane, 2011; Uhlhaas & Silverstein, 2005). In accord with this view, we are finding that persons with schizophrenia perform very much like "ungroup" subjects

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[7] Edge unification, by itself, is probably not sufficient for an interpolation advantage (Hou, Lu, Zhou, & Liu, 2005; the way that inducing edges are unified also matters. In our relatable displays, since inducers produced bowed contours, illusory edge locations for the fat and thin shapes differed more than the visible edge locations. Interpolated percepts thus ended up being more discernable than non-interpolated percepts for the fat/thin task.

(Keane, Mikkilineni, Papathomas, & Silverstein, 2012): they discriminate normally on non-relatable trials poorly on relatable trials, and normally in response to distractor lines for both trial types. Ringach and Shapley's methodology, therefore, is providing a promising means for distinguishing lower- and higher-level contributions to object perception in normal and pathological vision.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.cognition.2012.02.004.

References

Anderson, B. L. (2007). Filling-in theories of completion: Rejoinder to Kellman, Garrigan, Shipley, and Keane (2007) and Albert (2007). *Psychological Review, 114*(2), 509–527.

Bar, M. (2003). A cortical mechanism for triggering top-down facilitation in visual object recognition. *Journal of Cognitive Neuroscience, 15*(4), 600–609.

Bar, M., Kassam, K. S., Ghuman, A. S., Boshyan, J., Schmidt, A. M., Dale, A. M., et al. (2006). Top-down facilitation of visual object recognition. *Proceedings of the National Academy of Sciences, 103*, 449–454.

Baylis, G., & Driver, J. (1993). Visual location and objects: Evidence for hierarchical coding of location. *Journal of Experimental Psychology: Human Perception and Performance*, 451–470.

Brainard, D. H. (1997). The psychophysics toolbox. *Spatial Vision, 10*, 433–436.

Bravo, M. J., & Farid, H. (2003). Object segmentation by top-down processes. *Visual Cognition, 10*, 471–491.

Dallenbach, K. M. (1951). A puzzle-picture with a new principle of concealment. *American Journal of Psychology, 64*, 431–433.

Davis, G. & Driver, J. (2003). Effects of modal and amodal completion upon visual attention: A function for filling-in? In L. Pessoa & P. De Weerd (Eds.), *Filling-in: From perceptual completion to cortical reorganization* (pp. 128–150). New York, NY: Oxford.

Dillenburger, B., & Roe, A. W. (2010). Influence of parallel and orthogonal real lines on illusory contour perception. *Journal of Neurophysiology, 103*, 55–64.

Duncan, J. (1984). Selective attention and the organization of visual information. *Journal of Experimental Psychology: General, 113*, 501–517.

Fodor, J. A. (1983). *Modularity of mind*. Mass.: MIT Cambridge.

Freedman, D. J., Riesenhuber, M., Poggio, T., & Miller, E. K. (2003). A comparison of primate prefrontal and inferior temporal cortices during visual categorization. *Journal of Neuroscience., 23*(12), 5235–5246.

Freeman, E., Sagi, D., & Driver, J. (2001). Lateral interactions between targets and flankers in low-level vision depend on attention to the flankers. *Nature Neuroscience, 4*(10), 1032–1036.

Fulvio, J. M., Singh, M. & Maloney, L. T. (2006). Consistency of location and gradient judgments of visually-interpolated contours. *Computer Vision and Pattern Recognition, Proceedings, 186*.

Fulvio, J. M., Singh, M., & Maloney, L. T. (2008). Precision and consistency of contour interpolation. *Vision Research, 48*, 831–849.

Gauthier, I., James, T. W., Curby, K. M., & Tarr, M. J. (2003). The influence of conceptual knowledge on visual discrimination. *Cognitive Neuropsychology, 20*, 507–523.

Gellatly, A. R. H. (1982). Perceptual learning of illusory contours and color. *Perception, 11*, 655–661.

Giersch, A., Humphreys, G. W., Boucart, M., & Kovács, I. (2000). The computation of occluded contours in visual agnosia: Evidence for early computation prior to shape binding and figure-ground coding. *Cognitive Neuropsychology, 17*(8), 731–759.

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

Gold, J. M., & Shubel, E. (2006). The spatiotemporal properties of visual completion measured by response classification. *Journal of Vision, 6:5*(4), 356–365. doi:10.1167/6.4.5. http://journalofvision.org/6/4/5/.

Goldstone, R. (1994). Influences of categorization on perceptual discrimination. *Journal of Experimental Psychology: General, 123*, 178–200.

Gosselin, F., & Schyns, P. G. (2003). Superstitious perceptions reveal properties of internal representations. *Psychological Science, 14*, 505–509.

Grossberg, S., & Mingolla, E. (1985). Neural dynamics of form perception: Boundary completion, illusory figures, and neon color spreading. *Psychological Review, 92*(2), 173–211.

Grossberg, S., & Raizada, R. (2000). Contrast-sensitive perceptual grouping and object-based attention in the laminar circuits of primary visual cortex. *Vision Research, 40*, 1413–1432.

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

Hadad, B., Maurer, D., & Lewis, T. L. (2010). The development of contour interpolation: Evidence from subjective contours. *Journal of Experimental Child Psychology, 106*, 163–176.

He, Z. J., & Nakayama, K. J. (1992). Surfaces versus features in visual search. *Nature, 359*(6392), 231–233.

Hodsdoll, J., Mevorach, C., & Humphreys, G. W. (2009). Driven to less distraction: rTMS of the right parietal cortex reduces attentional capture in visual search. *Cerebral Cortex, 19*, 106–114.

Hoffman, D. D. (2000). *Visual intelligence. How we create what we see*. New York: Norton.

Hou, F., Lu, H., Zhou, Y., & Liu, Z. (2005). Amodal completion impairs stereoacuity discrimination. *Vision Research, 46*, 2061–2068.

Imber, M. L., Shapley, R. M., & Rubin, N. (2005). Differences in real and illusory shape perception revealed by backward masking. *Vision Research, 45*, 91–102.

Kahneman, D., & Frederick, S. (2005). A model of heuristic judgment. In K. J. Holyoak & R. G. Morrison (Eds.), *The Cambridge handbook of thinking and reasoning* (pp. 267–294). New York: Cambridge University Press.

Kalar, D. J., Garrigan, P., Wickens, T. D., Hilger, J. D., & Kellman, P. J. (2010). A unified model of illusory and occluded contour interpolation. *Vision Research, 50*, 284–299.

Kanizsa, G. (1955). *Margini quasi-percettivi in campi con stimulazoine omogenea*. Rivista di Psicologia.

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

Keane, B. P., Lu, H., Papathomas, T. V., Silverstein, S. M., & Kellman, P. J. (submitted for publication). Reinterpreting behavioral receptive fields: lightness induction alters visually completed shape.

Keane, B. P., Lu, H., & Kellman, P. J. (2007). Classification images reveal spatiotemporal contour interpolation. *Vision Research, 47*, 3460–3475.

Keane, B. P., Mettler, E., Tsoi, V., & Kellman, P. J. (2011). Attentional signatures of perception: Multiple object tracking reveals the automaticity of contour interpolation. *Journal of Experimental Psychology: Human Perception and Performance, 37*(3), 685–698.

Keane, B. P., Mikkilineni, D., Papathomas, T. V., & Silverstein, S. M. (2012). Impaired shape integration but normal illusory contour formation in schizophrenia: Evidence for a high level grouping deficit. Poster at Vision Sciences Society Conference, May, Naples, FL.

Kellman, P. J., Garrigan, P., & Shipley, T. F. (2005). Object interpolation in three dimensions. *Psychological Review, 112*(3), 586–609.

Kellman, P. J., Garrigan, P. J., Shipley, T., & Keane, B. P. (2007). Interpolation processes in object perception: Reply to Anderson (2007). *Psychological Review, 114*(2), 488–502.

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

Kellman, P. J., & Spelke, E. J. (1983). Perception of partly occluded objects in infancy. *Cognitive Psychology, 15*(4), 483–524.

Kristjánsson, Á., & Driver, J. (2008). Priming in visual search: Separating the effects of target repetition, distractor repetition and role-reversal. *Vision Research, 48*, 1217–1232.

Lee, S., & Nguyen, M. (2001). Dynamics of subjective contour formation in the early visual cortex. *Proceedings of the National Academy of Sciences, 98*, 1907–1911.

Lee, H., & Vecera, S. P. (2005). Visual cognition influences early vision: The role of visual short-term memory in amodal completion. *Psychological Science, 16*(10), 763–768.

Lesher, G. W. (1995). Illusory contours: Toward a neurally based perceptual theory. *Psychonomic Bulletin & Review, 2*(3), 279–321.

Li, W., Piëch & Gilbert, C. D. (2008). Learning to link visual contours. *Neuron, 57*(3), 442–451.

Liu, T., Fuller, S., & Carrasco, M. (2006). Attention alters the appearance of motion coherence. *Psychonomic Bulletin & Review, 13*, 1091–1096.

Lorenceau, J., & Alais, D. (2001). Form constraints on motion binding. *Nature Neuroscience, 4*(7), 745–751.

Macmillan, N. A., & Creelman, C. D. (1991). *Detection theory: A user's guide*. Cambridge: Cambridge University Press.

Maertens, M., Pollman, S., Hanke, M., Mildner, T., & Moller, H. (2008). Retinotopic activation in response to subjective contours in primary visual cortex. *Frontiers in Human Neuroscience, 2*, 1–7.

Maertens, M., & Shapley, R. (2008). Local determinants of contour interpolation. *Journal of Vision, 8*(7), 1–11.

Marcus, D. S., & van Essen, D. C. (2002). Scene segmentation and attention in primate cortical areas V1 and V2. *Journal of Neurophysiology, 88*(5), 2648–2658.

McMains, S., & Kastner, S. (2011). Interactions of top-down and bottom-up mechanisms in human visual cortex. *Journal of Neuroscience, 31*, 587–597.

Mendola, J. D., Dale, A. F., Fischl, B., Liu, A. K., & Tootell, R. B. H. (1999). The representation of illusory and real contours in human cortical visual areas revealed by functional magnetic resonance imaging. *Journal of Neuroscience, 19*(19), 8560–8572.

Milne, E., & Scope, A. (2008). Are children with autistic spectrum disorders susceptible to contour illusions? *British Journal of Developmental Psychology, 26*, 91–102.

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

Murray, M. M., Imber, M. L., Javitt, D. C., & Foxe, J. J. (2006). Boundary completion is automatic and dissociable from shape discrimination. *Journal of Neuroscience, 26*(46), 12043–12054.

Nagai, M., Bennett, P. J., & Sekuler, A. B. (2008). Exploration of vertical bias in perceptual completion of illusory contours: Threshold measures and response classification. *Journal of Vision, 8*(7), 1–17.

Nieder, A. (2002). Seeing more than meets the eye: Processing of illusory contours in animals. *Journal of Comparative Physiology A, 188*, 249–260.

Ostrovsky, Y., Meyers, E., Ganesh, S., Mathur, U., & Sinha, P. (2009). Visual parsing after recovery from blindness. *Psychological Science, 20*, 1484–1491.

Palmer, E. M., Kellman, P. J., & Shipley, T. F. (2006). A theory of dynamic occluded and illusory object perception. *Journal of Experimental Psychology: General, 135*(4), 513–541.

Papathomas, T. V. (1999). Is perception of 3-D surface configurations cognitively penetrable? *Behavioral and Brain Sciences, 22*, 388–389.

Pelli, D. G. (1997). The VideoToolbox software for visual psychophysics: Transforming numbers into movies. *Spatial Vision, 10*, 437–442.

Pestilli, F., & Carrasco, M. (2005). Attention enhances contrast sensitivity at cued and impairs it at uncued locations. *Vision Research, 45*, 1867–1875.

Peterhans, E., von der Heydt, R., & Baumgartner (1984). Illusory contours and cortical neuron responses. *Science, 224*, 1260–1262.

Pillow, J., & Rubin, N. (2002). Perceptual completion across the vertical meridian and the role of early visual cortex. *Neuron, 33*, 805–813.

Polat, U., & Sagi, D. (1993). Lateral interactions between spatial channels: Suppression and facilitation revealed by lateral masking experiments. *Vision Research, 33*, 993–999.

Polat, U., & Sagi, D. (2007). The relationship between the subjective and objective aspects of visual filling-in. *Vision Research, 47*, 2473–2481.

Pratt, J., & Sekuler, A. B. (2001). The effects of occlusion and past experience on the allocation of object-based attention. *Psychonomic Bulletin & Review, 8*, 721–727.

Purghé, F., & Coren, S. (1992). Subjective contours 1900–1990: Research trends and bibliography. *Perception & Psychophysics, 51*, 291–304.

Pylyshyn, Z. P. (1999). Is vision continuous with cognition? The case for cognitive impenetrability of visual perception. *Behavioral and Brain Sciences, 22*, 341–423.

Ramachandran, V. S., Ruskin, D., Cobb, S., Rogers-Ramachandran, D., & Tyler, C. W. (1994). On the perception of illusory contours. *Vision Research, 23*, 3145–3152.

Reichel, F. D., & Todd, J. T. (1990). Perceived depth inversion of smoothly curved surfaces due to image orientation. *Journal of Experimental Psychology: Human Perception and Performance, 16*(3), 653–664.

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

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

Schumann, F. (1904). Einige Beobachtungen über die Zusammenfassung von Gesichtseindrücken zu Einheiten. *Psychologische Studien, 1*, 1–32.

Seghier, M., & Vuilleumier, P. (2006). Functional neuroimaging findings on the human perception of illusory contours. *Neuroscience Biobehavioral Reviews, 30*, 595–612.

Sekuler, A. B., & Murray, R. F. (2001). Visual completion: A case study in grouping. In T. F. Shipley & P. J. Kellman (Eds.), *From fragments to objects: Segmentation and grouping in vision* (pp. 265–294). New York: Elsevier Press.

Shipley, T. F., & Kellman, P. (1992). Strength of visual interpolation depends on the ratio of physically specified to total edge length. *Perception & Psychophysics, 52*(1), 97–106.

Shpaner, M., Murray, M. M., & Foxe, J. J. (2009). Early processing in the human lateral occipital complex is highly responsive to illusory contours but not to salient regions. *European Journal of Neuroscience, 30*, 2018–2028.

Sigala, N., & Logothetis, N. K. (2002). Visual categorization shapes feature selectivity in the primate temporal cortex. *Nature, 415*(6869), 318–320.

Silverstein, S. M., & Keane, B. P. (2011). Perceptual organization impairment in schizophrenia and associated brain mechanisms: Review of Research from 2005–2010. *Schizophrenia Bulletin, 37*(4), 690–699.

Spehar, B. (2000). Degraded illusory contour formation with non-uniform inducers in Kanizsa configurations: The role of contrast polarity. *Vision Research, 40*, 2653–2659.

Sperling, G. (1960). The information available in brief visual presentations. *Psychological Monographs: General and Applied, 74*(11), 1–30.

Stanley, D. A., & Rubin, N. (2003). FMRI activation in response to illusory contours and salient regions in the human lateral occipital complex. *Neuron, 37*, 323–331.

Sugita, Y. (1999). Grouping of image fragments in primary visual cortex. *Nature, 401*(6750), 269–272.

Theeuwes, J., & Burger, R. (1998). Attentional control during visual search: The effect of irrelevant singletons. *Journal of Experimental Psychology: Human Perception and Performance, 24*, 1342–1353.

Tse, P. U. (2005). Voluntary attention modulates the brightness of overlapping transparent surfaces. *Vision Research, 45*(9), 1095–1098.

Uhlhaas, P. J., & Silverstein, S. M. (2005). Perceptual organization in schizophrenia spectrum disorders: Empirical research and theoretical implications. *Psychological Bulletin, 131*(4), 618–632.

Valenza, E., Leo, I., Gava, L., & Simion, F. (2006). Perceptual completion in newborn human infants. *Child Development, 77*(6), 1810–1821.

Vuilleumier, P., Valenza, N., & Landis, T. (2001). Explicit and implicit perception of illusory contours in unilateral spatial neglect: Behavioural and anatomical correlates of preattentive grouping mechanisms. *Neuropsychologia, 39*(6), 597–610.

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

Zemel, R. S., Behrmann, M., Mozer, M. C., & Bavelier, D. (2002). Experience-dependent perceptual grouping and object-based attention. *Journal of Experimental Psychology: Human Perception and Performance, 28*, 202–217.

Zhou, J., Tjan, B. S., Zhou, Y., & Liu, Z. (2008). Better discrimination for illusory than for occluded perceptual completions. *Journal of Vision, 8*(7:2), 1–17. doi:10.1167/8.7.26. http://journalofvision.org/8/7/26/.