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Attention, segregation, and textons: Bridging the gap between object-based attention and texton-based segregation

Ohad Ben-Shahar [a,*], Brian J. Scholl [b], Steven W. Zucker [c]

[a] *Department of Computer Science and the Zlotowski Center for Neuroscience, Ben-Gurion University, Beer-Sheva, Israel*
[b] *Department of Psychology, Yale University, New Haven, CT, USA*
[c] *Department of Computer Science, Yale University, New Haven, CT, USA*

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Abstract

Studies of object-based attention (OBA) have suggested that attentional selection is intimately associated with discrete objects. However, the relationship of this association to the basic visual features ('textons') which guide the segregation of visual scenes into 'objects' remains largely unexplored. Here we study this hypothesized relationship for one of the most conspicuous features of early vision: *orientation*. To do so we examine how attention spreads through uniform (one 'object') orientation-defined textures (ODTs), and across texture-defined boundaries in discontinuous (two 'objects') ODTs. Using the divided-attention paradigm we find that visual events that are known to trigger orientation-based texture segregation, namely perceptual boundaries defined by high orientation and/or curvature gradients, also induce a significant cost on attentional selection. At the same time we show that no effect is incurred by the absolute value of the textons, i.e., by the general direction (or, the 'grain') of the texture—in conflict with previous findings in the OBA literature. Collectively these experiments begin to reveal the link between object-based attention and texton-based segregation, a link which also offers important cross-disciplinary methodological advantages.

Keywords: Object-based attention; Texture segregation; Textons; Divided attention; Orientation gradients; Curvature

1. Introduction

The input to visual perception consists, at the earliest levels, of an undivided wash of visual features. Our perceptual experience, however, consists of structured scenes of discrete objects. A critical task for vision science is thus to determine when and how this segmentation of the visual field into objects occurs. Here we are particularly concerned with this question as it relates to the operation of visual attention. Because of the sheer amount of available visual information, we are forced to *select*, via the operation of attention, only a small part of the visual information available at any moment. The vast literature on 'object-based attention' (OBA) have suggested that this selection process is closely related to discrete 'objects' by demonstrating that attentional processes operate more efficiently *within* rather than *between* them (see Scholl, 2001, for a review).

But what counts as an 'object' for the purposes of attention? With the exceptions which we discuss below, studies of OBA have typically explored broad categories of *intuitively defined objects*, such as simple outlined geometric shapes. In contrast, other literatures in visual perception have focused on the processing of the basic features ('*textons*') which guide the initial segmentation of visual scenes. A primary goal of this paper is to promote a link between these two historically distinct research programs—object-based attention and texton-based segregation—for one of the most conspicuous features of early vision: *orientation*. Using experimental paradigms from the OBA literature,

* Corresponding author. Fax: +972 8 647 7975.
E-mail address: ben-shahar@cs.bgu.ac.il (O. Ben-Shahar).

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our general strategy is to explore how attention spreads[1] through static orientation-defined textures (ODTs; also referred to as static texture flows) and across various types of texture-defined boundaries. The visual scenes employed here are thus carefully structured, but *do not* involve the full-fledged (albeit intuitively defined) 'objects' characteristic of previous studies of OBA. By exploring attentional mechanisms with such stimuli we may further understand how the 'objects' of object-based attention are formed from simpler visual features. At the same time, such studies can also improve our understanding of orientation-based texture segregation (OBTS), for example by demonstrating attentional effects which are mediated by factors other than orientation gradients.

In the remainder of this section, we discuss in more detail the two research projects at the heart of our studies: object-based attention and orientation-based texture segmentation. We then report several experiments which link these areas, and demonstrate how the spread of attention is mediated by the orientation texton (i.e., by that conspicuous visual feature expressed by the local orientation of the stimulus).

1.1. Object-based attention

Intuitively, attention seems to be an extra processing capacity which can both intentionally and automatically select—and be effortfully sustained on—particular stimuli or activities. To what information can attention be directed? This question has provoked a vast amount of research in the past few decades. Traditional models characterized attention in spatial terms (see Cave & Bichot, 1999): attention was thought to be akin to a spotlight (or a variable 'zoom-lens') which could focus processing resources on whatever fell within its *spatial* extent (which could be an object, multiple objects, parts of multiple objects, or even nothing at all). Recent models of attention, in contrast, suggest that attention is not directed exclusively to spatial position but rather significantly affected by pre-attentively segmented discrete objects (see Scholl, 2001, for a review). Many types of evidence for this view have accrued, one of which will be especially important here: same-object advantages from *divided-attention* tasks.

Divided attention is an OBA paradigm which suggests that attention can more readily span multiple aspects of the *same* object, compared to multiple aspects of *different* objects. In one of the earliest studies to explicitly promote the idea of OBA, for example, subjects viewed brief masked displays, each containing a box with a single line drawn through it (Duncan, 1984). Both the box and the line varied on two dimensions: the box could be tall or short, and had a small gap on either its left or its right side; the line could be either dotted or dashed, and was oriented slightly off vertical, to either the left or the right. On each trial, subjects simply judged two of these properties, and were more accurate when the properties were drawn from the same object (e.g. the size of the box and the side of its gap) than when they were drawn from different objects (e.g. the size of the box and the orientation of the line). Because of the spatial overlap in these simple objects, this effect cannot be readily accounted for in terms of spatial selection (cf. Watt, 1988). This same-object advantage in dividing attention has been replicated many times, in particular for different types of 'objects' (e.g. Duncan & Nimmo-Smith, 1996; Kramer, Weber, & Watson, 1997; Lavie & Driver, 1996; Valdes-Sosa, Cobo, & Pinilla, 1998; Vecera & Farah, 1994), for 'objects' completed behind static occluders (Behrmann, Zemel, & Mozer, 1998; Moore, Yantis, & Vaughan, 1998), and for the individual parts of more complex objects (Barenholtz & Feldman, 2003; Singh & Scholl, 2000; Vecera, Behrmann, & McGoldrick, 2000, 2001). We note that 'same-object advantages' were also revealed with other experimental paradigms and dependent measures, most notably by measuring response time in spatial-cueing tasks (e.g., Atchley & Kramer, 2001; Egly, Driver, & Rafal, 1994; He & Nakayama, 1995; Lamy & Tsal, 2000; MacQuistan, 1997; Vecera, 1994). Here, however, we focus on divided attention as our experimental paradigm of choice.[2]

While divided attention, as well as spatial-cueing, provide strong evidence for an effect of scene structure on the operation of attention, the 'objects' employed in these and other paradigms are typically defined only intuitively, if at all. This raises a chicken-and-egg problem of sorts: if we do not begin such experiments with a pre-existing rigorous definition of objecthood, can we really claim that a resulting phenomenon (attentional or otherwise) is 'object-based'? Do 'same-object' attentional advantages provide support for a preexisting notion of object-based processing, or do such effects themselves provide the definition of what counts as an object? In other words, are visual 'objects' the independent *cause* of these attentional effects, or merely the *name* we give to their outcome?

While the concern over the intuitiveness of 'objects' has been lurking in the background of OBA research ever since its inception (e.g., Duncan, 1984), it was made explicit and stated clearly only recently (Driver, Baylis, Russell, Turatto, & Freeman, 2001; Lamy & Egeth, 2002; Watson & Kramer, 1999). In recognition of its critical implications, researchers have attempted to resolve this problem by

[1] The particular mechanism by which attentional selection operates is still a matter of controversy in the attention literature (e.g., see McCarley, Kramer, & Peterson, 2002). We chose to use the notion of attentional *spread* throughout our paper primarily for reasons of convenience and simpler presentation. We do remain, however, completely agnostic about the particular mechanism underlying attentional selection and this debate does not affect any of our conclusions.

[2] All experiments reported in this paper are currently being repeated with the spatial-cueing paradigm and preliminary results already support the conclusions reported here. A comparative analysis of this converging evidence, with some additional methodological heuristic for choosing between what are perhaps the two most popular OBA paradigms, will be discussed in length in a forthcoming paper.

endowing OBA research with the canons of perceptual organization—those perceptual principles that group visual elements into wholes (Wertheimer, 1955) that later serve as precursory units (namely, 'objects') which guide the interpretation of scenes (Witkin & Tenenbaum, 1983). For example, Watson and Kramer (1999) examined the role of uniform-connectedness (Palmer & Rock, 1994) and boundary curvature (Hoffman & Richards, 1984) to analyze OBA within the part-whole hierarchy. Specific details and findings aside, the advantage of putting OBA in such a framework rests in the ability to consequently infer *predictive rules* for when same-object advantage will be obtained, as indeed Watson and Kramer (1999) did explicitly.

The link between OBA and the laws of perceptual organization, which was studied by others as well (e.g., Driver et al., 2001; Lamy & Egeth, 2002; Moore et al., 1998), clearly takes OBA a step forward toward resolving the inherent ambiguity in the notion of 'attentional objecthood'. However, it is still lacking in the sense that it is still intuition and informality that guides our understanding of most perceptual organization principles, the intelligibility of their interaction, and the comprehension of the atomic (i.e., undividable) nature of the 'objecthood' of those elements to which these principles are typically applied. The uncertainties that this intuition generates clearly take a central role in the current scholarly debate (e.g., see Lamy & Egeth, 2002).

To better escape the problems that emerge from using intuitive 'objects', a more rigorous and still lower-level notion of 'objecthood' is required. In the current study, we attempt to achieve this by exploring OBA with simple texture stimuli wherein structure is determined by the *distribution of basic visual elements* ("textons"). As we argue below, such stimuli are in many ways more rigorous than the intuitive 'objects', or even groups of objects, of previous studies, and their 'objecthood' stems from the much better understood perceptual organization processes of low-level *texture segregation*. In his seminal paper, Duncan (1984) wrote: "Certainly, the [object-based] theory depends on the importance of perceptual grouping processes, because it is these that preattentively define what is treated as one object… If the object-based theory is correct, then the study of visual attention and of perceptual organization *must proceed together*" (Duncan, 1984, pp. 502, Emphasis added). Following those researchers that have explicitly pursued this agenda, our goal is to take OBA research one step further along this path.

1.2. Objects and orientation-based texture segregation

The interpretation of visual stimuli in terms of objects is intimately related to the process of visual *segregation*, whose outcome is the formation of boundaries between perceptually coherent regions, and thus the emergence of objects in the visual field based on some low level representation (e.g. Driver et al., 2001). It follows that objects, and thus OBA, can also be discussed from the point of view of segmentation processes. Not only that such a perspective can replace the intuitive notion of 'object' with the simpler and perhaps better understood one, but it is also backed by the numerous studies, extensive work, and rigorous models developed in the segmentation literature. Consequently, by viewing objects in terms of segmentation we can link this latter body of research directly to the study of OBA and endow OBA with a more solid concept of 'objecthood'.

One reasonably well-understood domain for such a project is that of *texture segregation*, in which the ability to effortlessly segregate texture stimuli into discrete, perceptually coherent regions has long been attributed to changes in the spatial distribution of elementary features, sometimes called *textons* (Julesz, 1981, 1986). One of the most conspicuous textons which has also been studied extensively is *orientation*. Although textures are rarely characterized solely by orientation, orientation-defined textures (ODTs) are very frequent in natural and artificial visual stimuli (see Fig. 1) and understanding the effect of orientation on texture segregation has been considered essential due to its direct neurophysiological basis (e.g. Hubel & Wiesel, 1977), its central role in perceptual organization (e.g. Kanizsa, 1979), and its close relationship to shape perception (e.g. Todd & Reichel, 1990).

The question of when (and how) an ODT is segregated into multiple coherent regions ('objects') has been studied extensively for more than two decades and from at least two main perspectives. Filter-based approaches (e.g. Bergen & Landy, 1991; Malik & Perona, 1990; Sagi, 1995) use the orientation content of textures via oriented filters to compute scalar energies from which segmentation is derived through non-linear transformation (typically, rectification) and detection of areas of high gradient. Feature-based models (e.g. Mussap & Levi, 1999; Nothdurft, 1991, 1993) suggest more generally that OBTS depends on the relationship between two orientation gradients (Fig. 2)—namely the change in orientation *between* coherent regions ($\Delta\theta_{\text{between}}$) and the change in orientation *within* regions ($\Delta\theta_{\text{within}}$). Varying these two parameters and measuring segregation accuracy reveals that reliable segregation occurs if and only if the ratio of these two gradients (between/within) is significantly larger than 1. These results were further extended to consider the relative texture/boundary configuration (Nothdurft, 1992; Olson & Attneave, 1970; Wolfson & Landy, 1995), and most recently were generalized to consider curvature as well (Ben-Shahar, 2006; Ben-Shahar & Zucker, 2004). All these results will play an important role in our exploration of OBA, as we discuss later on.

1.3. Bridging the gap: Object-based attention and orientation-based texture segregation

The ideas drawn from the OBTS literature provide a more rigorous basis for exploring the nature of 'objecthood' and suggest a wealth of stimuli whose partition into objects goes beyond intuitive appeal. Conversely, proven methodologies from the OBA literature provide new

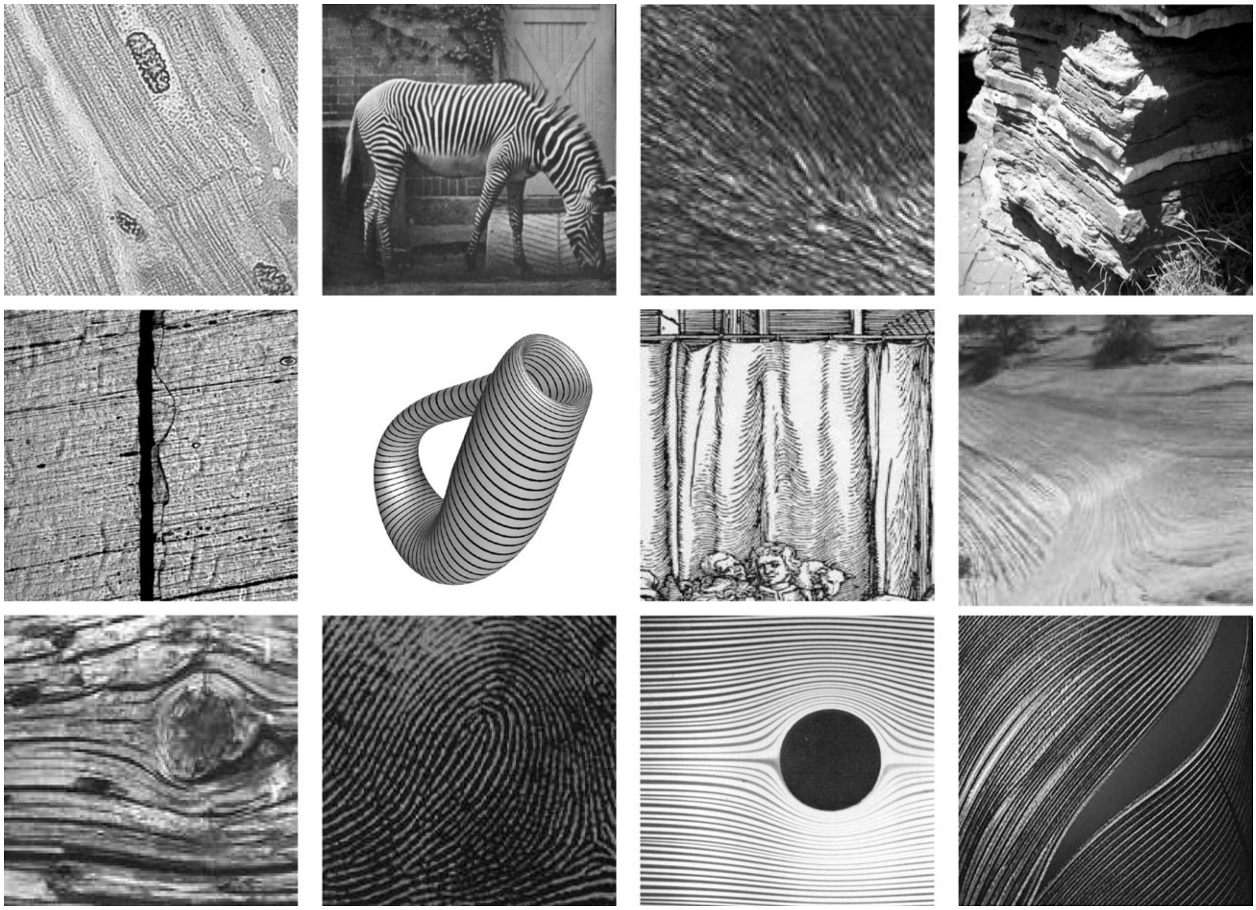

Fig. 1. Examples of natural and synthetic ODTs. In nature, these patterns are a result of diverse processes such as the morphogenesis of biological tissue, pigmentation on animals' skin, growth of hair, and even geological processes. In artifacts they are especially common in technical drawings and the visual arts.

opportunities to examine and further support ideas in the texture segregation literature. It is our goal in this paper to bring these two communities closer to a unified framework. To do so, we study how attention spreads through simple ODTs, and across their boundaries as defined by either orientation or curvature discontinuities.

Consider, for example, the ODTs in Fig. 3b. Each of these stimuli clearly is segregated into two separate, perceptually coherent regions. Now, however, this notion of segmented regions is not based solely on intuition. Rather, theories of OBTS suggest that the distribution of orientation texels in such a display should give rise to a perceptual boundary, and provide a computational recipe that links locally measurable properties to *predictions* about the emergence of (in this case—two) coherent 'objects'. Such displays are typical of the stimuli we explore here with the divided-attention paradigm which we briefly discussed above. They are highly related to grouping via good continuation, albeit in two dimensions, and unlike intuitive 'objects', these more primitive 'objects' are backed by rigorous and formal mathematical theories and to low-level representations of visual regions.

Below we report several experiments which explore how attentional selection is influenced by the structure of ODTs. The first experiment (and its adjunct) examines this issue along two independent stimulus dimensions (uniform vs. discontinuous and jittered vs. regular ODTs) in order to test for effects of the texture's dominant local direction, the role of orientation discontinuities, and the contribution of local vs. global structural cues. The last two experiments focus on the relationship between attentional selection and ODT *curvature discontinuities* (Ben-Shahar & Zucker, 2004). In general, we view all these studies as symbiotic for both the OBA and OBTS research programs: while OBTS provides us with more rigorous (and lower level) definition of 'objecthood' and an opportunity to understand the interaction between attention and atomic visual features, OBA furnishes us with a new type of methodology to examine the importance and consequences of subtle structures on texture segregation. We hypothesize that OBA effects will be found when current OBTS theories predicts segregation (Experiment 1), which motivates us to look for such effects where OBTS theories are still controversial (Experiments 2 and 3). The theoretical implications of the results revealed are discussed in Section 5.

2. Experiment 1: Attending to simple static ODTs

In our first study, we adapted the divided-attention task using what are in many ways the simplest possible ODTs:

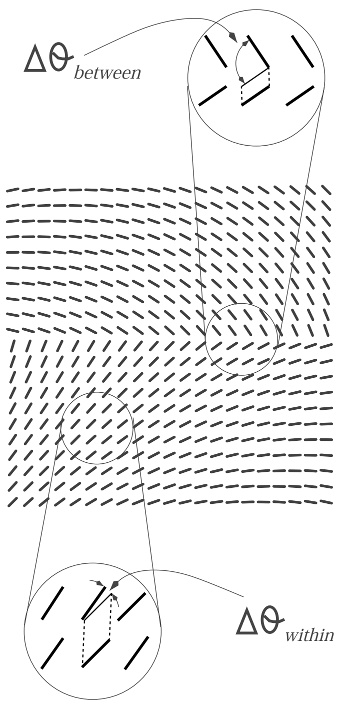

Fig. 2. Current models of OBTS involve two orientation gradients. Each orientation gradient reflects the amount of orientation change per unit distance, either within perceptually coherent regions ($\Delta\theta_{\text{within}}$) or across the perceptual boundary between them ($\Delta\theta_{\text{between}}$).

fields of uniformly oriented texels (Fig. 3a) and juxtapositions of two such fields of orthogonal orientations, with each half appearing on a separate side of the display (Fig. 3b). Each trial began with the appearance of the ODT followed shortly by the brief appearance of a pair of probes and then a mask (consisting of an ODT of random orientation texels; see Fig. 4). Each probe in the pair could be one of two predefined shapes of equal average luminance (a block letter 'T' or 'L') and the observers' task was to determine whether they were identical or different by pressing one of two designated keys. The dependent measure was observers' accuracy.

As is implied above, in this experiment the probes appeared on either uniform ODTs, or in discontinuous ODTs. For uniform ODTs, the probe pair appeared in two adjacent quadrants *along* the grain of the texture on 50% of the trials and in two adjacent quadrants *against* the grain of the texture in the remaining 50% of trials. The comparison between accuracy on with-the-grain trials vs. against-the-grant trials was designed to test whether or not attentional selection is influenced by the 'grain' of the texture. More accurate responses to probe pairs appearing along the grain, compared to probe pairs appearing against the grain, would indicate that such structure can guide the spread of attention.

For discontinuous ODTs, the probe pair appeared on the same side of the orientation-defined boundary on 50% of trials and on two opposite sides of the boundary on the remaining 50% of trials. The orientation of both the 'grain' of the texture and of the orientation discontinuity was counterbalanced across trials, and the comparison between the two types of trials would determine whether simple ODT boundaries can segment the display into two separate 'objects' of

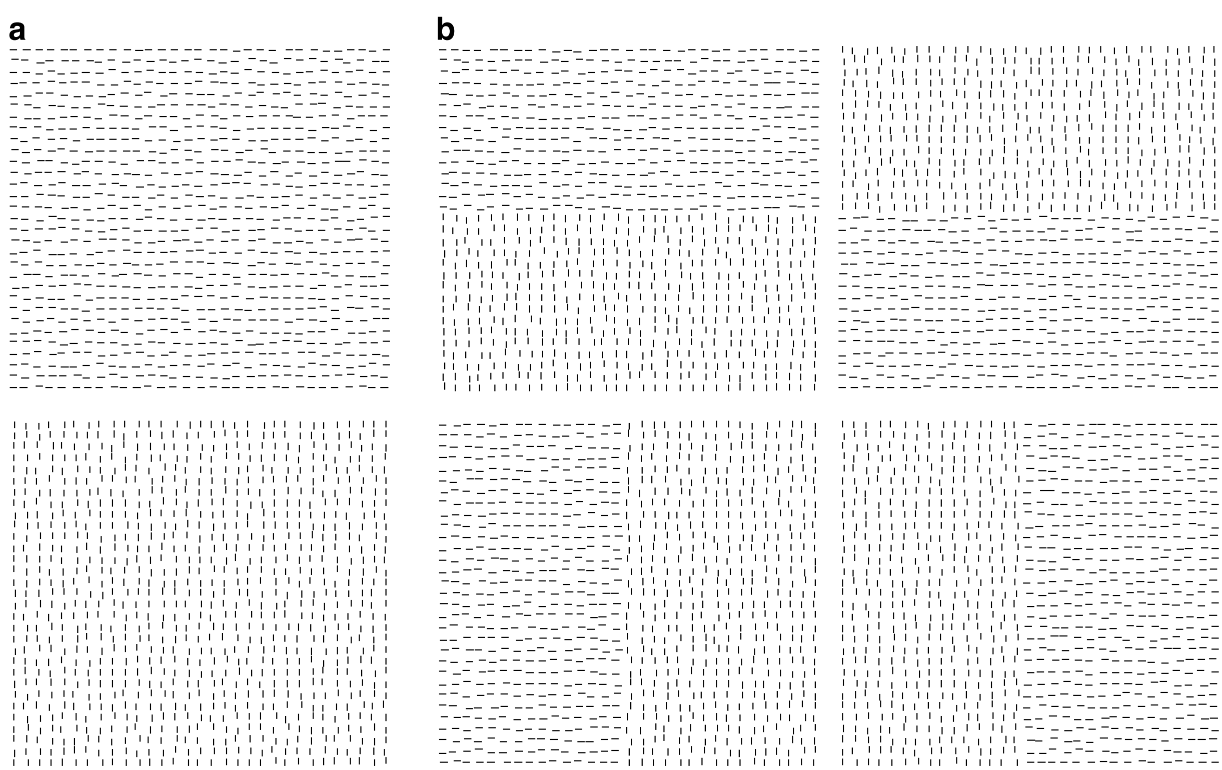

Fig. 3. The six stimuli used in Experiment 1 included both horizontally and vertically oriented uniform ODTs (a) and various combinations of discontinuous ODTs (b). While such jittered stimuli were used in the main experiment, a similar set of regular (non-jittered) ODTs was used in an adjunct experiment.

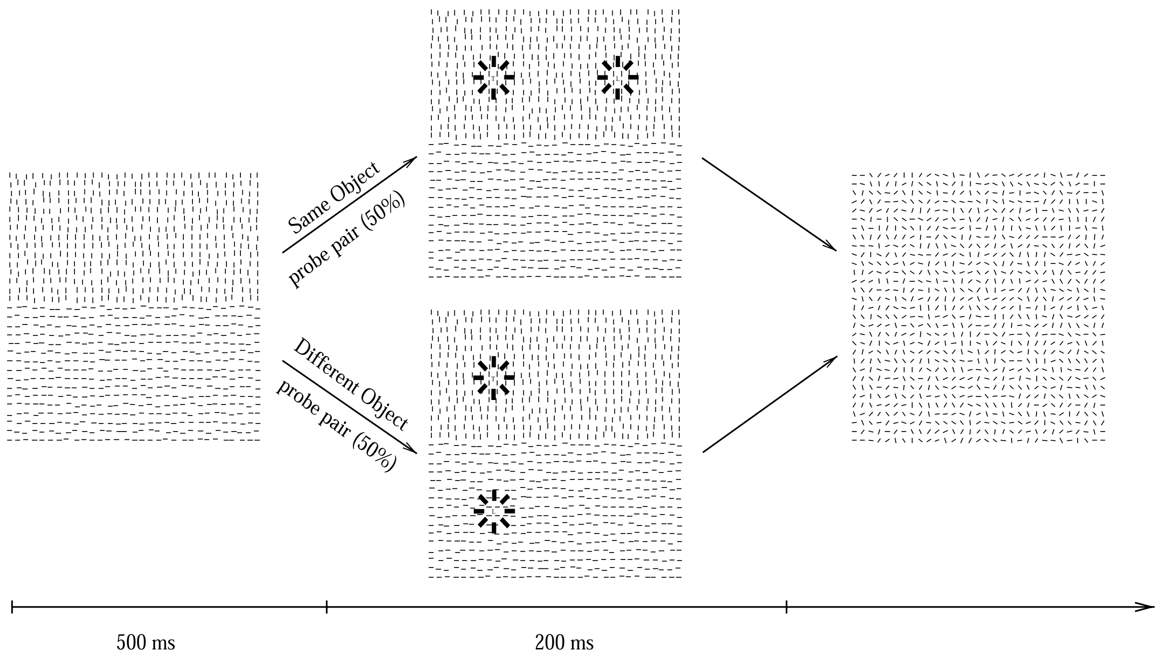

Fig. 4. The divided-attention task used in Experiment 1. The selected probe locations shown here—centered in different quadrants of the display and equidistant from fixation—are indicated with large asterisks, but in the actual experiments these were block-letter L's and Ts which did not overlap any of the texels (see text for details).

attention. Less accurate responses when the probe pair span such a boundary would indicate that the two halves of the screen are indeed treated as separate objects, as is implied by OBTS; a null effect here would indicate that such segmentation is not sufficient to drive 'object'-based attention and would imply that OBA does not apply at this level of primitive (though rigorous)'objects'.

The ODTs in our experiment consisted of jittered arrays of oriented texels, as is typical to OBTS research. In such displays, the oriented structure, the ODT grain, and perceptual boundaries, are all based on global image structure form by the overall spatial distribution of the orientation textons rather than any local continuation and alignment cues. To push our experiment to the limit, however, we also repeated it with *perfectly regular* ODTs where orientation texels were fully aligned to maximize the perception of the grain (stimuli are omitted for space reasons, but compare icons in Figs. 5a and b). Such displays are likely to give rise to much more robust internal representation and therefore test the effect of the grain at its maximal capacity. Better accuracy in with-the-grain trials vs. against-the-grant trials would cast doubt about the link between OBA and OBTS. A null effect, however, would strengthen any similar result with the jittered stimuli and would provide a conclusive evidence both for the dissociation of attentional spread from ODT grain and for the link between OBTS and OBA.

2.1. Methods

2.1.1. Participants

Eighteen (18) observers participated in the main experiment (jittered stimuli) and sixteen (16) participated in the adjunct experiment (regular stimuli). All observers were members of the Yale University community who participated in a 40-min session either to fulfill an introductory psychology course requirement or for a modest monetary payment. All observers had normal or corrected-to-normal acuity and all were naïve to the purpose of the experiment.

2.1.2. Materials

The displays were presented on the monitor of a Macintosh iMac computer using custom software written using the VisionShell graphics libraries (Comtois, 2003). Observers were positioned without head restraint approximately 46 cm from the monitor, the viewable extent of which subtended approximately 37 by 28 deg.

The ODTs were presented as black texels on a white square background which subtended 28.1 deg. Each texel was 0.7 deg long and 0.1 deg wide. Texels in uniform ODTs all shared the same orientation, and were first organized into perfectly parallel rows and columns. Each texel was separated from its nearest neighbor by 0.35 deg along the 'grain', and by 0.9 deg against the grain. Jittered stimuli were created by randomly shifting each texel up to 0.2 deg both horizontally and vertically.[3] Discontinuous ODTs were divided in half along either the horizontal or vertical axis; one half contained vertically oriented texels, the other half horizontally oriented texels. The individual texel

[3] The only texels *not* jittered in this way were the segments in each ODT quadrant which were in the immediate proximity of the probe locations. This local lack of jitter was totally unobservable, and ensured that the same cue/probe locations could be used both with the jittered and the regular ODTs without accidental overlap between the cue/probe and the nearby texels.

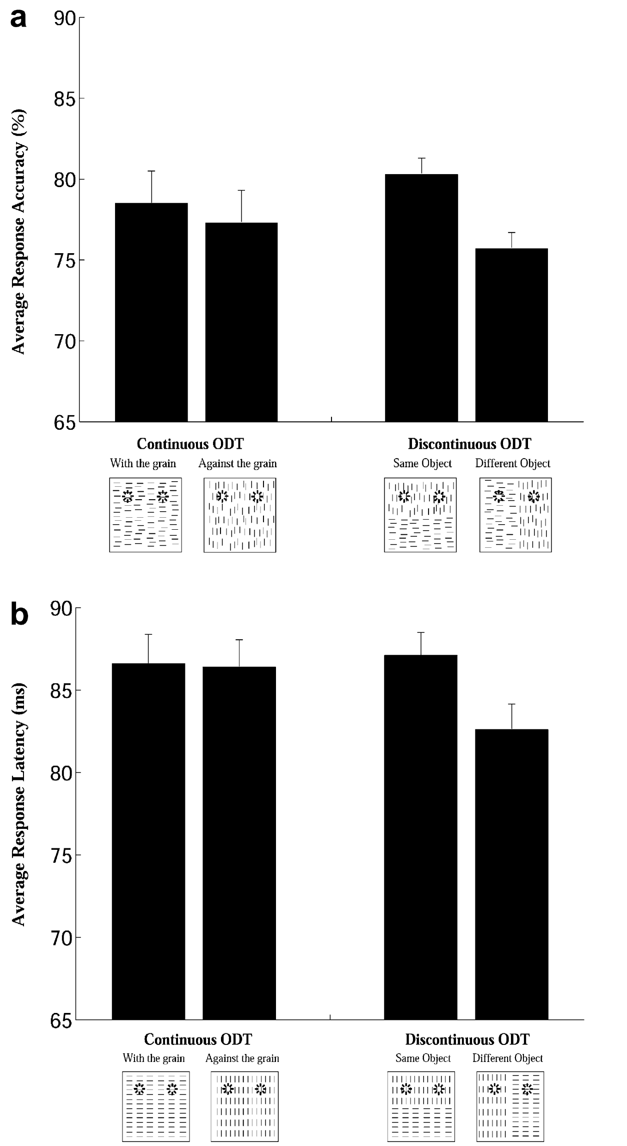

Fig. 5. Mean response accuracy in Experiment 1 broken down by condition. (a) Results of the main experiment with jittered ODTs. (b) Results of the adjunct experiment with perfectly regular ODTs. Error bars represent ±1 SE.

positions were always computed such that this boundary never interrupted any individual texels.

Probe pairs constituted the block letters 'T' and 'L', both 0.47 by 0.47 deg in visual area, and both presented in red. These probes could appear in the center of two neighboring quadrants of the display, thus in two of the same four possible locations on each trial, regardless of which ODT was presented. The positions of the texels and probes were computed such that the probes never overlapped any individual texel.

2.1.3. Procedure

A single trial proceeded as follows (see Fig. 4). Observers initiated the trial by pressing a key, which blanked the screen and showed the ODT. After 500 ms, the probe pair appeared for 200 ms, after which the whole display was masked with an ODT of randomly oriented texels until the subject responded. Subjects were instructed to press one designated key to indicate identical probes, and another key to indicate different probes. Being informed about the importance of the accuracy of their judgment, they were not limited in their response time.

2.1.4. Design

Each subject completed 80 trials for each of the six types of ODTs (Fig. 3) for a total of 480 trials (unblocked and fully randomized). Of the 80 trials in each trial type, 50% were 'same-object' trials in which the probe pair appeared in the center of two adjacent quadrants along the grain of the texture (for uniform ODTs) or on the same side of the boundary (for discontinuous ODTs). The other 50% were 'different-object' trials in which the probe pair appeared in the center of two adjacent quadrants against the grain of the texture (for uniform ODTs) or on opposite sides of the boundary (for discontinuous ODTs). Within each of these subdivisions, the probe pair appeared equally often in each possible pair of adjacent quadrants, such that overall orientation was perfectly counterbalanced. Every 80 trials, a message appeared informing the subjects that they could take a break before continuing, yielding 6 sessions of 80 trials. Before beginning the experiment, each subject completed 20 practice trials (including trials of all conditions), the results of which were not recorded.

2.2. Results

Of primary interest were differences in discrimination accuracy as a function of the different trial types. Fig. 5 depicts these mean accuracies broken down by condition for both the main and adjunct experiments. For uniform ODTs, there was no reliable difference between accuracy for with-the-grain trials and against-the-grain trials. This null effect was observed both in the main experiment using jittered stimuli (78.68% vs. 77.29%; $t(17) = 0.96$, $p = 0.35$) and in the adjunct experiment using perfectly regular ODTs (86.64% vs. 86.41%; $t(15) = 0.16$, $p = 0.87$). For discontinuous ODTs, in contrast, observers were more accurate when the probe pair appeared on the same side of the boundary compared to when the probe pair spanned the boundary. This significant effect was observed both with the jittered ODTs (80.31% vs. 76.66%; $t(17) = 3.65$, $p < 0.01$) and with the perfectly regular ODTs (87.07% vs. 82.58%; $t(15) = 4.16$, $p < 0.01$). Similar to the results in the uniform ODTs, no grain effect was observed within each perceptually coherent segment of the discontinuous ODTs.

2.2.1. A comment about probes' alignment effects

We also analyzed the accuracy data when broken down by overall alignment of the probe pair, which could be either horizontal (e.g., top case in Fig. 4) or vertical (e.g., bottom case in Fig. 4). Overall, accuracy was always better when the probes were aligned horizontally than when they were aligned vertically (e.g., 87.17% vs. 84.17% on average for regular ODTs). However, the results reported above held true regardless of this 'horizontal advantage'. For example, in regular uniform ODTs, the null effect held true for both horizontally oriented comparisons (89.38% vs. 87.66%; $t(15) = 0.90$, $p = 0.38$) and for vertically oriented comparisons (85.16% vs. 83.91%; $t(15) = 0.47$, $p = 0.65$). In regular discontinuous ODTs, the difference of roughly 5% in accuracy held true for both horizontally oriented comparisons (89.53% vs. 84.61%, $t(15) = 4.16$, $p = 0.01$) and vertically oriented comparisons (84.61% vs. 80.55%, $t(15) = 2.55$, $p = 0.02$). There was no reliable interaction between boundary and overall orientation ($F(1,15) = 0.23$, $p = 0.64$). More generally, we found a similar 'horizontal advantage' throughout our experiments, and despite its ecological validity, its origin remains unclear. (In particular, this result seems intuitively inconsistent with the observation that horizontal spread—but not vertical spread—is likely to involve processing in both hemispheres.) However, because this global orientation factor was fully counterbalanced with our same/different object manipulation, it never affected the comparisons of theoretical interest. Thus, in subsequent experiments we do not report these comparisons broken down by probe pair orientation, except to note here that they also followed this pattern.

2.3. Discussion

This first experiment yielded two conclusions with potentially important implications for the nature of object-based attention. First, the approximately 5% performance difference in our 'same vs. different' divided-attention task indicates that orientation discontinuities and OBTS in ODTs (as in Fig. 3b) appear to be sufficient for producing a cost on attentional selection. This implies that 'object'-based attention does not necessarily require the full-fledged 'objects' of our intuitive concepts. Rather, 'objects' of attention can be formed by proper distribution of elementary visual features and hence are linked directly to the low-level visual process of texture segregation and to low-level representations of visual stimuli, a conclusion that naturally extends previous work on the relationship between OBA and perceptual organization (e.g., Driver et al., 2001; Lamy & Egeth, 2002; Moore et al., 1998).

The second critical result of this first experiment involves the uniform ODTs. While orientation differences in the 'grain' of the texture induces both segmentation and OBA effects, the grain itself produced no such effect whatsoever: discrimination accuracy was no better (and virtually identical) when attention had to spread 'with' the grain of the texture, compared to when attention had to spread 'against' the grain of the texture. This result was obtained with both jittered ODTs, and more surprisingly, with perfectly regular ODTs where the perception of grain is maximized via local colinearity and perfect good continuation of the individual texels. This result is important on several levels. First, it demonstrates the surprising fact that attention will not simply respect any perceptually salient image structure, as may be intuitively (but wrongfully) attributed to the 'grain' of static ODTs. Second, it suggests that attention is influenced by changes in the *distribution* of textons, rather than in their *absolute value*, therefore placing attentional selection in agreement with models of OBTS (Landy & Bergen, 1991; Mussap & Levi, 1999; Nothdurft, 1991, 1993) which emphasize orientation *gradients* rather than texels' absolute orientation. Finally, this null effect strictly contradicts previous results in the OBA literature (Avrahami, 1999), an issue which we discuss at greater length in Section 5.

Our first, two part experiment already succeeds at our general goal of drawing links between the attention and segregation literatures. We see both how the 'objects' of OBA can be built from much simpler visual features drawn from the segregation literature (in this case, orientation), and how experimental paradigms from the OBA literature may be used to explore OBTS. The additional experiments reported below generalize and exploit these links to more advanced cases.

3. Experiment 2: The spread of attention across tangential-curvature-defined boundaries

The previous experiment provides evidence that discontinuities in ODTs affect attentional selection and the division of the visual field into attentional 'objects'. This implies that OBTS and OBA may be intimately coupled and that attention spreads more readily within coherent ODT regions than between them. The definition of *within* and *between* in these earlier experiments, however, was defined in especially explicit terms—by large orientation gradients, or orientation discontinuities, between ODTs patches of *constant* orientation. Because such constant ODTs—and the boundaries formed by completely orthogonal orientation differences between them—are well understood in the OBTS literature, they constituted a perfect first step for our studies. In particular, they demonstrated how the study of OBTS could usefully inform the study of OBA, and help to begin characterizing attentional objects in rigorous ways which go beyond intuitive appeal.

With this link between OBTS and OBA established, we were also interested in making it reciprocal by using OBA effects as a new type of evidence with which to test more contemporary ideas about OBTS. Experiments 2 and 3 do exactly this for the recently proposed role of ODT *curvatures* in OBTS (e.g., Ben-Shahar & Zucker, 2004).

3.1. The roles of orientation and curvature in defining ODT structure

ODTs are 2D projections of pattern-formation processes that cover surfaces (and sometimes volumes) in the real world—as for example fur covers a bear, wheat covers a field, and stripes cover a zebra (Fig. 1). Since these dense structures are defined locally by orientation, their abstract representation should make this orientation explicit at each point. Formally, this means that ODTs can simply be represented as a scalar orientation function $\theta(x,y)$, where (x,y) are retinotopic coordinates.

Although much of extant research on OBTS has concentrated on ODTs whose orientation function $\theta(x,y)$ is piecewise constant (e.g. Caputo, 1997; Caputo & Casco, 1999; Kwan & Regan, 1998; Li, 1998; Motoyoshi & Nishida, 2001; Nothdurft, 1985; Regan, Hajdur, & Hong, 1996; Wolfson & Landy, 1995, 1998), such (piecewise) constant oriented structure is encountered only very rarely in natural images. Indeed, such a form requires an accidental match between the surface geometry, the texture formation process, and the observer's view-point. Furthermore, perspective projection dictates that even perfectly parallel lines in the world are likely to give rise to a *non*-constant retinal ODT. Thus, when considering ODTs psychophysically, it is more appropriate to consider the larger scope of patterns with *varying* $\theta(x,y)$.

In the $\theta(x,y)$ representation, local changes in ODTs' orientations are captured, to a first approximation, by the *gradient* of $\theta(x,y)$. Indeed, when ODT variations have been explored (Mussap & Levi, 1999; Nothdurft, 1991, 1992), the notion of orientation gradient has been invoked, albeit in a somewhat restricted form. As mentioned in the Introduction (see also Fig. 2), OBTS has been found to depend on the relationship between *two* orientation gradients—one for the change in orientation *between* coherent regions ($\Delta\theta_{between}$) and the other for change in orientation *within* regions ($\Delta\theta_{within}$). Varying these two parameters and exploring segregation accuracy reveals that reliable segregation occurs only if the ratio of these two gradients is significantly larger than 1.

However, it was recently argued (Ben-Shahar & Zucker, 2004) that orientation gradients are incapable of fully explaining OBTS, either psychophysically or formally. They employed a frame field representation of ODTs that permits an object-centered geometrical examination of these structures, and which reveals two curvatures—one *tangential* and one *normal*—that emerge from differential properties of the moving frame (Fig. 6). In simplified terms, the tangential curvature describes the rate of change in ODT orientation in the direction 'with the grain', while the normal curvature does so in the direction 'against the grain'. Together, these two curvatures provide a complete description of the local variations in ODT orientation—and unlike the gradient of $\theta(x,y)$, they do so *intrinsically*, independent of a global reference frame.

A key finding in these studies (Ben-Shahar & Zucker, 2004) was that discontinuities in ODT curvatures predict certain OBTS phenomena that cannot be satisfactorily explained in terms of either orientation gradients (Mussap & Levi, 1999; Nothdurft, 1991) or boundary configuration (Nothdurft, 1992; Wolfson & Landy, 1995). More recently, these ODT curvatures were also shown to play a fundamental role in the perception of singularities in smoothly varying ODTs (Ben-Shahar, 2006). Inspired by these findings, we seek to examine the influence of discontinuities in

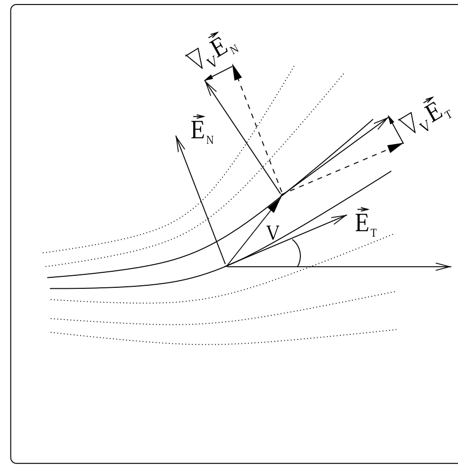

Fig. 6. Representing ODTs with a moving frame captures their intrinsic geometry. Attaching a natural (tangent and normal) frame to each point of the ODT (see Ben-Shahar and Zucker, 2003) and using it as a basis to represent the frame's differential behavior—also called its covariant derivative—gives rise to two ODT curvatures, κ_T and κ_N which represent the initial rate of change in the frame in the tangential and normal directions, respectively.

ODT *curvatures* on the spread of attention. In order to isolate the possible effect of curvature discontinuities from that of orientation discontinuities, the stimuli we used here were discontinuous *only* in curvature, and were *continuous* almost everywhere in orientation.[4] Experiments 2 and 3 that follows, therefore share the following goal: to test whether either of the two possible types of curvature discontinuities divide the visual field into attentional 'objects'. Such a finding would also provide strong support—and an entirely new type of support, relative to the existing OBTS literature—for the role of ODT curvatures, and their discontinuities, in OBTS.

In Experiment 2 we test whether boundaries defined by changes in *tangential* curvature (Fig. 7) have any effect on OBA. Relative to our previous experiment, here we limited our study in two ways: First, we tested only discontinuous ODTs. Second, we used only jittered (as opposed to regular) ODTs. In contrast to the stimuli used in Experiment 1, which represented perhaps the most obvious case of orientation-defined boundaries, the stimuli here (and in Experiment 3) represent the other extreme, wherein boundaries are formed from especially subtle changes in the distribution of orientation texels.

3.2. Methods

This experiment was identical to Experiment 1 except as noted here. Thirteen (13) observers participated, none of whom had participated in previous experiments. All stimuli

[4] In contrast, recall that the stimuli of Experiment 1 were discontinuous in orientation, but lacked curvature discontinuities. Indeed, both tangential and normal curvatures were identically zero in all parts of the stimuli used in the previous experiments.

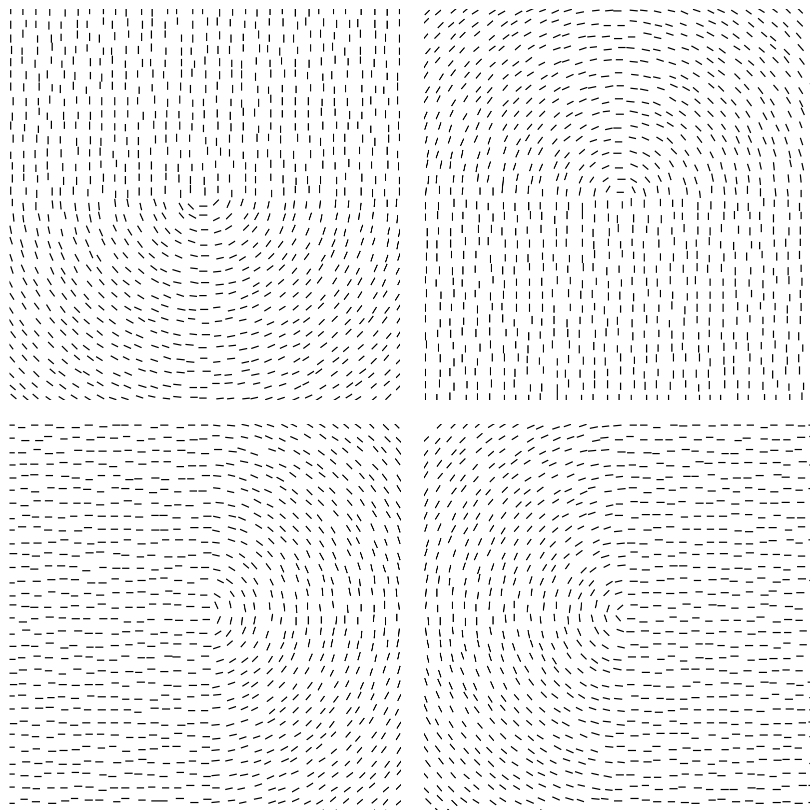

Fig. 7. The stimuli used in Experiment 2, employing discontinuity in tangential curvature and constant zero normal curvature.

were constructed as jittered ODTs as explained in Experiment 1. Each ODT had two rectangular regions, one with both curvatures identically zero (and thus constant orientation), and the other with a variable, everywhere-positive tangential curvature and identically zero normal curvature. Except for one singular point at the center of the stimulus,[5] the two regions met continuously in terms of orientation, along a vertical or horizontal line, as is illustrated in Fig. 7.

Due to the variation in orientation in these stimuli, the probes that we used in Experiments 1 and 2 (the block letters 'T' and 'L') were now prone to intersect nearby texels in undesired ways. Hence we replaced them in this experiment with small outlined circles (drawn with a stroke of 0.2 deg), whose curvature made them unlikely to group perceptually with the adjacent linear texels. Each of the two circular-probes on each trial had a 0.30 deg gap in its contour facing either right or left (the choice being random), and the subjects' task was to determine whether the two probes had gaps facing the same or opposite directions. Each subject completed 320 such trials where the configuration of the discontinuity (horizontal and vertical), relative probe-pair orientation, same vs. different gap direction, and same vs. different 'object' conditions were fully counterbalanced as in Experiment 1.

3.3. Results

Observers' accuracy was recorded on each trial and the results, broken down by condition, are depicted in the left half of Fig. 8. Performance was reliably better when the probe pair appeared in the same ODT region than when the probe pair spanned the curvature boundary (74.33% vs. 71.11%; $t(12) = 2.39$, $p = 0.03$).

3.4. Discussion

Experiment 1 (and its adjunct) revealed that the spread of attention through static ODTs is influenced by orientation-defined boundaries. Experiment 2 revealed similar effects for boundaries defined by tangential curvature rather than orientation. Because orientation-defined boundaries have been classical stimuli in the OBTS literature for decades, the first experiment can be considered a case of OBTS research informing OBA research. In contrast, Experiment 2 tested a form of texture segregation which has only very recently been explored in the OBTS literature. As such, this experiment can be interpreted not

[5] Note that ODTs which are continuous in orientation and discontinuous in tangential curvature must have such a singularity, and that it should be located within the visible area of the ODT in order to maximize the magnitude of the discontinuity in curvature (and thus the possibility of an attentional effect), and also to allow counterbalancing of the visual field (both right/left and upper/lower) in which the probe pair appeared. When the singularity is located at the center of the image, however, it is unlikely to interact with the probes at the centers of the four quadrants, or the spread of attention between them.

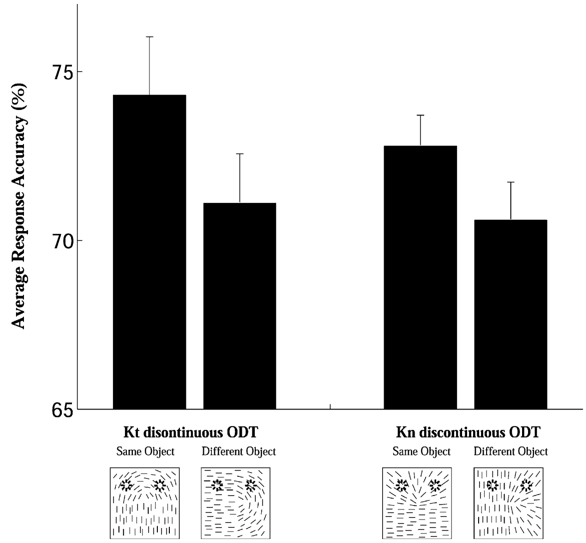

Fig. 8. Mean response accuracy in Experiments 2 and 3, broken down by condition. Error bars represent ±1 SE.

only in terms of increasingly detailed evidence for subtle ways of forming attentional objects from the orientation texton, but also in the opposite way: here we have shown how OBA effects can be used as a tool with which to experimentally verify theoretical innovations in the OBTS literature and to study image structure in general (see Section 5).

Indeed, discontinuities in tangential curvature *without* any orientation gradient may not be as salient structure as orientation gradients, and perceptually, the stimuli in Experiment 2 may not be interpreted as two different 'objects'. However, the perceptual structure, and the corresponding internal representation, can easily qualify as two different *parts* of a more complex object and in this sense link our study directly to similar hierarchies in the OBA literature (Barenholtz & Feldman, 2003; Singh & Scholl, 2000; Vecera et al., 2000, Vecera, Behrmann, & Filapek, 2001).

4. Experiment 3: The spread of attention across normal-curvature-defined boundaries

In the perceptual frame field theory (Ben-Shahar & Zucker, 2003), changes in tangential and normal curvature are equally important for driving OBTS, a theoretical statement that received further recent support from exploration of perceptual singularities *without* feature gradient in smoothly varying ODT (Ben-Shahar, 2006). Because of this, it is important to test for effects of each type of curvature independently, and here we move to boundaries defined solely in terms of normal curvature discontinuities (Fig. 9). This additional experiment is important in terms of completeness and symmetry, but it becomes particularly interesting once we realize that perceptual effects of normal curvature are less intuitive (and arguably less salient) than those of tangential curvature. Consequently, one would

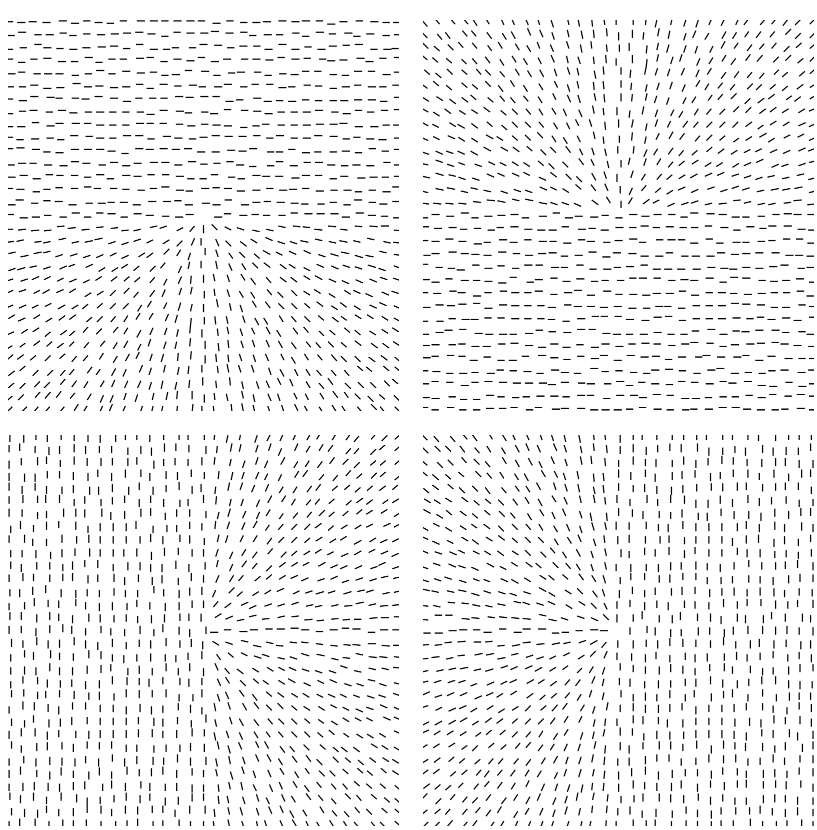

Fig. 9. The stimuli used in Experiment 4, employing discontinuity in normal curvature and constant zero tangential curvature.

predict that changes in curvature 'against the grain' would result in either minimal or non-existent attentional effects. However, the evidence thus far clearly suggests that in fact there is *not* a one-to-one correspondence between attentional effects and salient perceptual structure. (Experiments 1 and 2 clearly demonstrated this for the 'grain' of ODTs and discontinuities in tangential curvature.) Thus, we cannot comfortably assume that less salient image structure will not influence attention. Moreover, effects of normal curvature on OBTS have been argued psychophysically to affect internal low-level representation of ODTs (Ben-Shahar & Zucker, 2004), and changes in normal curvature can also be found in natural visual situations, even without abrupt changes in orientation (Fig. 10). For all of these reasons, here we test whether such configurations can also influence attentional selection.

4.1. Methods

This experiment was identical to Experiment 2 except as noted here. Twenty-four (24) observers participated, none of whom had participated in the previous experiments. Each ODT had two rectangular regions, one with both curvatures identically zero, and the other with a variable and everywhere-positive normal curvature and identically zero tangential curvature (Fig. 9).

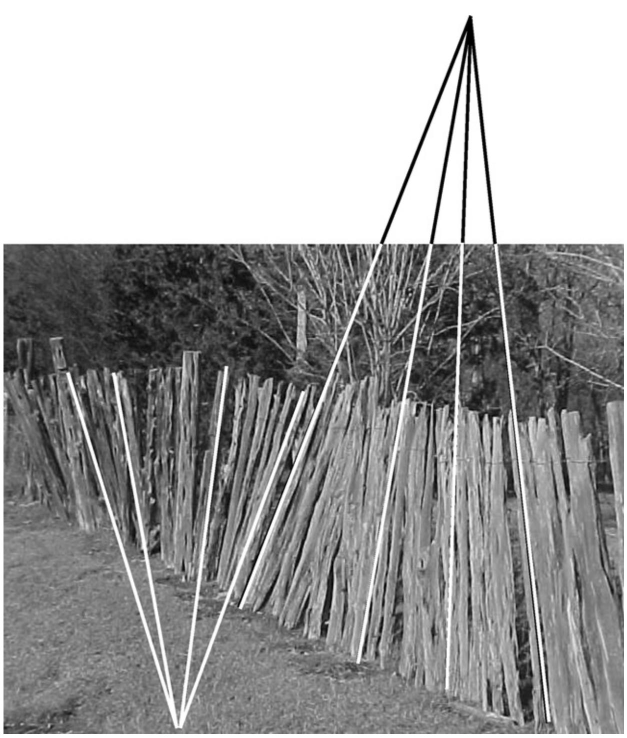

Fig. 10. Although their occurrence in natural images is intuitively less obvious, discontinuities in normal curvature can be found in natural visual scenes as commonly as those in tangential curvature. Here we show an example of this even without orientation discontinuities. This image of the fence defines an ODT with two geometrically coherent regions and a rapid change in normal curvature in between them. Note the two different singular points of the two sections and observe the constant zero tangential curvature along the fence ODT.

4.2. Results

Observers' accuracy was recorded on each trial and the results, broken down by condition, are depicted in the right hand side of Fig. 8. Performance was marginally better when the probe pair appeared in the same ODT region than when the probe pair spanned the curvature boundary (72.81% vs. 70.65%; $t(23) = 1.92$, $p = 0.06$).

4.3. Discussion

The results of this experiment are marginal but they are nevertheless consistent with the previous experiments and with the idea that curvature is important in OBTS (Ben-Shahar & Zucker, 2004). Since the ODTs boundaries in this experiment are defined in what are arguably less perceptually salient discontinuities in the normal curvature, we consider this result complementary to the null effect obtained with uniform ODTs in Experiment 1: seemingly salient image structure can fail to influence attention, while especially subtle image structure, and subtle types of variations in the distribution of the orientation texton, can yield reliable effects. The results of Experiments 2 and 3, taken together, are especially important in this regard, since they comprise one of the first demonstrations that curvature of this type is taken into account by processes of object-based attention. Such results are encouraging in terms of the ecological validity of OBA effects, given the ubiquity and importance of curvature in real-world scenes and objects (Fig. 1).

5. General discussion

The overarching goal of this study has been an attempt to join two largely distinct research programs: object-based attention, and texton-based texture segregation. We have done so in this paper for the orientation texton—one of the most salient features of early vision—with two complementary goals. On one hand, the theories and models of segmentation processes from the OBTS literature can usefully inform studies of OBA by helping to characterize attentional objects in rigorous ways which go beyond intuitive appeal. On the other hand, the experimental tools which have been developed in the OBA literature can be adapted to provide new ways of testing models of OBTS. Doing so emphasizes that early segregation processes and low-level representations can drive many aspects of visual processing (such as attention) even without further elaborated high-level object structure. With these dual goals in mind, our studies of orientation texton-based OBA yielded three primary results.

First, we found that low-level segregation cues in static ODTs yield distinct attentional objects, even in the absence of other common cues to objecthood such as closure or curve continuity. Subjects were less accurate at making various visual judgments when the relevant information spanned an orientation-defined texture boundary (as in

Fig. 3b), compared to when the information appeared within a single, perceptually coherent ODT region.

Second, we found that the spread of attention in ODTs is influenced by changes in the *distribution* of texels, rather than their absolute values. The boundaries which yielded robust attentional effects in discontinuous ODTs were defined only by *differences* in their main direction or 'grain' across two regions. In contrast, the overall grain of a texture region had no effect: attention operated no more readily 'with the grain' than 'against the grain' in uniform ODTs (as in Fig. 3a). This null effect was well supported in our studies, since it was replicated in separate experiments wherein the other trials with discontinuous ODTs did yield robust attentional effects.

Third, we found that attentional objects could be formed by texture boundaries which were defined not only in terms of orientation, but also solely in terms of curvature. This result was especially striking given that the role of curvature in mediating texture segmentation has only recently been stressed in the OBTS literature. Since such segmentation constitutes an especially subtle (and arguably less salient) form of segregation which is formed by the distribution of the orientation texton, it could possibly be linked to object-part hierarchies (Singh & Scholl, 2000; Vecera et al., 2000, 2001) rather than multiple high level intuitive objects. In any case, this result demonstrates that OBA may be driven by low-level representations rather than full blown high-level objects.

5.1. The units of attention and the foundations of OBA

The research program of OBA has focused largely on a dichotomous debate, over whether the underlying units of attention can in some cases be discrete objects, as opposed to spatial areas or unbound visual features (see Scholl, 2001). As such, the vast majority of stimuli used in such studies have been constructed haphazardly, using simple geometric shapes which intuitively seem like 'good' objects, while very few studies have explored in detail what can count as an 'object' of attention in the first place. Objects are sometimes contrasted with other high-level classes of entities, such as groups (Driver et al., 2001), parts (Vecera et al., 2000, 2001), or non-solid substances (vanMarle & Scholl, 2003). But for the most part such studies have paid little attention to the individual image cues from which objects are formed. The few recent studies which have bucked this trend and strongly motivated our approach have studied the roles of closure (Avrahami, 1999; Marino & Scholl, 2005), curvature minima (Barenholtz & Feldman, 2003; Singh & Scholl, 2000; Watson & Kramer, 1999), and connectedness (Scholl, Pylyshyn, & Feldman, 2001; Watson & Kramer, 1999).

Here we have shown how attentional objects can be formed by distributions of the orientation texton, which is one of the most important (and better-understood) aspects of early visual processing. These results have shown several ways in which the objects of attention transcend intuitive notions of objecthood. Perhaps the most important implication of our results for the nature of object-based attention is just that attentional 'objects' can be formed from simpler visual features in stimuli which do not meet all of our intuitive criteria for objecthood. The two sides of the ODTs in Fig. 3b, for example, are naturally conceived of in terms of different *regions*, or *areas* of the ODT, but many would balk at referring to them as full-fledged objects, given that they lack the cues of boundedness, continuous contours, and closure which are normally taken to be definitive of full-fledged objects (e.g. Spelke, Gutheil, & Van de Walle, 1995). Still, our studies have shown that such cues—global ODT boundaries defined by either orientation or curvature discontinuities—are sufficient to form attentional objects, and therefore imply that attentional selection may be driven by low-level representations of perceptually coherent segments rather than high-level representations of intuitive perceptual objects.

Our null results with uniform ODTs have equally important implications for the understanding of object-based attention. It could have turned out that *any* perceptually salient structure would constrain the spread of attention. However, the main direction ('grain') of ODTs failed to do so here, despite being just as perceptually salient as any visual structure can possibly be. Indeed, we had some reason—based on both intuition and previous results (as discussed below in Section 5.2)—to expect that attention would spread more readily 'with the grain' than 'against the grain' of uniform ODTs. The fact that it did not is critically important to the foundations of OBA. In principle, there is an *arbitrary* relationship between objects in the world and the ODTs that may cover them: even intuitively, we can appreciate that the very same object can be covered in many different ways (e.g. combing the hair of a dog in various ways). If it *had* turned out that attentional selection was sensitive to the absolute values of the orientation texels—i.e. by the particular way in which the object is 'painted' with an ODT—this would undermine the theoretical link to objecthood: attention would be constrained not by the structure of the perceptual object itself, but by its superficial ODT 'paint'. Fortunately, we have shown here that this is not the case.

Methodologically, these results highlight the importance of grounding studies of OBA in rigorous computational or geometrical models of image structure. Had we simply cleaved to intuition, we would have continued to assume that the grain of an ODT would constrain attention just as other types of image structure do. The object-centered 'frame field' geometrical model of OBTS (Ben-Shahar & Zucker, 2003), however, clearly implies that the two main directions of an ODT—the tangential (with the grain) and the normal (against the grain)—are equally significant and should not be biased relative to each other. That this surprising prediction was borne out in our OBA studies is a strong demonstration of why it is important to ground studies of 'objecthood' in rigorous geometrical or computational models of image structure.

Our finding regarding the effect of the ODT's grain (or the lack thereof) do seem to conflict with at least the spirit of one other OBA study (Avrahami, 1999), which also urged researchers to explore the particular image cues which form attentional objects. Using the 'two-rectangles' stimuli (cf. Egly et al., 1994) in a spatial-cueing task as its starting point, Avrahami (1999) suggested that neither closure nor proximity may in fact be required to produce same-object advantages, and thus she employed instead a set of regularly spaced parallel lines with which a similar same-'object' advantage was found: subjects responded faster to invalidly cued targets when the cue and target were oriented parallel to the lines, compared to when they were oriented perpendicularly to them. Avrahami's displays did not contain full-fledged (intuitive) objects. Rather, their primary perceptual feature was an overall salient direction, or a grain, defined by the lines. Thus, these same-object advantage results—combined with a failure in some cases to observe such an advantage when using 'ribbons' (which enjoyed 'objecthood' but arguably lacked an overall grain)—led Avrahami (1999) to conclude that the putative object-based effect in the 'two-rectangles' stimulus is primarily a result of efficient line-tracing operations based on the overall grain of the display, rather than being an effect of objecthood per se. In our experiments, in contrast, we consistently failed to find any such effect of the salient grain of ODTs (Experiment 1 and its adjunct).

We remain unsure why our studies obtained such conflicting results. Certainly there were important differences in the stimuli we employed: we used ODTs, whereas Avrahami (1999) used arrays of widely spaced, regular, and continuous parallel lines, which may not genuinely qualify as textures. However, both of these classes of stimuli contain salient main directions (grains) which are roughly equivalently salient, and as such it seems that if the grain had been the source for the attentional advantage in Avrahami (1999), it should have entailed a similar effect with our ODTs. That said, we are especially confident in our null result, not only because of the multiple replications, but also because the trials with uniform ODTs were always randomized together with the discontinuous ODTs which did produce robust effects on attention—thus ruling out any general insensitivity of either the paradigm or the observers. Thus we do not think that the object-based effects in earlier studies are due to 'grain-based' line-tracing. Supporting our finding is also the fact that same-object advantage was indeed reported in 'two-rectangles' stimuli even when their grain was severely interrupted by occluders (Moore et al., 1998). One possibility for the difference, however, is that the extent of the effect is directly related to the type of internal representation that is built for stimuli in the visual system. Our stimuli clearly can be considered and represented as dense oriented textures, while the stimuli used by Avrahami (1999) could possibly be interpreted, and therefore represented internally, as a collection of separated line objects. These differences could have critical implications on subsequent visual processes, attentional selection included. These possibilities, and the findings mentioned above, all emphasize the need to further explore multiple low-level image cues and their combinations in the study of OBA.

5.2. OBA as a tool for testing models of OBTS

OBTS—and, indeed, texture segregation in general—have been extensively studied in psychophysics, yielding a wealth of accumulated experimental and theoretical knowledge, based on many experimental techniques. Theories of OBTS have explored many different specific factors—such as orientation gradients (e.g. Nothdurft, 1985), edge orientation (Appelle, 1972; Wolfson & Landy, 1995), configural effects (Nothdurft, 1992; Olson & Attneave, 1970; Wolfson & Landy, 1995), and curvature (Ben-Shahar, 2006; Ben-Shahar & Zucker, 2004; Hel-Or & Zucker, 1989)—and these variables have been tested with many different approaches, including contrast-detection (e.g. Motoyoshi & Nishida, 2001), measurements of visual evoked potentials (e.g. Bach & Meigen, 1992; Caputo & Casco, 1999), analyses of saccade targets (Deubel, Findlay, Jacobs, & Brogan, 1988), and the common forced-choice paradigm using perceptual judgments (e.g. Ben-Shahar & Zucker, 2004; Hel-Or & Zucker, 1989; Landy & Bergen, 1991; Mussap & Levi, 1999; Wolfson & Landy, 1995, 1998).

Here we have shown that OBTS can also be studied with proven methodologies from the OBA literature. In these experiments, we have not only provided converging evidence for theories of OBTS, but have imported entirely new type of experimental paradigm for studying segregation. Using divided attention, we have demonstrated that subtle differences in the spread of attention through scenes can be diagnostic of the underlying processes of OBTS. These new types of evidence are particularly useful, since they do not require subjects to make an explicit perceptual report of segmentation (as does the typical forced-choice method); rather, the nature of texture segregation can be indirectly inferred from the patterns of observers' responses in tasks which do not themselves involve an explicit segregation judgment. As such, these paradigms are perhaps less susceptible to the higher-level biases which may sometimes infect experiments which rely on direct perceptual reports.

6. Conclusions

Collectively, the experiments reported here constitute the first step in a much larger project. Until now, studies of object-based attention and texton-based segregation have proceeded in largely independent subcultures of vision science. Here we have demonstrated one way in which these literatures can usefully inform each other in the context of the orientation texton. In fact, we think that such cooperation will be possible in the context of many other types of cues (e.g. stereopsis and motion) which have been loosely involved in OBA stimuli, but which are embodied in rigorous formal computational and geometrical models in the visual segregation literature. Generalizing this project to such other cues may continue to provide new ways of psychophysically testing segmentation models, and of discovering how the 'objects' of attention are formed from simpler visual features.

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