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Bridging the Gap Between Object-Based Attention and Texton-Based Segmentation: How Attention Spreads Through Orientation-Defined Textures

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Many recent studies of object-based attention (OBA) have suggested that the underlying units of attention are often discrete objects, through which attention readily spreads. However, the relationship of such experiments to the basic visual features ('textons') which guide the segmentation of visual scenes into 'objects' remains largely unexplored. Here we bridge this gap for one of the most conspicuous features of early vision: orientation. We do so in a study of how attention spreads through simple static orientation-defined textures (ODTs), and across texture-defined boundaries. Much work in the segmentation literature suggests that orientation-based texture segmentation (OBTS) is guided by orientation gradients, and our previous work suggests that it is also influenced by ODT *curvatures*. We suggest here that *attention* should respect ODT boundaries defined by both orientation and curvature differences, and we also predict that the flow of attention should *not* depend on the general direction (i.e. the 'grain') of the texture — in contradiction to previous findings in the OBA literature. We explore such predictions using both spatial-cueing and divided-attention paradigms on various ODTs, both uniform (one 'object') and discontinuous (two 'objects'). Contrary to previous studies, we find that the texture's 'main direction' has no effect: attention flows just as readily with vs. against the 'grain' of ODTs. At the same time, texture-defined discontinuities have a major effect: attention flows less readily across texture boundaries which are defined by either orientation or curvature. These effects replicated across multiple paradigms and dependent measures, and also held for jittered ODTs, wherein the effects must be due to global structure as opposed to local good continuation. We conclude that uniform ODTs are single objects from an attentional point of view, while discontinuous ODTs — with the discontinuities defined in either orientation or curvature — are processed as multiple objects. Collectively these experiments begin to reveal how the 'objects' of OBA are formed from simpler visual features.

The input to visual perception consists, at the earliest levels, of an undivided wash of visual features. The contents of conscious perception, in contrast — and the focus of our actions — are structured scenes of discrete objects. A critical task for vision science is thus to determine when and how this segmentation of the visual world occurs. Here we will be 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. Many recent studies have suggested that the underlying 'units' of this selection process are often discrete objects — i.e. that attention acts primarily on pre-attentively segmented visual representations. A vast literature on 'object-based attention' (OBA) has supported this view, demonstrating that attention will often spread more readily through visual objects (see Scholl, 2001, for a review).

But what counts as an 'object' for the purposes of attention? With few exceptions, studies of OBA have explored only 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. Our project in this paper is to begin to

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bridge the gap between these two historically distinct research programs — object-based attention and texton-based segmentation — for one of the most conspicuous features of early vision: orientation. Using experimental paradigms from the OBA literature, our general strategy is to explore how attention spreads 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 how attention spreads through such stimuli, we may begin to understand how the 'objects' of object-based attention are formed from simpler visual features. At the same time, such studies can also increase our understanding of orientation-based texture segment-ation (OBTS), for example by demonstrating atten-tional 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 bridge these areas, and demonstrate how the flow of attention is mediated by the orientation texton.

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. The core aspects of attention comprise three phenomena (Pashler, 1998): (1) the fact that we can process some incoming stimuli more than others (*selectivity*), (2) an apparent limitation on the ability to carry out simultaneous processing (*capacity-limitation*), and (3) the fact that sustained processing of even visual stimuli seems to involve a sense of exertion (*effort*). The processes which give rise to these phenomena — which we collectively term 'attention' — are thought to be responsible for a number of salient features of our day-to-day experience: Why do certain events seem to automatically distract us from whatever we are doing ('capturing' our attention)? How is it that you can sometimes focus so intently on a task that you fail to perceive otherwise-salient events occurring around you? Why is it sometimes necessary to search for objects which are in full view in cluttered scenes (and how does such search occur)? Current theories of attention propose answers to such questions (see Styles, 1997, for a review), and suggest that in many cases we are only consciously aware of that information to which we attend (e.g. Mack & Rock, 1998; Most et al., 2001; Rensink, 2000).

To what information can attention be directed? This question has provoked a vast amount of research in the past few decades, and there has recently been a sea-change, from thinking of the 'units' of attention as necessarily spatial, to being fundamentally object-based. 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 in many cases the underlying units of attention are already pre-attentively segmented discrete objects (Scholl, 2001). Many types of evidence for this view have accrued, two of which will be especially important here: 'same-object advantages' from both spatial cueing tasks, and from divided-attention tasks.

The first type of evidence for OBA which we will employ suggests that when only a single region of an object is attended, attention will subsequently spread within the entire object. For example, consider the simple display depicted in Figure 1. In one well-known study (Egly, Driver, & Rafal, 1994; see also He & Nakayama, 1995), one end (labeled 'C') of one of two rectangles was exogenously cued on each trial, using cues which were 75% valid. After this cue, one end of one of the bars underwent a subtle luminance decrement (the 'probe'), which observers simply had to detect and report via a speeded keypress. Of course, observers were faster to detect probes in the cued locations — a standard spatial cueing effect. For the invalid cues, however, subjects were faster to detect targets that appeared on the uncued end of the cued bar ('S' for 'same object' in Figure 1), compared to the near end of the uncued object ('D' for 'different object'). Because S and D are equidistant from C, this effect cannot be spatially mediated. Rather, it is a 'same-object advantage', explained by the spread of attention within an object: Even though it was location C which was cued, the resulting allocation of attention eventually encompassed location S as well. This same-object advantage mediated by spatial cueing has now been replicated many times, and with several types of 'objects' (e.g. Atchley & Kramer, 2001; Lamy & Tsal, 2000; MacQuistan, 1997; Vecera, 1994).[1]

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[1] Another study using this paradigm — Avrahami (1999) — explored the degree to which the spread of attention was influenced by a group of parallel lines, with no closure cues as in Egly et al. (1994). This study is highly relevant to our project, given

A similar 'same-object advantage' is seen in a class of 'divided-attention' paradigms, wherein the dependent measure is usually *accuracy* rather than *response latency*. 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 the right side; the line could be either dotted or dashed, and was oriented slightly off vertical, to either the left or the right (see Figure 2 for two examples). 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 scenes, this effect cannot be readily accounted for in terms of spatial selection (cf. Watt, 1988). Theoretically, the idea is that attention can more readily span multiple aspects of a single object, compared to multiple aspects of different objects.

This same-object advantage in dividing attention has also been replicated many times, using several different types of 'objects' (e.g. Duncan & Nimmo-Smith, 1996; Kramer et al., 1997; Valdes-Sosa et al., 1998; Vecera & Farah, 1994). When viewing stimuli such as the crossing dashed lines, for example, observers can more readily report two targets (either gaps or shorter dashes) when they appear in the same line (Figure 3a) rather than in different lines (Figure 3b; Lavie & Driver, 1996). Similar effects hold when the 'objects' must be completed behind static occluders: observers can more readily report whether two sets of 'bumps' have the same cardinality when both sets are located on the same object (Figure 3c) rather than on different objects (Figure 3d; Behrmann et al., 1998; see also Moore et al., 1998). More recent studies have also noted that this last effect also holds for the individual parts of more complex objects (Barenholtz & Feldman, 2003; Vecera et al, 2000; Vecera et al., 2001).

While both the spatial-cueing and divided-attention paradigms provide strong evidence for an effect of scene structure on the flow of attention, the 'objects' employed in both of these paradigms (and most others) 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 pre-existing 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? In many cases this circularity may seem to be weakened by using the term 'object-based' simply to refer to *any* effect of visual structure, beyond purely spatial processing. At best, however, such uses still lead to confusion as to whether such effects really depend on our common-sense notion of what it means to be an *object* — since there are clearly many types of visual structure which are not objects in the fullest sense of the term.

To escape such problems, a more rigorous and lower-level notion of 'object' is required. Thus, in the current study we employ the standard OBA paradigms (both spatial-cueing and divided-attention) to explore how attention spreads through simpler stimuli wherein structure is determined by the distribution of orientation elements in static ODTs.[2] Such stimuli are in many ways simpler than the intuitive 'objects' of previous studies, and their 'objecthood' stems from much better understood processes of lower-level visual segmentation.

1.2 Objects and Orientation-Based Texture Segmentation

The interpretation of visual stimuli in terms of objects is intimately related to the process of visual *segmentation*, whose outcome is the formation of boundaries between perceptually coherent regions, and thus the emergence of objects in the visual field (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. Such a perspective not only replaces the intuitive notion of 'object' with the simpler and perhaps better understood concept of 'elementary visual feature' (on which segmentation depends), but it is also backed by the numerous studies and extensive work in the segmentation literature. Consequently, by viewing

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that orientation and parallelism were the only available cues to guide attention. Because our results consistently conflicted with those of Avrahami's experiments, we defer a discussion of this important study until the General Discussion.

[2] It has recently been argued that the results of many divided attention studies are due to the fact that automatic attentional spread has a greater area to fill with two objects than with one object, and that no same object advantages are observed when this confound is removed (e.g. Davis, Driver, Pavani, & Shepard, 2000). The details of this interpretation still implicate object-based attention, but the mechanism responsible is seen to be automatic spread of attention, as in the spatial cueing studies. For our purposes this difference will not matter, since either interpretation implicates an effect of image structure on the flow of attention.

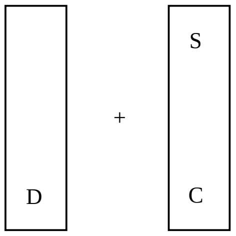


Figure 1: Example of the ’two-rectangles’ display introduced by Egly et al. (1994). ’C’ indicates a possible cued location, ’S’ indicates the corresponding same-object target location, and ’D’ indicates the corresponding different-object target location. See text for details.

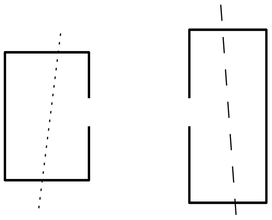


Figure 2: Sample displays from Duncan (1984). Each stimulus has four degrees of freedom: the line can be either dashed or dotted and can be tilted to the right or left, and the box can be either tall or short and have a right gap or left gap. Subjects are better at reporting two features from a single object compared to two features from two different objects.

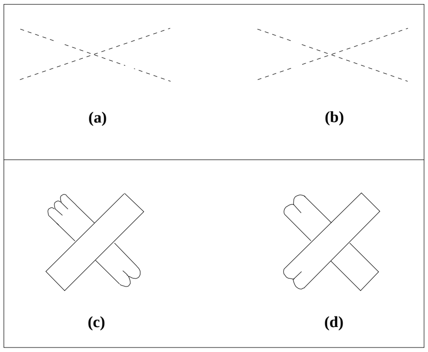


Figure 3: **(a) & (b)** Sample displays from Lavie and Driver (1996), wherein subjects could more readily respond to two probes which occurring on the same line (a), compared to probes which occurred on different lines (b). **(c) & (d)** Sample displays from Behrmann et al. (1998), wherein observers could more readily determine whether two sets of ’bumps’ had the same cardinality when they occurred on the same amodally completed object (c) than on different objects (d).

objects in terms of segmentation we can link this body of research directly to the study of OBA.

One reasonably well-understood domain for such a project is that of *texture segmentation*, in which the ability to effortlessly segregate texture stimuli into discrete coherent regions has long been attributed to changes in the spatial distribution of elementary features, sometimes called *textons* (Julesz, 1981, 1986). One such texton that has been studied extensively is that of *orientation*, and indeed orientation-defined textures (ODTs) are frequent in natural and artificial visual stimuli (see Figure 4). Though textures are rarely characterized solely by orientation, an understanding of the effect of orientation on texture segmentation 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 segmented into multiple coherent regions ('objects') has been studied extensively for at least two decades and from at least two main perspectives. Filter-based approaches (e.g. Landy & Bergen, 1991; Malik & Perona, 1990) use the orientation content of ODTs to compute scalar energies from which segmentation is derived through nonlinear 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 (Figure 5) — 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 segmentation accuracy reveal that reliable segmentation occurs if and only if the ratio of these two gradients (between/within) is significantly larger than 1.

Recently it has also been argued that orientation gradients cannot fully explain OBTS, either psychophysically or formally. While the gradients may describe ODT changes in a global coordinate system, an object-centered geometrical examination of these structures reveals two curvatures (Ben-Shahar & Zucker, 2003), whose discontinuities predict OBTS phenomena that orientation gradients alone cannot explain (Ben-Shahar & Zucker, 2002, in press). These results also predict extrinsic configural observations which relate OBTS performance to the relationship between the perceptual boundary and the orientation texels (oriented texture-elements) in its proximity (Nothdurft, 1992; Olsen & Attneave, 1970; Wolfson & Landy, 1995). (This work on the role of curvature in OBTS is introduced in greater detail in Section 6.1.)

1.3 Bridging the Gap: Object-Based Attention With Orientation-Defined Textures

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 opportunities to examine and further support ideas in the segmentation literature. It is our goal in this paper to join, for the first time, these two communities in 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 ODT in Figure 6. Such a stimulus clearly is segmented into two separate coherent regions. Indeed, theories of OBTS suggest that the distribution of orientation texels in such a display should give rise to a perceptual boundary, and thus to the emergence of two coherent 'objects'. This display is typical of the stimuli we explore here with the spatial-cueing and divided attention methods discussed in the previous section.

Below we report six experiments which explore how the flow of attention is influenced by the structure of orientation-defined textures. Experiment 1 uses the spatial cueing paradigm to examine the spread of attention in both uniform and discontinuous ODTs, in order to test for effects of both the texture's main direction (with vs. against the 'grain' of the texture) and the role of orientation discontinuities. Experiment 2 repeats the same study using a divided attention paradigm. To our knowledge, these are the first studies to explore same-object advantages using identical stimuli in both the spatial-cueing and divided attention paradigms. Such replication provides converging evidence from different experimental designs — and, indeed, from different types of dependent measures (RT and accuracy) — but it also allows us to compare the relative sensitivity of these two paradigms across studies. (As we shall see, the divided-attention paradigm yields results which are consistently more robust in several ways.)

Experiments 1 and 2 use regular ODT stimuli and were designed this way in order to approximate previous related work (Avrahami, 1999). However, such stimuli raise the possibility that an effect due to ODT discontinuities could be driven purely by local colinearity of the orientation texels and the perfect good continuation between them. To control for this possibility and to examine whether such effects can be driven only by underlying *global* orientation structure, Experiments 3 and 4 repeat Experiments 1 and 2 with a different set of stimuli, wherein all

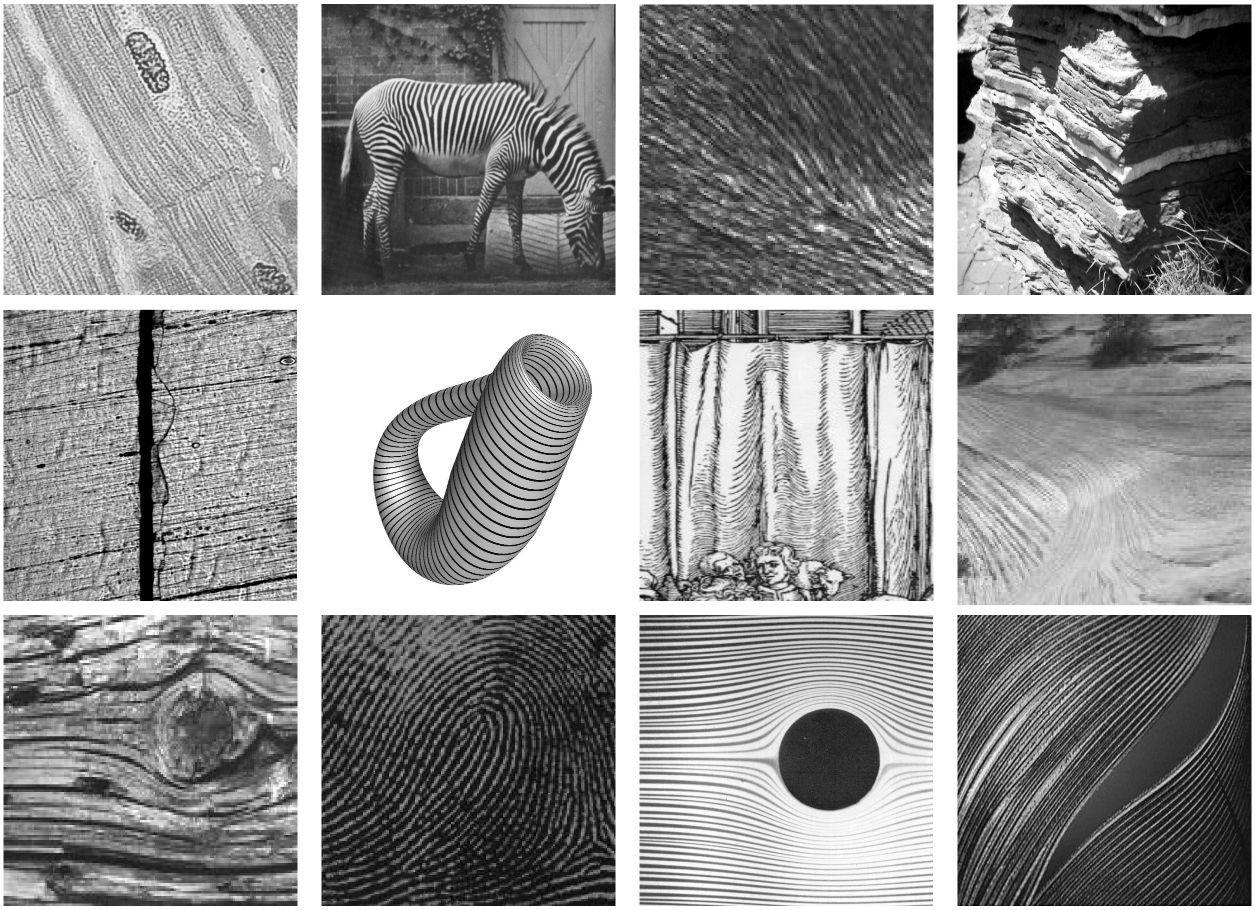


Figure 4: Examples of natural and synthetic ODTs. In nature, these patterns are a result of diverse processes such as the morphogenesis of biological tissue, pigmentation on animals' skin, growth of hair, and even geological processes. In artifacts they are especially common in technical drawings and the visual arts.

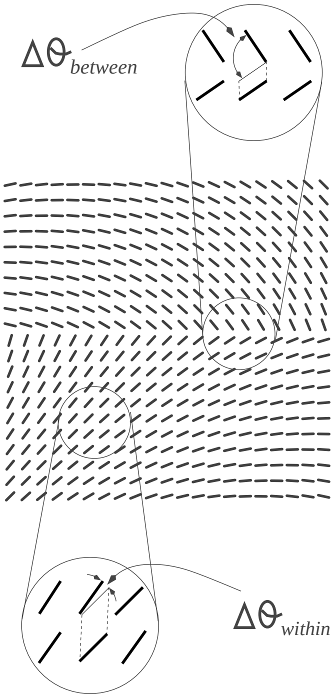


Figure 5: Current models of OBTS suggests that two orientation gradients are involved in the process - one that describes the orientation contrast between coherent regions ($\Delta\theta_{Between}$) and another that relates to changes within coherent regions ($\Delta\theta_{Within}$). Varying both parameters and checking accuracy of segmentation reveals that reliable segmentation occurs only when the ratio of the two gradients is sufficiently larger than 1.

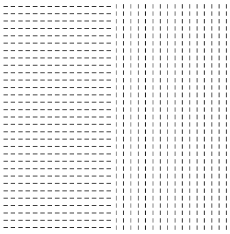


Figure 6: An example of an ODT with two perceptually coherent regions ('objects'). Here we define our stimuli in terms of the rigorous and relatively well-understood process of low-level segmentation, in contrast to the more intuitive and informal 'objects' used in most OBA studies.

texels are jittered to prevent grouping due to good continuation.

The first four experiments concentrate on both continuous ODTs and on those with orientation discontinuities. Recent findings in the segmentation literature, however, suggest that *curvature* discontinuities also have an effect on OBTS (Ben-Shahar & Zucker, 2002, in press). Thus, Experiments 5 and 6 explore the spread of attention in stimuli which are continuous in orientation (almost everywhere) but not in curvature. These studies demonstrate the subtlety of the structural cues which can influence the spread of attention, and they provide new type of evidence for the importance of curvature discontinuities in ODTs.

In general, we view these studies as symbiotic for both the OBA and OBTS research programs. From the perspective of OBTS, we are exploiting the methods of OBA in order to generate new types of evidence for the importance and consequences of subtle forms of texture segregation. From the perspective of OBA, we are exploiting the rigorous nature of the stimuli and theories used in OBTS studies in order better understand the interplay between attention and simpler visual features, and how attentional 'objects' are built from simpler visual features.

2. EXPERIMENT 1:

ATTENDING TO SIMPLE STATIC TEXTURE FLOWS IN A DETECTION TASK

In our initial studies we employ what are in many ways the simplest possible ODTs: regular fields of uniformly oriented texels (as in Figure 7a) and juxtapositions of two such fields of orthogonal orientations, with each half appearing on a separate side of the display (as in Figure 7b). We adapt the spatial cueing task (see Section 1.1) for use with these stimuli as follows (see Figure 8). Each trial begins with the appearance of the ODT followed shortly by the brief appearance of a salient cue (a bright-green circle). Shortly after the cue offset, the probe (a gray disc) appears, and observers must make a speeded response to indicate that they detected the probe. The cues and probes appeared on either uniform ODTs as in Figure 7a, or in discontinuous ODTs as in Figure 7b. The orientation of both the 'grain' of the texture and of the orientation discontinuity was counterbalanced across trials. The cue was equally likely to appear in any quadrant of the display. On 70% of trials, the cue was valid, and perfectly predicted the location of the probe. On 20% of trials, the cue was invalid and the probe appeared in a different location (either horizontally or vertically offset into another quadrant, but never in the opposite quadrant). The remaining 10% of trials were catch trials in which no probe appeared.

For uniform ODTs, the probe appeared in the quadrant along the same 'grain' of the texture from the cued quadrant on 50% of the invalidly-cued trials; in the remaining half, the probe appeared in the quadrant against the grain of the texture from the cued quadrant. For discontinuous ODTs, the probe appeared on the same side of the orientation-defined boundary as the cue on half the invalidly-cued trials; in the remaining half, the probe appeared across the boundary from the cued location.

Of critical interest in our studies is the relative speed of probe detection between the two classes of invalidly-cued trials for both uniform and discontinuous ODTs. For the uniform ODTs, this comparison tests whether the flow of attention is influenced by the 'grain' of the texture. Faster responses to invalid probes appearing along the same grain, compared to invalid probes appearing 'against the grain', would indicate that such structure can guide the flow of attention, even without inducing any segmentation. For the discontinuous ODTs, the comparison between the two types of invalid trials will determine whether simple orientation-defined texture boundaries can segment the display into two separate 'objects', from the perspective of attention. Slowed responses when the cue and probe span such a boundary would indicate that the two halves of the ODT are indeed treated as separate objects; a null effect would indicate that such segmentation cues are not sufficient to drive truly 'object'-based attention.

2.1 Method

Participants. Twenty-six naive members of the Yale University community 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.

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

The ODTs were presented as black texels on a white square background which subtended 28.1 deg. Each texel was .7 deg long and .1 deg wide. Texels in uniform ODTs all shared the same orientation, and were organized into perfectly parallel rows and

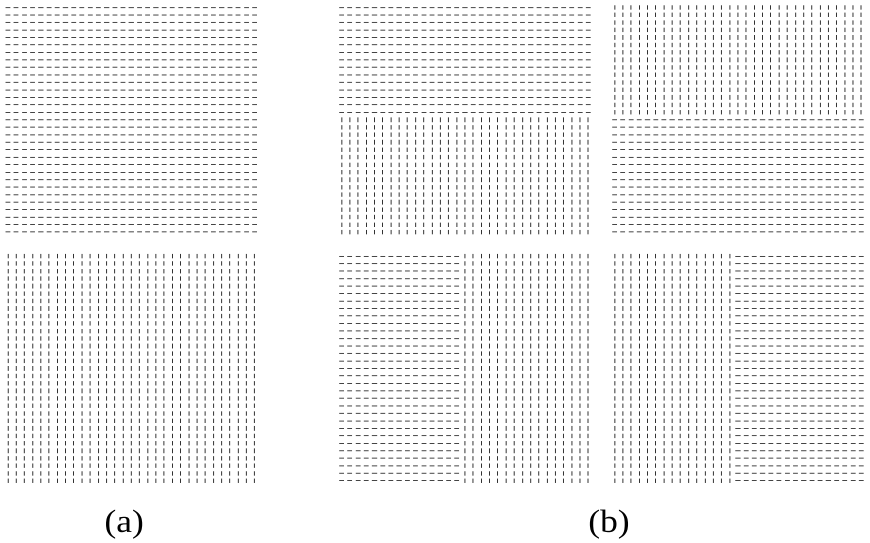

(a) (b)

Figure 7: The six ODTs used in Experiment 1, with perfectly regular (non-jittered) grids of texels employed in both horizontal and vertically oriented uniform ODTs (a) and in various combinations of discontinuous ODTs (b).

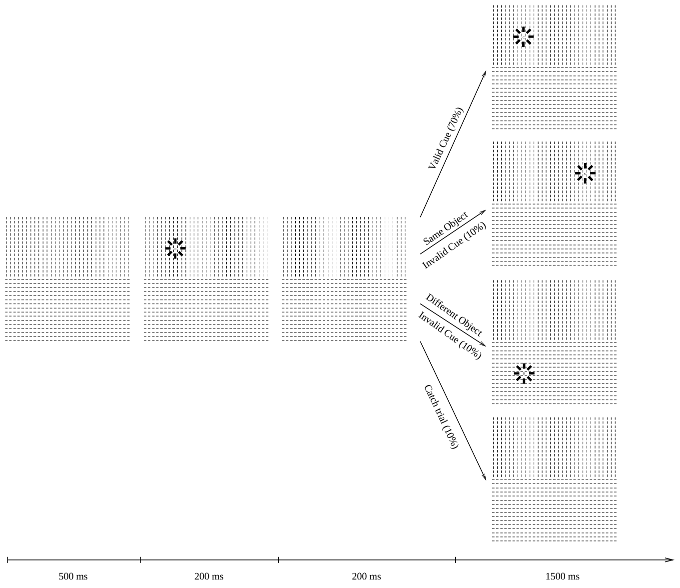


Figure 8: The spatial cueing task used in Experiment 1. Each trial begins with the appearance of the ODT (500 ms) followed shortly by the brief appearance of a salient cue (200 ms). Shortly after the cue offset (200 ms), the probe appears, and observers must make a speeded response to indicate that they detected the probe. Trials terminated after 1500 ms if not response was made. The four potential cue and probe locations - centered in each quadrant of the display - are indicated with large asterisks, but in the actual experiments these were small discs which did not overlap any of the texels (see text for details).

columns. Each texel was separated from its nearest neighbor by .35 deg along the 'grain' of the uniform ODT, and by .9 deg against the grain. In discontinuous ODTs the square background was divided in half along either the horizontal or vertical axis; one half of this display contained vertically oriented texels, the other half horizontally-oriented texels. The individual texel positions were always computed such that this boundary never interrupted any individual texels.

Cues were presented as bright green circles subtending .4 deg (drawn as a single .15-deg-thick outline, containing an empty central region). Probes were presented as light gray filled-circles subtending .4 deg. Cues and probes could appear in the center of each quadrant of the display; thus the cue and probe could each appear in one of the same four possible locations on each trial, regardless of which ODT was presented. The positions of the texels, cues, and probes were computed such that the cues and probes never overlapped any individual texels.

Procedure. A single trial proceeded as follows (see Figure 8). Observers initiated the trial by pressing a key, which blanked the screen. After 500 ms, the ODT appeared and remained until the end of the trial. One second after the ODT onset, the cue appeared for 200 ms. 200 ms after the cue offset, the probe appeared for 200 ms, after which the ODT remained until the subject responded or the trial timed out. Subjects were instructed simply to press a designated key on the keyboard as quickly as possible when they detected the probe; they were to withhold a response when no probe appeared. After a maximum response window of 1500 ms the trial terminated without a response.

Design. Each subject completed 480 trials in a different randomized order. Eighty trials of each of six types were presented (unblocked and fully randomized): the two type of uniform ODTs (depicted in Figure 7a) and the 4 types of discontinuous ODTs (varying the orientation of both the boundary and texture 'grain', as depicted in Figure 7b).

Of the 80 trials in each trial type: (a) 8 (10%) were catch trials in which no probe appeared; (b) 56 (70%) were valid-cue trials in which the probe appeared at the cued location; (c) 8 (10%) were 'same-object' invalid-cue trials in which the probe appeared in the adjacent quadrant along the grain of the texture (for uniform ODTs) or on the same side of the boundary (for discontinuous ODTs); and (d) 8 (10%) were 'different-object' invalid-cue trials in which the probe appeared in the adjacent quadrant against the grain of the texture (for uniform ODTs) or across the boundary (for discontinuous ODTs). Within each of these subdivisions, the cue appeared equally often in each quadrant, 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

Each subject's accuracy and response latency (measured from the onset of the probe) was recorded for each trial. Overall, subjects had very few errors, with a mean false-alarm rate of 1.3% and a miss rate of 1.4%. As expected, there was an overall cue-validity effect: RTs on validly-cued trials (mean: 336.41 ms) were faster than on invalidly cued trials (710.92 ms; $t(25) = 13.06$, $p < .01$). Of primary interest were the RTs on the different types of invalidly cued trials. Figure 9 depicts these mean response latencies broken down by condition. For uniform ODTs, there was no reliable difference between RTs for 'with-the-grain' trials (704.28 ms) and 'against-the-grain' trials (729.42 ms; $t(25) = 1.07$, $p = .30$). For discontinuous ODTs, in contrast, RTs were reliably faster when the cue and probe appeared on the same side of the boundary (685.34 ms), compared to when the cue and probe spanned the boundary (724.65 ms; $t(25) = 2.22$, $p = .04$).

2.2.1 Cue-Probe Alignment Effects. We also analyzed the invalid-cue RT data when broken down by overall cue/probe orientation. RTs were faster when the cue and probe were horizontally aligned relative to each other (636.44 ms) than when they were vertically aligned (773.55 ms; $t(25) = 5.07$, $p < .01$). In uniform ODTs, this 'horizontal advantage' was true whether the cue and probe appeared along the grain of the texture ($t(25) = 4.34$, $p < .01$) or not ($t(25) = 4.64$, $p < .01$). Similarly, in discontinuous ODTs this horizontal advantage was true whether the cue and probe spanned the boundary ($t(25) = 3.93$, $p < .01$) or not ($t(25) = 4.85$, $p = < .01$). In general, this horizontal advantage acted independently of the 'same-object advantage': when both factors were combined into the a 2x2 repeated-measures ANOVA, both main effects were reliable (orientation: $F(25) = 25.72$, $p < .01$; same vs. different object: $F(25) = 4.91$, $p = .04$), but their interaction was not ($F(1, 25) = .31$, $p = .58$). Additional planned comparisons confirmed that there was no effect of texture 'grain' in the uniform ODTs for either cue/probe orientation (horizontal: $t(25) = .40$, $p = .40$; vertical: $t(25) = 1.28$, $p = .21$), and that there was a reliable effect of boundary in the discontinuous ODTs for the horizontal cue/probe orientation ($t(25) = 2.11$, $p = .04$) but not for the vertical orientation ($t(25) = 1.22$, $p = .23$). In fact, we

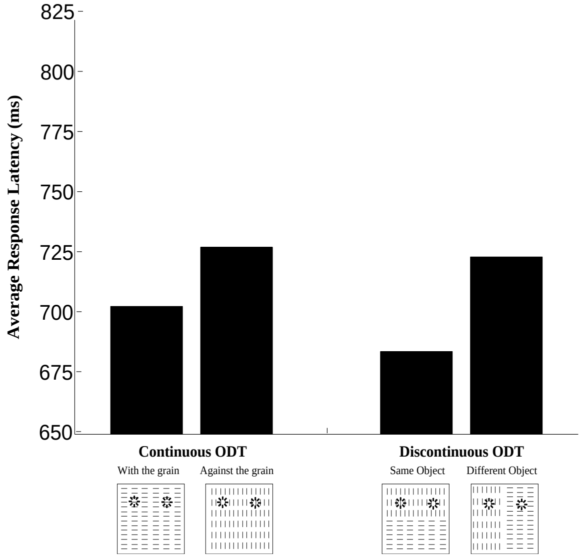


Figure 9: Mean response latencies in Experiment 1 broken down by condition.

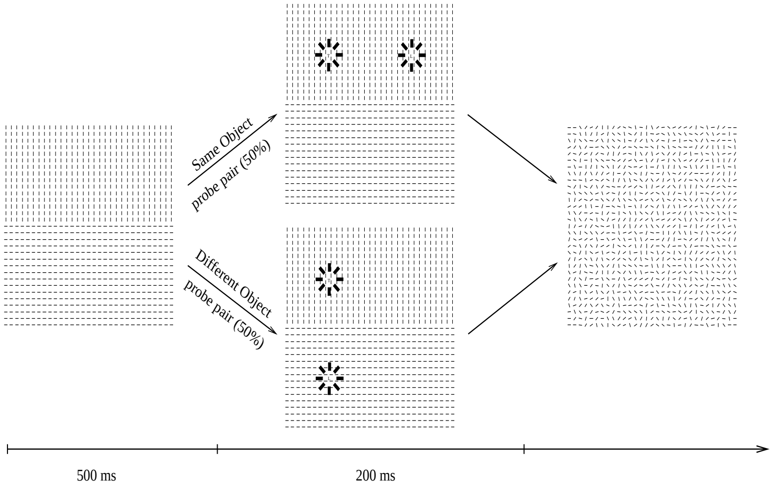


Figure 10: The divided-attention task used in Experiment 2. Each trial began with the appearance of the ODT (500 ms) followed shortly by the brief appearance of the probe pair (200 ms) and then a mask. Observers reported whether the two probes (block Ts and Ls) were identical or not. The four probe locations - centered in each quadrant of the display - 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).

found a similar 'horizontal advantage' throughout our experiments — replicating across multiple paradigms and dependent measures — and despite its ecological validity, its origin remains unclear. (In particular, this result seems intuitively inconsistent with the observation that horizontal — but not vertical — spread is likely to involve processing in both hemispheres.) Because this global orientation factor was fully counterbalanced with our same/different object manipulation, however, it never affected the comparisons of theoretical interest. Thus, in future experiments we do not report these comparisons broken down by orientation, except to note that they also followed this pattern.

2.3 Discussion

This initial experiment yielded two primary conclusions, both of which have important theoretical implications for the nature of object-based attention. First, OBTS in discontinuous ODTs (as in Figure 7b) appears to be sufficient for dividing the display into different attentional 'objects': on invalidly-cued trials in such displays (at least when the boundaries are vertically oriented, such that attention flows horizontally), attention flowed less readily when it had to cross the texture-defined boundary (from the cue to the probe), than when both the cue and probe were located on the same side of the boundary. This implies that 'object'-based attention does not require the full-fledged 'objects' of our intuitive concepts: even in a simple static ODT, an orientation-defined discontinuity influences the flow of attention. In other words, 'objects' of attention can be formed by manipulations of basic visual features and linked directly to the low-level visual process of segmentation.

The second critical result of this first experiment involved the uniform ODTs. Despite the fact that the segmentation which resulted from the discontinuous ODTs was defined only by an orientation difference in the 'grain' of the texture, that grain itself had *no effect* when there was no segmentation cue (as in Figure 7a): response times to invalidly-cued trials were no faster when attention had to flow 'with' the grain of the texture (from the cue to the probe), compared to when attention had to flow 'against' the grain of the texture. This (perhaps surprising) result is important on several levels (each of which is discussed at length in the General Discussion):

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*. *Third*, this null effect (which we replicate several times in the next few experiments) contradicts previous results in the OBA literature (Avrahami, 1999), as discussed at length in the General Discussion. *Finally*, this null effect, though perhaps intuitively surprising, is actually in agreement with feature-based models of OBTS (Landy & Bergen, 1991; Mussap & Levi, 1999; Nothdurft, 1991, 1993), which depend on orientation *gradients* rather than on texels' orientations. Further, it is also in direct agreement with recent computational models of ODTs (Ben-Shahar & Zucker, 2003), which suggest that their two main directions — the tangential (with the grain) and the normal (against the grain) — are equally significant and should not be biased relative to each other. The results of Experiment 1 imply that this "isotropic coherence" at the computational level, which has been found for OBTS, applies to the spread of attention and OBA as well.

This initial experiment already succeeds at our general goal of drawing links between the attention and segmentation literatures. We see both how the 'objects' of OBA can be built from much simpler visual features drawn from the segmentation literature (in this case, orientation), and how experimental paradigms from the OBA literature can be used to measure OBTS. The additional experiments reported below generalize these effects to other paradigms and related stimuli, and rule out several alternate explanations for the present results.

3. EXPERIMENT 2:

ATTENDING TO SIMPLE STATIC TEXTURE FLOWS IN A DIVIDED-ATTENTION TASK

In order to obtain converging evidence for the conclusions of Experiment 1, and to demonstrate their robustness across multiple tasks and dependent measures, Experiment 2 replicates Experiment 1 using the divided attention paradigm (see Section 1.1). Early pilot results suggested that the this paradigm replicates results from spatial cueing, but does so with fewer observers and with far greater reliability. We thus expected even more robust results in this experiment, and in particular we predicted that the effect of orientation-defined boundaries would exist for all orientations (whereas in Experiment 1 it was statistically significant only for vertically-oriented boundaries).

Using the identical set of stimuli as in Experiment 1 (see Figure 7), each trial began with the appearance of the ODT followed shortly by the brief appearance of a probe pair and then a mask (consisting of an ODT of random orientation texels). See Figure 10 for a depiction of this task. Each probe in the pair could be one of two predefined shapes (a block letter 'T' or 'L') and the observers' task was to determine whether they were identical (i.e. both Ls or both Ts) or different (one T and one L) by pressing one of two designated keys. The probes were equally likely to appear in any two adjacent quadrants, either vertically or horizontally, and as in Experiment 1, the orientation of both the 'grain' of the texture and of the discontinuity was counterbalanced across trials.

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. 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.

In all trials we measure observers' accuracy (RT was recorded by not used in the analysis). For uniform ODTs, the comparison between accuracy on with-the-grain trials vs. against-the-grant trials tests whether the flow of attention is influenced by the 'grain' of the texture. More accurate responses to probe pairs appearing along the same grain, compared to probe pairs appearing against the grain, would indicate that such structure can guide the flow of attention. For the discontinuous ODTs, the comparison between the two types of trials will determine whether simple orientation-defined texture boundaries can segment the display into two separate 'objects' of 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 truly 'object'-based attention.

3.1 Method

Participants. Sixteen naive members of the Yale University community 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.

Materials. The hardware, software, and ODTs were identical to Experiment 1. Probe pairs constituted the letters 'T' and 'L', both .47 by .47 deg in visual area, and both presented in red without overlapping any individual texels.

Procedure. A single trial proceeded as follows (see Figure 10). 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 a ODT of randomly-oriented texels until the subject responded. Subjects were instructed simply 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.

Design. Each subject completed 480 trials similar to Experiment 1 (see Section 2.1). Of the 80 trials in each trial type, 50% were 'same-object' trials in which the probe pair appeared in the adjacent quadrant along the grain of the texture (for uniform ODTs) or on the same side of the boundary (for discontinuous ODTs) and 50% were 'different-object' trials in which the probe pair appeared in the adjacent quadrant 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. Breaks between sessions and practice trials before the experiment were similar to Experiment 1.

3.2 Results

Observers' accuracy was recorded on each trial. The overall mean accuracy was 85.67%. Of primary interest were differences in accuracy as a function of the different trial types. Figure 11 depicts these mean accuracies broken down by condition. (Note that in this and other divided attention experiments, 100% of the trials can be used in the critical analyses. This stands in sharp contrast to spatial cueing studies such as Experiment 1, in which only the 20% invalid-cue trials contained the relevant information.) For uniform ODTs, there was no reliable difference between accuracy for with-the-grain trials (86.64%) and against-the-grain trials (86.41%; $t(15) = .16$, $p = .87$), and this null effect held for both horizontally-oriented comparisons (89.38% vs. 87.66%; $t(15) = .90$, $p = .38$) and for vertically-oriented comparisons (85.16% vs. 83.91%; $t(15) = .47$, $p = .65$). For discontinuous ODTs, in contrast, observers were more accurate when the probe pair appeared on the same side of the boundary (87.07%), compared to when the probe pair spanned the boundary (82.58% ; t(15) = 4.16, p < .01). This difference of roughly 5% also held for both horizontally-oriented comparisons (89.53% vs. 84.61%, $t(15) = 4.16$, $p = .01$) and vertically-oriented comparisons (84.61% vs. 80.55%, $t(15) = 2.55$, $p = .02$). There was no reliable interaction between boundary and overall orientation ($F(1, 15) = .23$, $p = .64$).

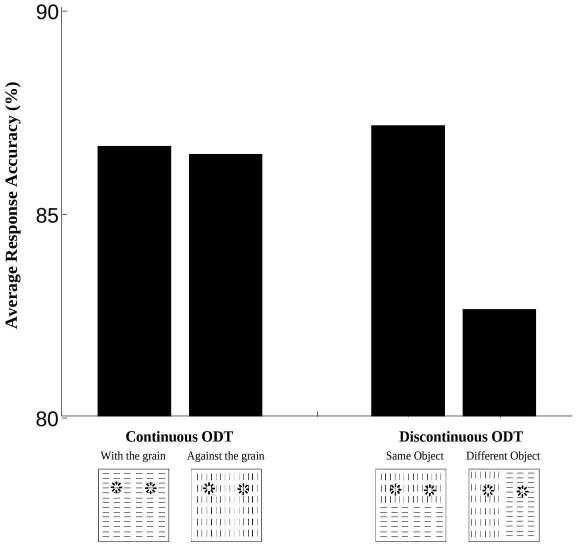
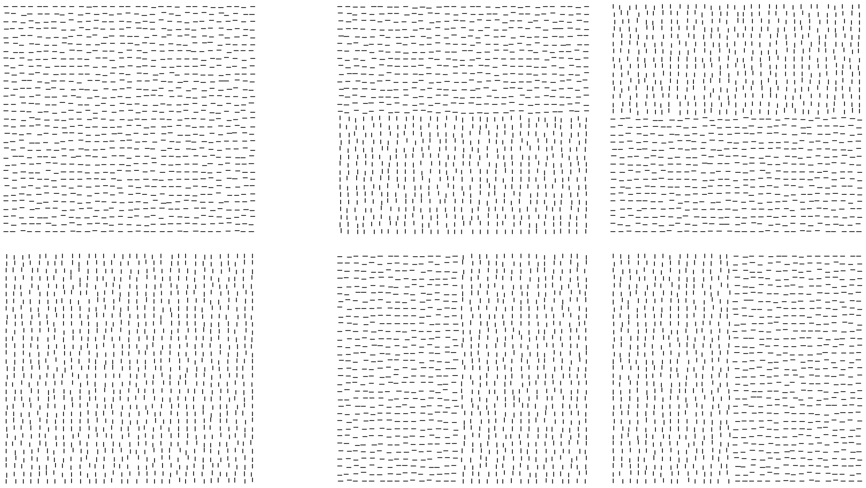


Figure 11: Mean response accuracy in Experiment 2 broken down by condition.



(a) (b)

Figure 12: The ODTs used in Experiment 3, with jittered texels to remove local good continuation cues and other grid-related artifacts.

3.3 Discussion

The results of Experiment 2 replicate and strengthen those of Experiment 1 in all ways and yield the same implications for the nature of object-based attention. This was true despite the change in task and dependent measure. Again we conclude that orientation-defined boundaries are sufficient to parse the display into different attentional objects: attention flowed less readily across such boundaries, and more readily within coherent regions, as reflected in the accuracy of observers' responses. Equally important, we again found that the grain of ODTs appears to have no direct effect itself on the spread of attention: attention flowed just as readily against the grain as with the grain. In conjunction, these two main results demonstrate a direct link between OBTS and OBA; they show how the distribution of textons, and not their absolute value, is the critical factor which influences attention; and they reinforce the null effect of Experiment 1, in contradiction to previous results in the OBA literature (Avrahami, 1999; see General Discussion), but in accord with recent computational modeling results (Ben-Shahar & Zucker, 2003).

The results of Experiment 2 not only supported those of Experiment 1, but proved ultimately even more reliable. Despite involving one third fewer observers, the p-values for the boundary effects were smaller, and the boundary effect occurred for both orientations alone, in addition to the overall effect. We thus tentatively conclude that the divided-attention paradigm is a more sensitive test of OBA than is the spatial-cueing paradigm, though both show essentially the same patterns of results. To our knowledge, this is the first direct comparison of these two popular paradigms using identical stimuli. This comparison is replicated in Experiments 3 and 4 using a different set of stimuli, and the methodological conclusion is discussed at length in the General Discussion.

4. EXPERIMENT 3:

ATTENDING TO STATIC TEXTURE FLOWS WITHOUT LOCAL CONTINUITY CUES (DETECTION TASK)

Experiments 1 and 2 provide evidence that orientation-defined boundaries in static texture flows are sufficient to parse displays into different attentional objects. These boundaries are defined in terms of orientation differences between the grains of two ODT regions, despite the fact that the grain of an ODT in uniform flows does not directly influence attention. It remains possible, however, that the boundary effects observed in Experiments 1 and 2 could be driven primarily by the local good continuation within uniform ODT regions, due to the perfectly regular structure of the displays (see Figure 7). Of most concern is that the boundary effect could be driven only by the resulting perfectly-aligned T-junction-like cues. While effects due to such good continuation and perfectly aligned structure would still be interesting, we were interested in the possibility that attention was influenced in these displays not by the perfectly regular local cues per se, but rather by the global image structure formed by the overall spatial distribution of the orientation texels.

To address this issue, Experiment 3 replicates Experiment 1 using altered displays in which the local continuity cues are eliminated by randomly jittering the positions of all texels to destroy the gridlike regularity (Figure 12). As a result, this experiment tests whether the global structure of ODTs with orientation-defined boundaries can influence the spread of attention. We test such displays using the spatial-cueing paradigm as in Experiment 1.

4.1 Method

This experiment was identical to Experiment 1, except as noted here. Twenty-three observers participated, none of whom had participated in the previous experiments. The stimuli were identical to those used in Experiment 1, except that most individual texels were randomly jittered from their original grid locations both horizontally and vertically. The only texels *not* jittered in this way were the six segments in each ODT quadrant which were in the immediate proximity of the cue/probe locations. This local lack of jitter was unobservable, and ensured that the same cue/probe locations from Experiment 1 could be used without any accidental overlap between the cue/probe and the nearby texels.

4.2 Results

Observers' response times were recorded for each trial and the results, broken down by condition, are depicted in Figure 13. As in Experiment 1, uniform ODTs induced no reliable difference between RTs for with-the-grain trials (774.15 ms) and against-the-grain trials (801.62 ms; t(22) = 1.31, p = .21). In contrast to Experiment 1, however, there was no reliable difference between RTs when the cue and probe appeared on the same side of the boundary, vs. when they spanned the boundary. Though this difference was in the predicted direction (755.88 ms vs. 769.37 ms), it did not reach significance (*t*(22) = .85, p = .41).

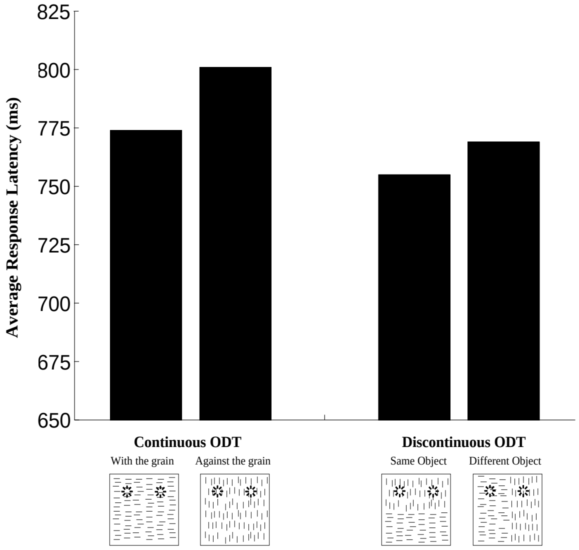


Figure 13: Mean response latencies in Experiment 3 broken down by condition.

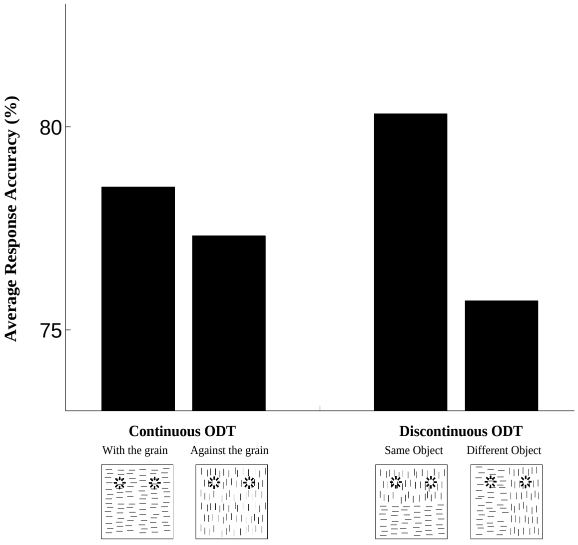


Figure 14: Mean response accuracy in Experiment 4 broken down by condition.

4.3 Discussion

As in the previous experiments we are interested in effects of both the grain of the ODT in the uniform flows, and in the effects of orientation-defined ODT boundaries. This study provided the third demonstration so far that the main direction of the ODT (with vs. against the grain) does not influence the spread of attention.[3]

In contrast to our earlier results, however, this experiment revealed no evidence for an effect of orientation-defined texture boundaries on the flow of attention. In other words, the two local ODT regions separated by this boundary did not appear to function as distinct 'objects' of attention in this experiment. This null result, in contrast to the robust effect observed in Experiments 1 and 2, could be due to the jittering of the local texels: perhaps attention is not influenced by global image structure of this type after all, and was driven instead in our earlier experiments by the perfectly regular grid structure, the resulting perfect local good continuation within regions, and the perfectly aligned T-junction-like structures at the boundary. On the other hand, this null result may simply reflect the relative insensitivity of the spatial-cueing paradigm to detect effects of global structure. Thus we regarded these results as equivocal, and we employed the divided-attention paradigm to choose between these competing interpretations.

5. EXPERIMENT 4:

ATTENDING TO STATIC TEXTURE FLOWS WITHOUT LOCAL CONTINUITY CUES (DIVIDED ATTENTION TASK)

The comparison between Experiments 1 and 2 demonstrated that, compared to the spatial cueing paradigm, the divided attention paradigm is more sensitive in several ways to the influence of ODT structure on the flow of attention. Accordingly, we employed the divided attention paradigm here with the locally jittered stimuli of Experiment 3 to test for effects of global ODT structure. If the results of this experiment replicate the null boundary effect of Experiment 3, we may conclude that the robust boundary effects in Experiments 1 and 2 do in fact require perfectly regular local good continuation, and that the global structure of static texture flows cannot by itself influence the allocation of attention. If the results of this experiment reveal a significant effect of globally-defined boundaries, however, then we will conclude that even global image structure in ODTs can influence the flow of attention, and that the null effect in Experiment 2 reflects the relative insensitivity of the spatial cueing paradigm.

5.1 Method

Eighteen observers participated, none of whom had participated in the previous experiments. This experiment was identical to Experiment 2, except that it used the locally-jittered ODTs of Experiment 3.

5.2 Results

Observers' accuracy was recorded on each trial and the results, broken down by condition, are depicted in Figure 14. There was no effect of the overall global grain of the ODT in the uniform texture flows: observers were just as accurate when the two probes were aligned against the global grain (77.29%) as when they were aligned with the grain (78.68%; $t(17) = .96$, $p = .35$). For discontinuous ODTs, in contrast, observers were more accurate when the probe pair appeared on the same side of the boundary (80.31%), compared to when the probe pair spanned the boundary (76.77% ; $t(17) = 3.65$, $p < .01$). This difference was significant for both horizontally-oriented comparisons (82.85% vs. 78.68%, $t(17) = 2.27$, $p = .04$) and vertically-oriented comparisons (77.78% vs. 74.86%; $t(17) = 2.41$, $p = .03$). There was no reliable interaction between boundary and overall orientation ($F(1, 17) = .26$, $p = .62$).

5.3 Discussion

Unlike the spatial cueing test in Experiment 3, this experiment yielded a robust effect of orientation-defined boundaries between ODT regions. (We also observed our fourth demonstration in this study of the *lack* of any direct effect of the ODT's main direction in uniform flows.) Because the local regularity and local good continuation was absent in the ODTs employed here (as in Experiment 3), we conclude that attention can be influenced not only by local image cues in texture flows, but also by segmentation defined by global image structure.

These results, when contrasted with those of Experiment 3, provide an especially strong demonstration that the divided attention paradigm is a more sensitive test of OBA effects than is the spatial cueing paradigm. We observed this pattern in Experiments 1 and 2, where the contrast was only quantitative. Here, however, we see how the choice

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[3] Note that the null effect of the overall grain of the ODT in this experiment replicated our earlier results, but that in a way it is a weaker test. In this experiment, the grain was defined only by the global structure of the ODT, given the locally jittered texels. In contrast, Experiment 1 had a perceptually salient grain defined by *both* global structure and perfect local good continuity. Thus we might expect any effect of the overall grain to be even stronger in Experiment 1 — which nevertheless did not exhibit such an effect either.

of paradigm can radically affect one's conclusions, since we observed boundary effects with the divided attention paradigm which were not even close to significant with spatial cueing (even though we again used fewer subjects for the divided-attention test). We draw the general lesson, as explored in the General Discussion, that OBA researchers should use the divided-attention paradigm rather than spatial cueing for all but the most robust of effects. More proximally, we now abandon spatial cueing for the remainder of the present study; the final two experiments presented below both employ the divided-attention paradigm.

6. EXPERIMENT 5:

THE FLOW OF ATTENTION ACROSS TANGENTIAL-CURVATURE-DEFINED BOUNDARIES

The previous four experiments provide evidence that discontinuities in ODTs affect the flow of attention and the division of the visual field into attentional 'objects'. This implies that OBTS and OBA may be intimately coupled and that attention flows more readily within coherent ODT regions than between them. The definition of *within* and *between* in these earlier experiments, however, was defined in especially direct terms — by large orientation gradients, or orientation discontinuities, between *constant* ODTs. 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 this link symmetric by using OBA effects as a new type of evidence with which to test more contemporary ideas about OBTS. Experiments 5 and 6 do exactly this for the recently proposed role of ODT *curvatures* in OBTS (Ben-Shahar & Zucker, 2002, in press).

6.1 The Roles of Orientation and Curvature in Defining Structure in Static Texture Flows

Orientation-defined textures 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 (see Figure 4). Since these dense structures are defined by local 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 $\theta(x,y)$.

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; Landy & Bergen, 1991; Li, 1998; Motoyoshi & Nishida, 2001; Nothdurft, 1985; Regan et al., 1996; Wolfson & Landy, 1995, 1998), such 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 $\theta(x,y)$ — i.e., by the vector $\nabla\theta(x,y)$. 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 scalar form (as opposed to a vectorial one). As we have mentioned in the Introduction (see Figure 5), OBTS was found in these cases to depend on the relationship between *two* orientation gradients — one for the change in orientation *between* coherent regions ($\Delta\theta_{\text{between}}$) and the other for change in orientation *within* regions ($\Delta\theta_{\text{within}}$). Varying these two parameters and exploring segmentation accuracy reveals that reliable segmentation occurs if and only if the ratio of these two gradients (between/within) is significantly larger than 1.

However, Ben-Shahar and Zucker (2002, in press) recently argued 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* — which emerge from the *covariant derivatives* of the frame (Figure 15). The tangential curvature describes the rate of change in ODT orientation in the direction tangential to the ODT's orientation (i.e. the direction 'with the grain'), while the normal curvature does so in the normal direction (i.e. the direction 'against the grain'). Together, these two curvatures provide a complete description of the local variations in ODT orientation — and unlike $\nabla\theta(x,y)$, they do so *intrinsically*, independent of a global reference frame.

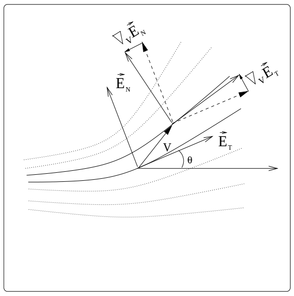

Figure 15: Representing ODTs with frame fields captures their intrinsic geometry and gives rise to two ODT curvatures. Ben-Shahar and Zucker (2003) attached a natural (tangent and normal) orthonormal frame to each point of the ODT and used it as a basis to represent the covariant derivative ∇_V of the pattern. The covariant derivative vector quantifies the initial amount of rotation the ODT undergoes as we translate point q in the direction V. Describing this vector in the frame $\{E_T, E_N\}$ yields two ODT scalars at each point, a tangential curvature κ_T and a normal curvature κ_N.

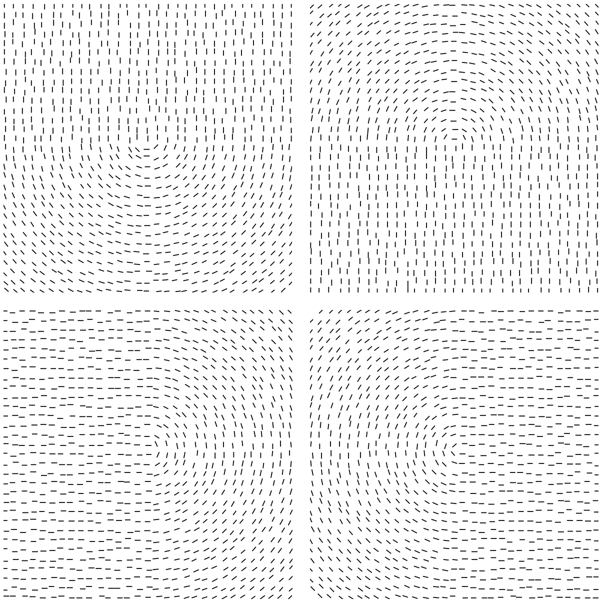

Figure 16: The stimuli used in Experiment 5, employing discontinuity in tangential curvature and constant zero normal curvature.

A key finding in these studies (Ben-Shahar & Zucker, 2002, in press) 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). Accordingly, we sought in this experiment to examine the influence of discontinuities in ODT *curvatures* on the flow 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] We test for possible attentional effects of each type of curvature separately: this experiment tests ODTs with discontinuities only in tangential curvature, and Experiment 6 tests ODTs with discontinuities only in normal curvature. These experiments share the same goal: to test whether either curvature discontinuity divides the visual field into attentional 'objects'. Such a finding would 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.

This experiment thus tests for effects on attention of boundaries defined by changes solely in tangential curvature (Figure 16). Relative to our previous experiments, we limited this experiment in three ways: First, we employed only the divided attention paradigm, since it was shown in our earlier experiments to be more sensitive than spatial cueing. Second, we tested only discontinuous ODTs, since the previous four experiments all demonstrated that attention is not influenced by the main direction of ODTs in uniform flows. Finally, because we discovered in Experiment 4 that the divided attention paradigm is sensitive enough to reveal effects of global structure, we used only jittered (as opposed to regular) local texels. In contrast to the stimuli used in Experiments 1 and 2, which represented perhaps the most obvious case of orientation-defined boundaries, the stimuli here (and in Experiment 6) represent the other extreme, wherein boundaries are formed from especially subtle changes in the distribution of orientation texels.

6.2 Method

This experiment was identical to Experiment 4 except as noted here.

Participants. Thirteen observers participated, none of whom had participated in the previous experiments.

Materials and Task. All stimuli were constructed as jittered ODTs as explained in Experiment 3. Each ODT had two rectangular regions, one with both curvatures identically zero, 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, the two regions met continuously in terms of orientation, along a vertical or horizontal line, as is illustrated in Figure 16.[5]

Due to the variation in orientation in these stimuli, the probes that we used in Experiments 2 and 4 (the block letters 'T' and 'L') were now prone to group with nearby texels in undesired ways. Hence we replaced them in this experiment with small outlined circles (drawn with a stroke of .2 deg), whose curvature made them unlikely to group with the adjacent linear texels. Each of the two circular-probes on each trial had a 30 deg gap in its contour facing either right or left (the choice being random), and the subjects' task was to press one of two keys on each trial to indicate whether the two gaps were facing the same direction or facing opposite directions.

Design. Each subject completed 320 trials. Discontinuity orientation (horizontal and vertical), relative probe-pair orientation (same vs. different gap direction), and same vs. different 'object' conditions were fully counterbalanced as in Experiments 2 and 4.

6.3 Results

Observers' accuracy was recorded on each trial and the results, broken down by condition, are depicted in the left half of Figure 17. Performance was reliably better when the probe pair appeared in the same ODT region (74.33%) than when the probe pair spanned the curvature boundary (71.11%; $t(12) = 2.39$, $p = .03$).

6.4 Discussion

Experiments 1 through 4 revealed that the flow of attention through static ODTs is influenced by

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[4] In contrast, recall that the stimuli of Experiments 1 through 4 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.

[5] Note that ODTs which are continuous in orientation and discontinuous in tangential curvature must have such a singularity, and that it must be located within the visible area of the ODT in order to maximize 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.

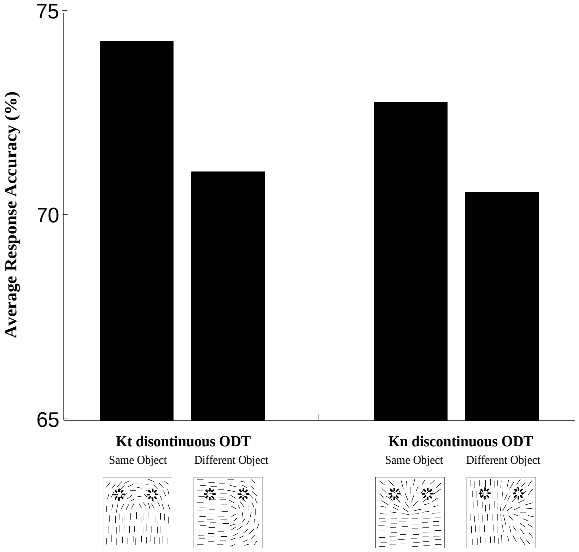

Figure 17: Mean response accuracy in Experiments 5 and 6, broken down by condition.

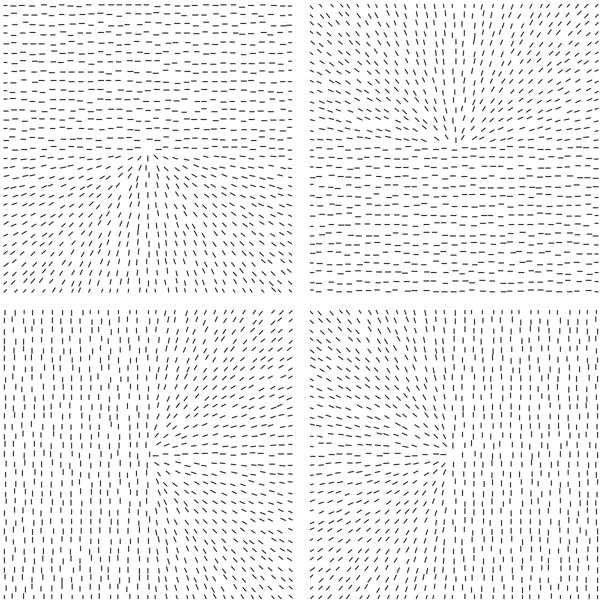

Figure 18: The stimuli used in Experiment 6, employing discontinuity in normal curvature and constant zero tangential curvature.

orientation-defined boundaries. This experiment 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 four experiments are best seen in terms of the research in OBTS informing research on OBA, by grounding attentional 'objects' in more rigorously understood units of segmentation. In contrast, this experiment tested a form of texture segmentation which has only very recently been employed in the OBTS literature. As such, this experiment can be interpreted not 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. We thus conclude that these results provide new evidence (and a new *type* of evidence!) in support of the importance of curvature in OBTS (Ben-Shahar & Zucker, 2002, in press). This illustrates the utility of attention-based paradigms in the study of image structure.

7. EXPERIMENT 6:

THE FLOW OF ATTENTION ACROSS NORMAL-CURVATURE-DEFINED BOUNDARIES

In the frame field theory of Ben-Shahar and Zucker (2002, in press), changes in tangential and normal curvature are equally important for driving OBTS. Because of this, it is important to test for effects of each type of curvature independently, and this experiment tests for effects of boundaries defined in terms of normal curvature (as in Figure 18), whereas the previous experiment demonstrated an effect of tangential curvature.

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. Intuitively, one would predict that changes in curvature 'against the grain' would result in either minimal or nonexistent 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. Indeed, Experiments 1 - 4 clearly demonstrated this for the 'grain' of ODTs. Thus, we cannot comfortably assume that less salient image structure will not influence attention. Moreover, the importance of normal curvature has been established formally (Ben-Shahar & Zucker, 2003), (b) its effect on OBTS has been argued psychophysically (Ben-Shahar & Zucker, 2002, in press), and (c) changes in normal curvature can be found in natural visual situations, even without changes in orientation (Figure 19). For all of these reasons, we test here whether such configurations can also influence the flow of attention, again using the divided attention paradigm.

7.1 Method

This experiment was identical to Experiment 6 except as noted here. Twenty-four 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 (see Figure 18).

7.2 Results

Observers' accuracy was recorded on each trial and the results, broken down by condition, are depicted in the right half of Figure 17. Performance was marginally better when the probe pair appeared in the same ODT region (72.81%) than when the probe pair spanned the curvature boundary (70.65%; $t(23) = 1.92$, $p = .06$).[6]

7.3 Discussion

The results of this experiment provide further support for the recent idea that curvature is important in OBTS (Ben-Shahar & Zucker, 2002, in press), and does so using ODT boundaries which are defined in what is perhaps a less intuitive type of curvature discontinuity (normal, in contrast to the tangential curvature studied in Experiment 6). In a sense, this result is complementary ot the null effects obtained with uniform ODTs in Experiments 1 - 4: seemingly salient image structure can fail to influence attention, while subtle images structure does yield reliable effects.

Looked at from the perspective of OBA, these results constitute the strongest demonstration yet that the flow of attention can be constrained by global image boundaries formed by especially subtle types of variations in the distributions of the orientation texton, in static ODTs. The results of Experiments 5 and 6, taken together, are especially important in this regard, since they comprise one of

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[6] This marginal effect becomes more robust — 73.15% vs. 70.54%: $t(23) = 2.42$, $p = .02$ — when we remove a single outlying subject, whose same-object accuracy was the lowest of all 24 observers. However, throughout this paper we have avoided trimming the data in this fashion.

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 (see Figure 4).

8. GENERAL DISCUSSION

The overarching goal of this study has been to join two largely distinct research programs: object-based attention, and orientation-based texture segmentation. We have done so in this paper for the orientation texton — one of the most salient features of early vision — with two symmetric 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 segmentation processes can *directly* influence many aspects of visual processing (such as attention) even without further elaborated 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 segmentation cues in static ODTs yield distinct attentional objects, even in the absence of other common cues to objecthood such as closure and continuous unbroken contours, and even when such cues exist only in the global structure of the ODTs, without local good continuation. Subjects were slower and less accurate at making various visual judgments when the relevant information spanned an orientation-defined texture boundary (as in Figures 7b and 12b), compared to when the information appeared within a single ODT region.

Second, we found that the flow of attention in ODTs is influenced by the overall *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. Despite this, the overall grain of a texture region had no *direct* effect: attention flowed no more readily with the grain than against the grain in uniform ODTs (as in Figures 7a and 12a). This null effect was especially well supported in our studies, since it was replicated in four separate experiments, across multiple tasks and dependent measures, and in 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, and since such segmentation constitutes an especially subtle (and arguably less salient) form of global segmentation which can be formed by distributions of the orientation texton.

In the remainder of this paper we briefly stress the importance and implications of these results for our understanding of what it means to be an 'object' of attention (Section 8.1), for the relative efficacy of different OBA paradigms (Section 8.2), for the interpretation of previous conflicting results in the OBA literature (Section 8.3), and for the status of OBTS theories and models themselves (Section 8.4).

8.1 The Units of Attention and the Foundations of OBA

The research program of object-based attention has been 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 nonsolid substances (vanMarle & Scholl, in press). 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 have studied the roles of closure (Avrahami, 1999; Marino & Scholl, under review), curvature minima (Barenholtz & Feldman, 2003; Singh & Scholl, 2000; Watson & Kramer, 1999), and connectedness (Scholl, Pylyshyn, & Feldman, 2001; Watson & Kramer, 1999).[7]

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

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[7] See also Feldman (2002, 2003), who has suggested an abstract way of thinking about the role of all of these image cues, as well as a formal means of combining them based on hierarchical lattice models.

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 Figure 6, 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 et al., 1995). Still, our studies have shown that such cues — global ODT boundaries defined by either orientation or curvature — are sufficient to form attentional objects.

In principle we could approach our results in two ways, in terms of their relation to visual objects. We could cleave to the full-fledged intuitive definition of objects, and thus take our results as evidence for a new type of attention (texton-based attention?). This type of rhetoric, however, can quickly lead to an ugly proliferation of 'types' of attention: object-based attention, contour-based attention, group-based attention, part-based attention, etc. Without some reason for thinking that these effects are mediated by distinct processes, it seems more parsimonious to assume that all such effects reflect a single process (which we will call 'object'-based attention), driven by multiple cues to objecthood on multiple hierarchical levels. In this context, our studies are investigating some of the simplest types of attentional 'objects', and are linking them to perhaps the simplest object-formation processes — namely early visual segmentation.

Our null results with uniform ODTs have equally important implications for our understanding of object-based attention. It could have turned out that *any* perceptually salient structure would constrain the flow of attention. However, the main direction ('grain') of ODTs failed to do so here, despite being just as perceptually salient as other types of visual structure. Indeed, we had some reason — based on both intuition and previous results (as discussed below in Section 8.3) — to expect that attention would flow 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 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 attention was constrained by 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.

8.2 Comparing Spatial Cueing and Divided-Attention Paradigms: Methodological Conclusions

The results of Experiments 1 through 4 also have direct methodological lessons for the OBA literature. The object-based nature of visual attention has been explored using several very different paradigms and phenomena, including visual search (e.g. Mounts & Melara, 1999), negative priming (e.g. Tipper et al., 1990), inhibition of return (e.g. Reppa & Leek, 2003; Tipper et al., 1991), multiple-object tracking (e.g. Pylyshyn & Storm, 1988; Scholl & Pylyshyn, 1999), object-reviewing (e.g. Kahneman et al., 1992; Mitroff, Scholl, & Wynn, in press), attentional capture (e.g. Hillstrom & Yantis, 1994), visual illusions (e.g. Cooper & Humpherys, 1999) and many other methods. The two most popular methods for studying OBA, however, have surely been variants of spatial cueing (e.g. Atchley & Kramer, 2001; Avrahami, 1999; Egly et al., 1994; He & Nakayama, 1995; Lamy & Tsal, 2000; Macquistan, 1997; Shomstein & Yantis, 2002; Vecera, 1994) and variants of divided attention paradigms (e.g. Barenholtz & Feldman, 2003; Behrmann et al., 1998; Chen, 1998; Davis et al., 2000; Duncan, 1984; Duncan & Nimmo-Smith, 1996; Kramer et al., 1997; Lavie & Driver, 1994; Valdes-Sosa et al., 1998; Vecera & Farah, 1994; Vecera et al., 2000, 2001; Watson & Kramer, 1999).

To our knowledge, this is the first study in which the relative sensitivity of spatial cueing and divided attention have been directly compared in studies using identical stimuli. The results of this comparison are clear: divided-attention paradigms (measuring accuracy) are more sensitive and possess several other advantages over spatial cueing (measuring response time). In Experiments 1 through 4 we directly compared these paradigms using both regular ODTs (Experiments 1 and 2) and jittered ODTs (Experiments 3 and 4). In the experiments which possessed *both* global structure and strong local continuity cues (Experiments 1 and 2), the difference between the two paradigms was merely *quantitative*: both paradigms yielded roughly the same pattern of results, though the divided-attention method yielded more robust differences, and with fewer subjects. In the experiments without local good-continuation cues (Experiments 3 and 4), however, the two paradigms yielded *qualitatively* different results: spatial-cueing yielded no evidence of effects of global structure, while divided-attention did (again using fewer subjects). (We have also observed such qualitative differences in other recent studies exploring other image cues. For example, in some cases divided-attention methods can reveal subtle effects of closure and line-tracing that are not apparent when using spatial cueing; Marino & Scholl, under review.)

We conclude that divided attention methods can be more sensitive than spatial cueing, at least in certain situations, and accordingly we urge other researchers to employ divided-attention measures when studying the role of subtle image cues in producing attentional objects. Of course, spatial cueing could still be used for those studies which employ known robust image cues, but there seems to be little motivation for doing so — especially since the spatial cueing paradigm inherently requires that we throw away the vast majority of the collected data (viz. the valid-cue trials), whereas every trial in divided-attention experiments is informative. Since the two paradigms may ultimately reflect the same underlying processes anyway (see Davis et al., 2000), it seems that the divided-attention method is simply a more sensitive way of studying such processes.

8.3 Conflicts with Earlier Research (Avrahami, 1999)?

Our results do seem to conflict with at least the spirit of one other spatial-cueing study, which also urged researchers to explore the particular image cues which form attentional objects. This clever study (Avrahami, 1999) took the 'two-rectangles' stimuli (Figure 1) as its starting point, and suggested that closure may not in fact be required to produce same-object advantages. Avrahami's study employed a regular grid of parallel lines (Figure 20a), and found a similar same-'object' advantage: the lines defined an overall grain in the display, and subjects responded faster to invalidly-cued targets when the cue and target were oriented along this grain, compared to when they crossed the grain. This result — combined with a failure in some cases to observe a same-object-advantage when using 'ribbons' (which enjoyed closure but 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, using either spatial cueing (Experiments 1 and 3) or divided attention (Experiments 2 and 4). We are especially confident in this null result, not only because of the multiple replications across tasks and dependent measures, 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 experiments are due to 'grain-based' line-tracing. Indeed, our study suggests, at least for the case of the orientation texton, that only the global distribution of texels in ODTs can influence attention. 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 used arrays of continuous parallel lines (Figure 20a) which may not qualify as textures. Despite these differences, these two classes of stimuli both contain salient main directions (grains) which are roughly equivalently salient, and as such it seems certain that Avrahami's results do not reflect a universal effect of contour grain on the flow of attention, of the sort which would generalize to ODTs. In the case of ODTs, in any case, this null result is directly predicted by geometrical theories in which neither direction is biased relative to the other (Ben-Shahar & Zucker, 2002, 2003).

In general, however, we do have other reasons to think that display details can affect the outcomes of OBA studies in subtle ways. For example, while Avrahami (1999) found no effect of closure using regular layouts of parallel lines such as those in Figure 20a, Marino and Scholl (under review) did find an effect of closure when the lines were organized by proximity into two groups, as in the original 'two-rectangles' stimuli (Egly et al., 1994). Using stimuli such as those in Figure 20b with the divided attention paradigm, Marino and Scholl

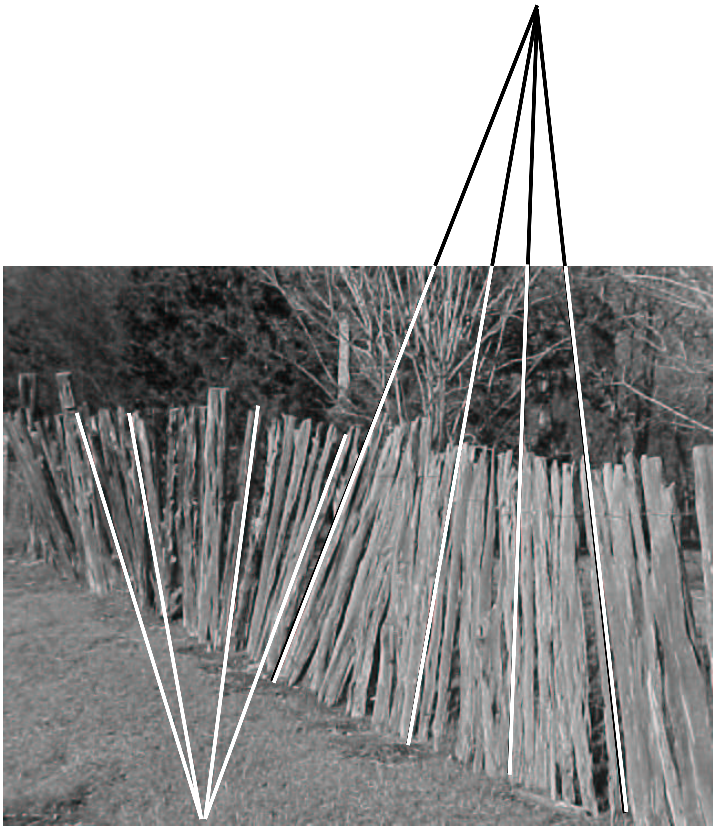
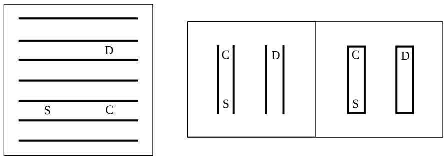


Figure 19: Although their occurrence in natural images is intuitively less obvious, discontinuities in normal curvature can be found in natural visual scenes as commonly as those in tangential curvature. Here we depict an example of this even without orientation discontinuities. This image of the fence 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.



(a) **(b)**

Figure 20: (a) Example of the line-tracing stimulus used by Avrahami (1999). 'C' indicates a possible cued location, 'S' indicates the corresponding same-object target location, and 'D' indicates the corresponding different-object target location. (b) Examples of the stimuli used by Marino and Scholl (under review) to explore the role of closure in OBA. See text for details.

found that even groups of parallel lines without closure can yield object-based effects — but that such effects were significantly stronger when the groups of lines were closed into rectangles. They thus conclude that same-object advantages can be observed even without full-fledged intuitive 'objects' (a result made even more strongly in the present studies), but that object-based attention is not an all-or-nothing phenomenon: object-based effects can be independently strengthened or weakened by multiple cues to objecthood. Such findings highlight the importance of studying multiple low-level image cues and their combinations.

8.4 OBA as a Tool for Testing Models of OBTS

OBTS — and, indeed, segmentation in general — has 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 & Zucker, 2002, in press; 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 et al., 1988), and the common forced-choice paradigm using perceptual judgments (e.g. Ben-Shahar & Zucker, 2002, in press; 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 types of experimental paradigms for studying segmentation. Using both spatial-cueing and divided attention, we have demonstrated that subtle differences in the flow 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 OBTS can be indirectly inferred from the patterns of observers' responses and response times, on tasks which do not themselves involve an explicit segmentation 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.

8.5 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 segmentation 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, however, 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 segmentation 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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