# Chapter Three: Investigating the Visual Discrimination of *Data-Driven Spots* Layers

## Introduction

Chapter Two describes a new visualization technique, Data-Driven Spots (DDS), and presents examples and arguments for the effectiveness of the DDS technique. The key components of DDS that make it a new and powerful technique are (1) multiple two-dimensional single-valued functions are *sampled* by Gaussian spots and (2) *overlaid* in a single image such that (3) each variable layer is *visually distinct* from the rest. With the experimental evaluation of DDS I report in this chapter, I explore the third property in depth to determine whether individual variable layers are visually discriminable in a multi-layer visualization. This chapter attempts to answer the question:

In a single DDS image that displays nine two-dimensional single-valued binary functions, $F_k(i,j)$, are viewers able to attend to individual and pairs of layers, switching the focus of their attention at will?

The experiments presented here test this question with a task that requires the participants to see, understand, and answer questions about the spatial extent of the functions displayed. In the experiments the functions are chosen to represent a simple case – they are binary functions whose "1" levels form basic elementary shapes such as triangles, squares, ellipses, circles, and rectangles. Two tasks are used to evaluate whether or not participants can see the data displayed in the DDS layers. First, participants are asked to estimate the percentage of overlap between two target layers. Next, participants are asked to sketch the intersection region of the same targets. Figure 3.1 shows examples of target shapes represented by variable layers, as well as the correct intersection region formed when the targets are overlaid. DDS trial images are shown in Figure 3.2. The overlap estimation and sketch tasks represent not only a test of the participants' ability to assess the spatial correlation of two target layers, but also a test of their ability to see and understand relationships among function layers.

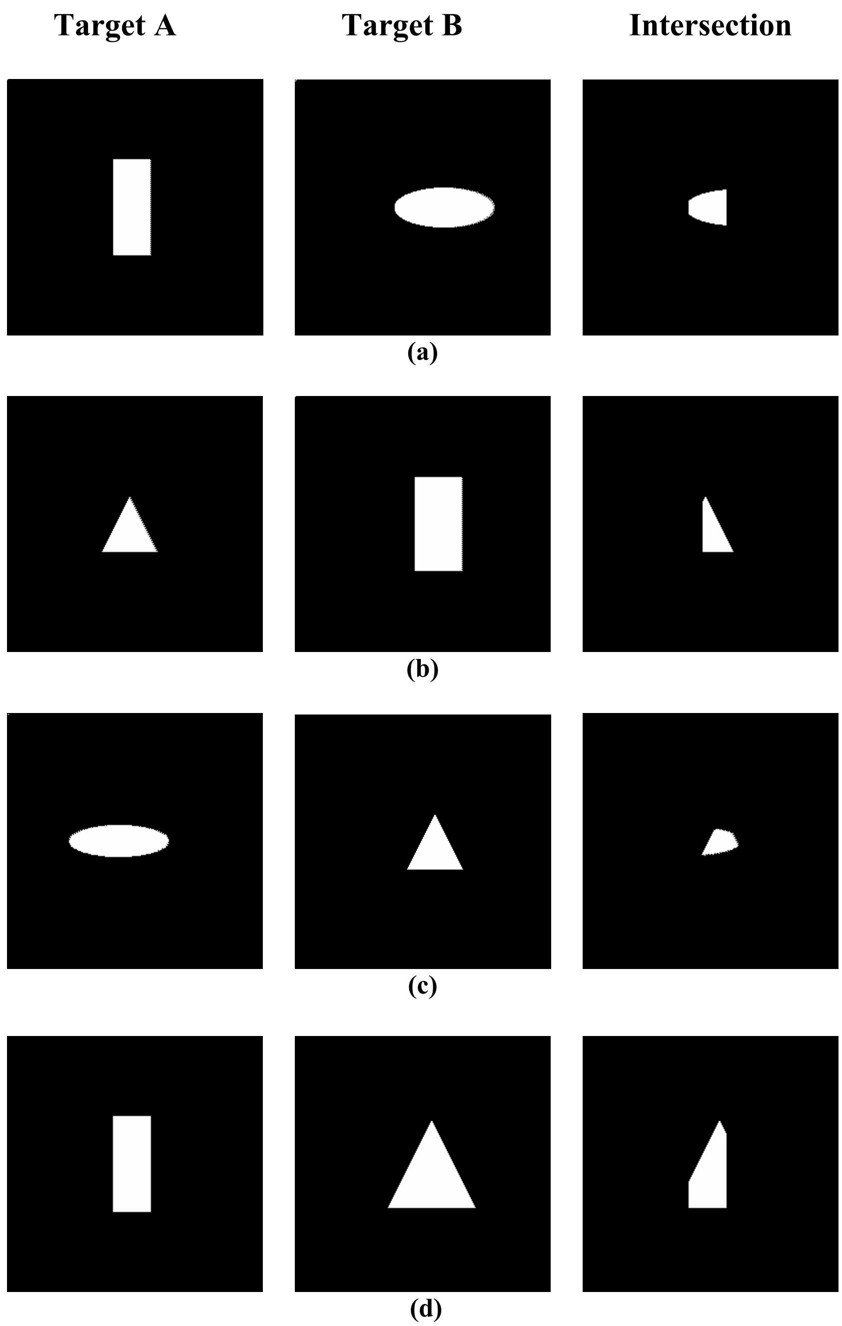
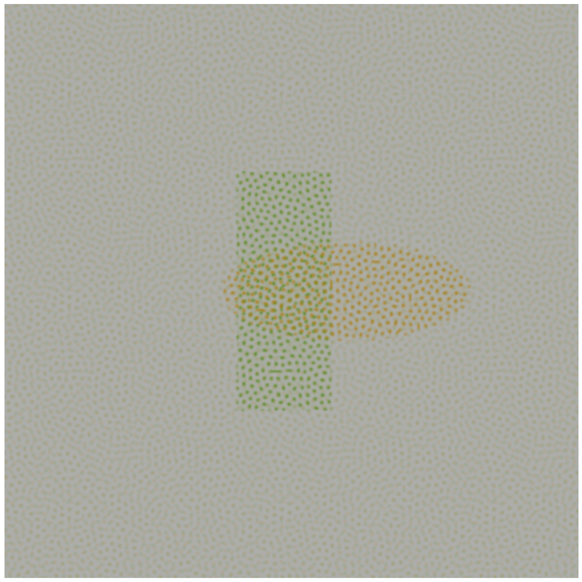
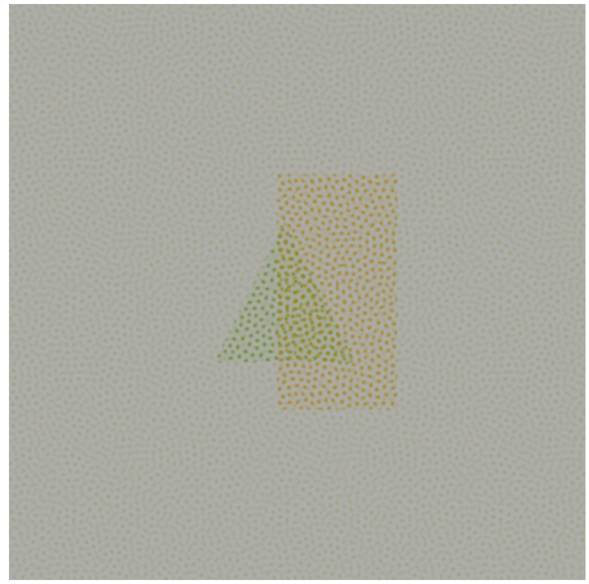
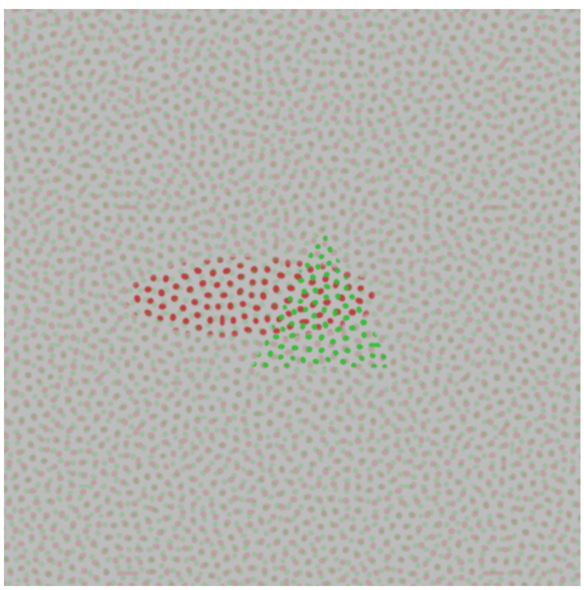


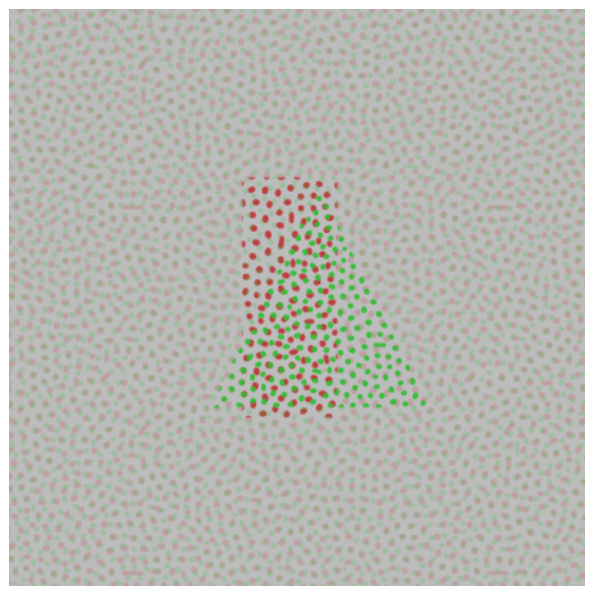

**Figure 3.1:** Example of target shapes and the intersection regions. Participants estimate the percentage of target A (left column) that is overlapped by target B (second column from left). Next participants are asked to sketch the intersection of the two shapes; the third column shows the correct intersection. Examples (a) and (b) are from the pilot study; (c) and (d) are from the main study. In example (a) 29.6% of target A is overlapped by target B, in (b) the overlap is 60%, (c) it is 28.8%, and (d) it is 64%. These four target-pairs (a-d) will be used throughout the chapter to illustrate the experimental conditions.





**(a)** **(b)**





**(c)** **(d)**

**Figure 3.2:** DDS images for the target pair examples in Figure 3.1. Figures (a) and (b) are from the pilot study and Figures (c) and (d) are from the main study. The images are shown at 30% original size.

To evaluate the effect of additional layers in a multi-layer DDS visualization on visual discrimination of targets, each trial image contains between zero and seven additional layers, each displaying one two-dimensional single-valued function, $F_k(i,j)$. These functions are drawn from the same pool of basic elementary shapes. Images with seven additional layers contain a total of nine DDS layers: two target layers and seven additional, *distractor* layers. If the DDS layers are visually discriminable, as I claim in the thesis statement presented in Chapter One, then the presence of distractor layers should have minimal impact on the participants' ability to judge accurately the percentage of overlap between the targets and to sketch accurately the intersection region of the targets. For DDS to be a viable new visualization technique I must show both a benefit for displaying data overlaid in a single image and that overlaid DDS layers do not significantly diminish the viewer's ability to see each layer individually.

*Question One:* Does overlay provide a performance benefit for an overlap estimation task and an intersection-sketch task? How do participants perform with overlaid multi-layer DDS images compared to single-layer DDS images shown side-by-side?

*Question Two:* Where is the benefit crossover? If presenting targets overlaid in a single image allows for more accurate performance for an overlap estimation task and an intersection-sketch task, then is there a point where the multitude of additional layers causes enough visual interference that the task is more accurately performed looking at the targets side-by-side?

*Question Three:* Are DDS alpha-blended layers more visually salient than DDS bump-mapped layers in a multi-layer visualization? How do the display parameters of individual target DDS layers influence their visual salience in the presence of distractors?

These three questions are represented in the study by the independent and dependent experimental variables. The first independent variable represents both the number of distractors in a test image, which ranges from zero to seven, and whether the targets are shown overlaid or side-by-side. In side-by-side images the targets are always shown as single DDS layers and never with distractors. This first experimental variable is termed *Display Condition*.

The second independent variable represents how the target layers are displayed, whether with DDS alpha-blending, DDS bump-mapping, or both. It has three different values: *Color-Color*, where both targets are displayed with DDS alpha-blending, distinguished by hue and size of the spots; *Color-Bump*, where one target is displayed with DDS alpha-blending and the other with DDS bump-mapping; and *Bump-Bump*, where both targets are displayed with DDS bump-mapping, distinguished by size of the bumps. This experimental variable is referred to as *Target Display Type*. Examples for each *Target Display Type* with *Display Conditions* zero through seven distractor layers are shown in Figures 3.19 through 3.34 and Figures 3.49 through 3.65, for the pilot and main study, respectively.

The responses to the overlap estimation task and the intersection sketch task are the two dependent measures in the experiment.

***Note on Images***

Chapter Two of this dissertation presents two different texture generation techniques, one based on reaction-diffusion textures, the other based on a random placement of Gaussian spots [Turk, 1991; Witkin and Kass, 1991]. The experiments were conducted before the Gaussian spot textures replaced the reaction-diffusion textures in the DDS visualization technique, thus the images used in the experiment and presented in this chapter use textures generated by reaction-diffusion.

Figure 3.79, at the end of this chapter, shows an example of a trial image sampled with Gaussian spots. The Gaussian spots provide both clearer boundary definitions and more uniform spot intensity – and therefore a more uniform sampling of the data. Thus it is fair to predict that the positive results of this experiment would hold at least as well for images generated with Gaussian spots.

## Literature Review

In this section I discuss examples of work in the field of human visual perception. The goal of DDS visualizations is that each separate function be visually distinct. There is much work in human visual perception that investigates what visual aspects of an object make it stand out from its surround. The work I describe discusses cues such as color, orientation, and shape variations in both preattentive and attentive visual processing. The tasks involve proportional area estimation, single-target search, and boundary distinction, all of which are involved in studying a DDS visualization. Hopefully, this section will shed light on what visual cues increase the visual salience of DDS layers.

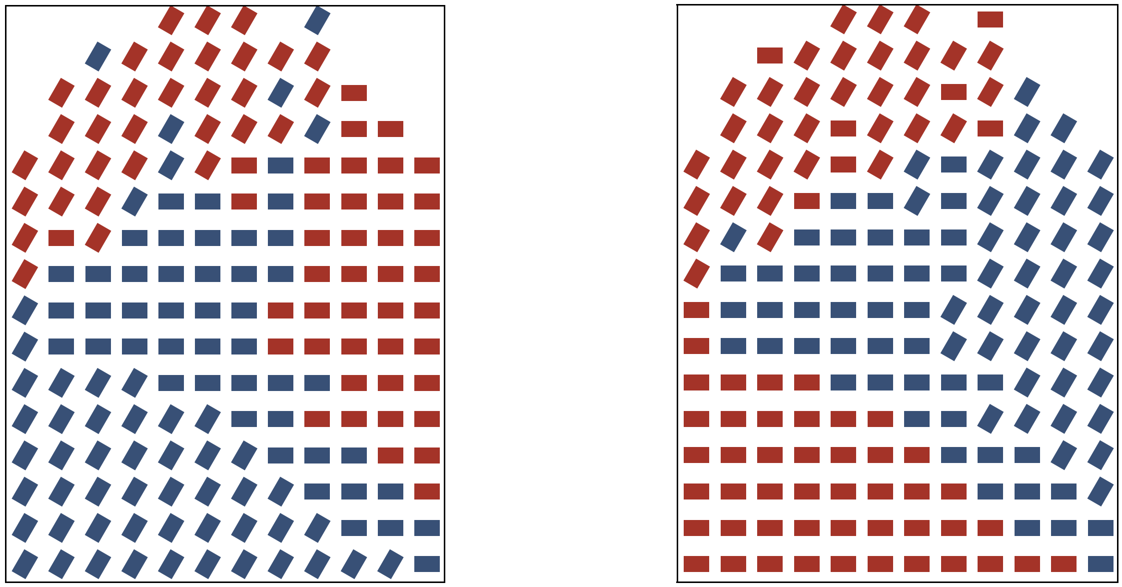
### *Preattentive Processing of Color and Shape in an Area Estimation Task*

In the experimental evaluation of DDS, participants are tested on their ability to judge area overlap between two target shapes in the presence of distractors. In a similar study, Healey, Booth, and Enns [1996] test visual assessment of proportional area for preattentive image exposures (less than 200 milliseconds). Targets were distinguished either by hue (red or blue) or by component orientation (zero-degree rotation, or sixty-degree rotation). Two example images from their study are shown in Figure 3.3. When targets were distinguished by hue, some target elements were displayed with zero-degree rotation and others with sixty-degree rotation. In order to estimate the target area accurately, participants had to perceive both red areas, regardless of orientation. Likewise, when targets were distinguished by orientation, one sub-area was displayed with red and the other with blue, and participants had to combine the areas of both the red and blue sixty-degree rotated lines to accurately estimate area. The results showed that participants were able to estimate areas rapidly and accurately to within approximately 6% of the true area, and irrelevant changes in orientation or hue did not influence participants' performance. There are two important differences in experimental design between this study and ours. First, the images did not have overlapping distractor layers. Second, the images were presented for a very brief duration, whereas in the evaluation of DDS images remain on the screen for as long as the participants desired.

### *Visual Cues that are Processed Preattentively*

*Preattentive visual processing* is defined as visual processing that occurs in less than 200ms. Some visual features that are processed preattentively are color, orientation, and direction of motion [Ware, 2000]. It has been shown that people can identify the presence or absence of targets, perceive boundaries, and accurately estimate area when the target, boundaries, or areas differ from the background elements along one or more visual features that are processed preattentively [Ware, 2000].

Preattentive processing is immediate, as if the visual system processes the entire stimulus in parallel, whereas non-preattentive processing requires a serial search of the visual stimulus. Figure 3.4 based on [Ware, 2000] is an example. Searching a list of numbers for a particular target requires a serial search, unless we distinguish the target such that it can be detected preattentively.



**(a)** **(b)**

**Figure 3.3:** Images from a study that investigated the rapid estimation of proportional areas. The results of the study showed that differences in hue had no effect on area discrimination based on orientation and that orientation differences did not affect discrimination based on hue. Images courtesy of Christopher Healey [Healey et al. 1996].

Work by Treisman and Gelade [1980] argues that color and shape are processed automatically and in parallel by the visual system. They present evidence that the visual search for a target that differs in one dimension, either color or shape, from the background elements does not depend on the number of distractor elements – that the target pops out. For example searching for a red letter 'R' in a sea of blue 'R's does not depend on the number of blue 'R's, Figure 3.5 shows an example.

Color is processed preattentively, but some colors are more visually prominent than others. Figure 3.6 shows an example with a red circle in a surround of magenta circles and a magenta circle in a surround of red circles.

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05457802780455078064540878754016508745415498784159604874351087874334530480315489788178
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85451048978817896687135048187085458748946451031070450933830984080455078064540878754016
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**Figure 3.4:** An example of attentive and preattentive search, based on [Ware, 2000]. Finding the number 2 in the first series requires attentive, sequential search, whereas searching for the bold **2** in the second series or the red **2** in the third series does not require focused attention.

For some people the magenta target will stand out more clearly than the red. There is evidence that color category is an important factor in the visual discrimination of color [Healey, 1997]. *Color category* is defined based on color naming conventions. *Ideal colors* are defined as pure, highly saturated hues (bright red, royal blue) ; other colors are defined by their distance from the ideal. Lime-green, sea-green, and hunter-green all fall in the green color category. Figure 3.7 shows an example. Healey et al. [1996] conducted experiments that found that up to seven different perceptually isoluminant colors could be rapidly and accurately distinguished from one another. In selecting the colors he considered color category, color distance (the Euclidean distance between colors as measured in a perceptually linear color space), and linear separation (when a target can be separated from non-target elements by a straight line through the color space) [Healey, 1996].

The colors for the first experiment presented in this chapter were selected to be perceptually isoluminant; unfortunately there are several perceptual processes that break down at isoluminance, such as the perception of form, depth, and motion [Livingstone and Hubel 1988]. The colors for the second experiment were not perceptually isoluminant.

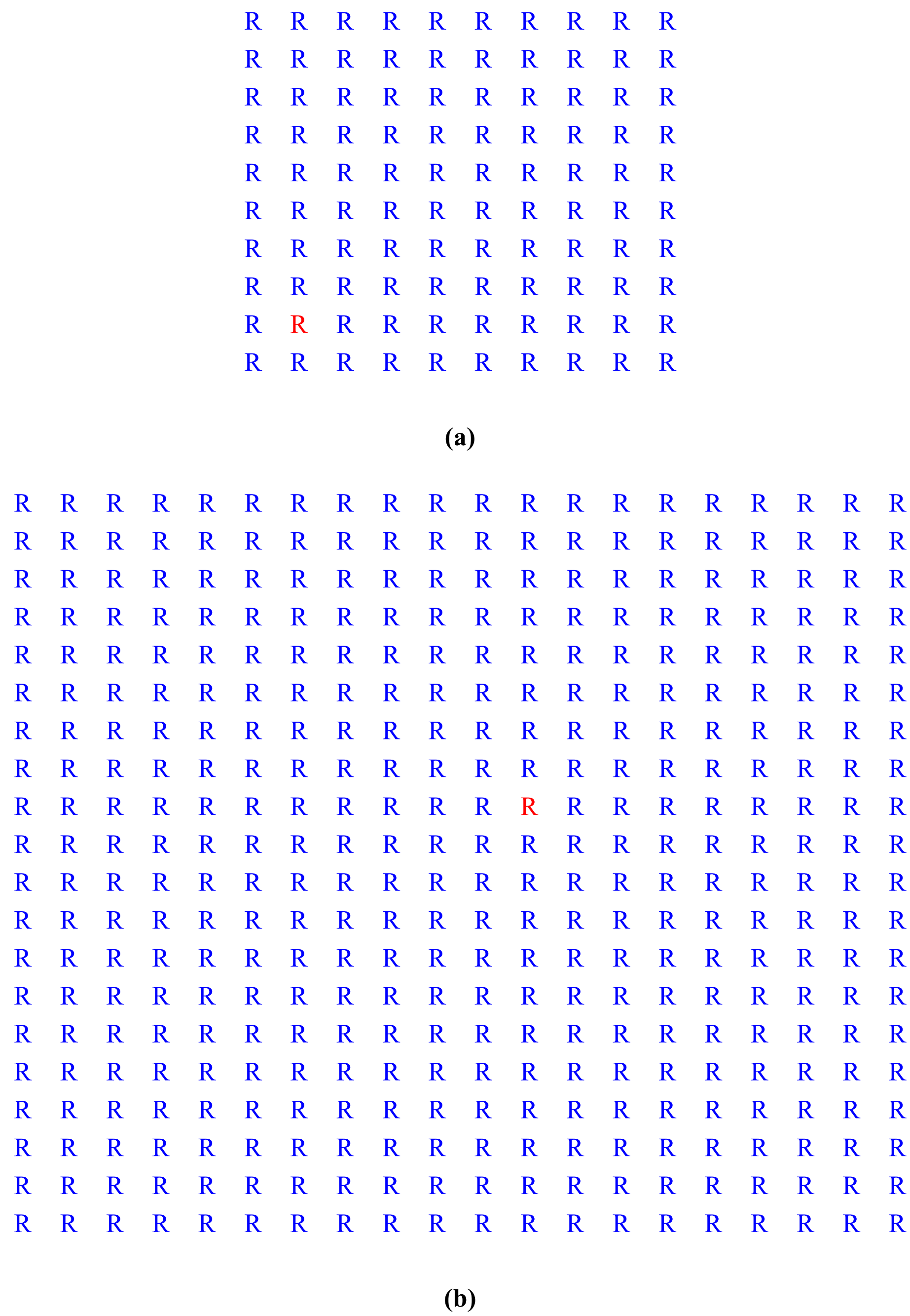
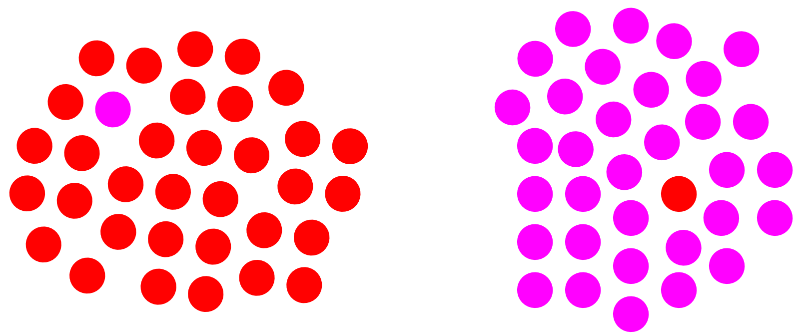



**Figure 3.5:** Color is processed preattentively. Search for the red ‘R’ among blue ‘R’s is independent of the number of blue ‘R’s. This example is based on the work of Treisman and Gelade [1980].



**(a)** **(b)**

**Figure 3.6:** Color is processed preattentively, however some colors are more salient than others. For some people the magenta circle will pop out more when surrounded by red than the red circle when surrounded by magenta. Many factors influence pop-out and visual salience.

Ware [2000] lists features that are processed preattentively. The preattentive features important for DDS alpha-blended layers are size, curvature, spatial grouping, numerosity, hue, and, for animated layers, direction of motion. Size and curvature of circular spots are inversely related. The number and distribution of the Gaussians in the Gaussian array, constructed as described in Chapter Two, depends on the size of the Gaussian. A Gaussian array built from smaller spots is more numerous. When each DDS alpha-blended layer is displayed with a different Gaussian array distinguished by the size of the Gaussians, each of these features – size, curvature, number, and spatial grouping – is different. Because these features have been shown to be processed preattentively, we can expect that the DDS alpha-blended layers will be visibly distinct in the presence of multiple layers.

In the experiments described below, the textures were based on a reaction-diffusion technique [Turk, 1991; Witkin and Kass, 1991]. The reaction-diffusion technique produces textures with almost all circular spots. Any such texture, whether generated with reaction-diffusion or using Gaussians, will have different values for curvature, spatial grouping, and numerosity, when the size of the spots is different. In the design of the experiments, hue was used as the distinguishing feature. In fact in the pilot study multiple pairs of DDS alpha-blended layers had the same size spots, thus were distinguishable only through hue, whereas in the main experiment all DDS alpha-blended layers had different size spots, and thus were distinguishable along both hue and size.

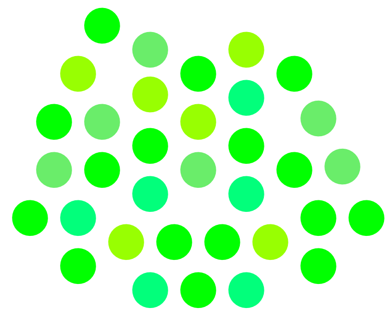


**Figure 3.7:** How many different greens are presented here? Some research suggests that for perceptually isoluminant colors to be preattentively distinct from one another they should be in different color categories [Ware, 2000; Healey, 1996].

The DDS bump-mapped layers are based on the same underlying textures as the DDS alpha-blended layers. Therefore, the same preattentive features also distinguish among bump-mapped layers: size, curvature, spatial grouping, and numerosity. Hue is not used to distinguish among bump-mapped layers. The dominance of hue over texture or shape characteristics is discussed in more detail below.

Although each DDS layer has several preattentive features that distinguish it from others in the image, Ware [2000] points out an important aspect of preattentive processing: the strength of the preattentive pop-out effect depends on the variety of the distractors. The more uniform the distractors, the stronger the effect, the more differences in distractors, the weaker the effect. He demonstrates this with an image that shows several shapes, all of which are preattentively different from the others, yet none stand out. His observation is stated eloquently on page 167 of his book:

> *"[...] pre-attentive symbols become less distinct as the variety of distractors increases. It is easy to spot a single hawk in a sky full of pigeons, but if the sky contains a greater variety of birds, the hawk will be more difficult to see. A number of studies have shown that the immediacy of any pre-attentive cue declines as the variety of alternative patterns increases, even if all the distracting patterns are individually distinct from the target."* [Ware, 2000 p.167]

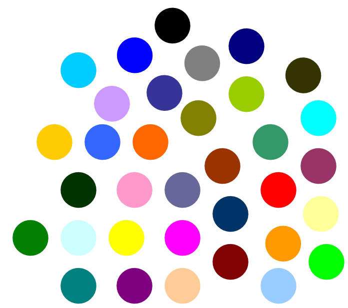


**Figure 3.8:** Although color is processed preattentively, the strength of the pop-out effect is influenced by the variety of the distractors [Ware, 2000]. Each of the 32 circles has a different color. Compare the visual pop-out of the red and magenta spots with that for Figure 3.6.

Figures 3.8 and 3.9 show examples of strength of pop-out – one with circles of different colors and another with ellipses of different colors and orientations. It is interesting to compare the visual salience of the red and magenta circles in Figure 3.8 with the salience of the red and magenta circles in Figure 3.6. In a DDS image with nine layers there are up to six different colored layers; the visual salience of the different colors may lessen as more layers are added – but then again they may not. I believe that a person viewing a DDS image can selectively focus on the DDS layer distinguished by red spots and then switch his attention to the DDS layer distinguished by blue spots. It is also interesting to compare the visual salience of the vertical ellipse in the four series in Figure 3.9. Although both color and orientation are processed preattentively, is color more salient than orientation?

Local contrast is another factor influencing preattentive pop-out [Nothdurft, 1993]. The vertical target in Figure 3.9b is surrounded by near-vertical ellipses, decreasing the local contrast so it pops out less than the horizontal target. Weigle, Emigh, Liu, Taylor, Enns, and Healey, [2000] conducted experiments showing that 15 degree orientation differences were adequate to distinguish between small lines. The experiments did not study the effects of random variations in background elements, local contrast, or layering of multiple oriented lines.

One natural question is what aspects of a visual stimulus are the strongest preattentively, i.e. do color targets stand out more clearly than targets based on orientation or shape? The literature on preattentive visual processing does not always agree on this question, and many of the results depend on the nature of the distractors: how different they are from the target, and whether the distractors are uniform or random.

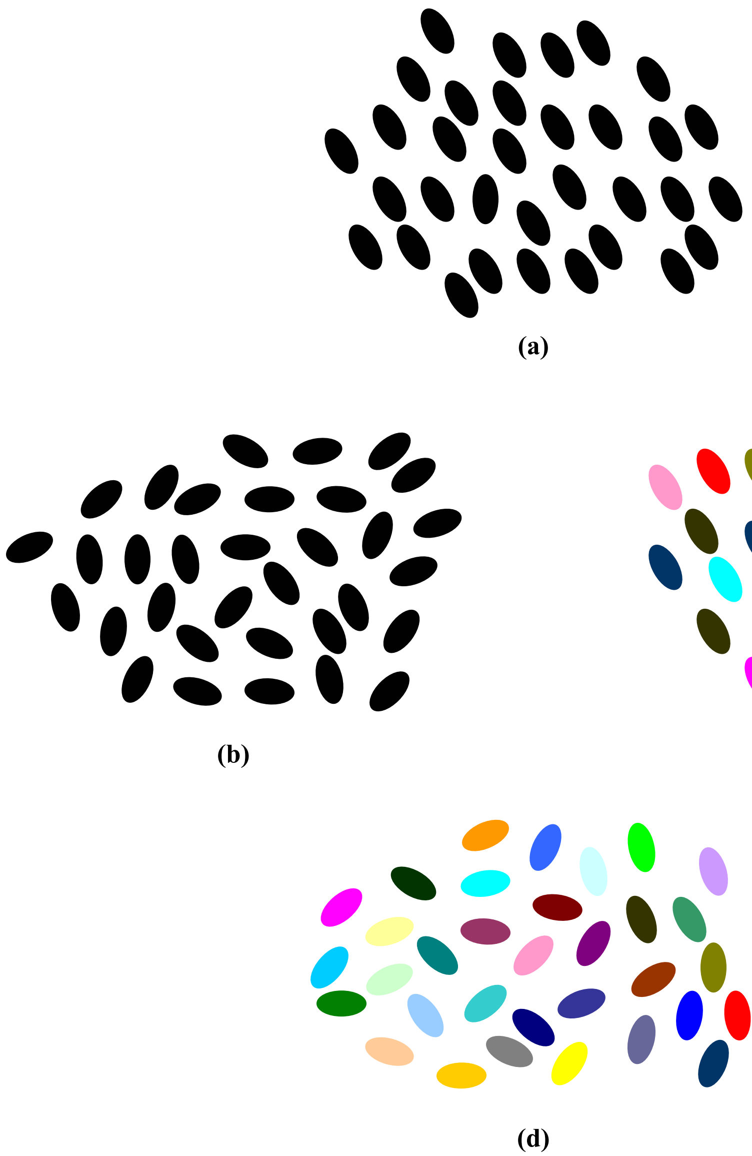


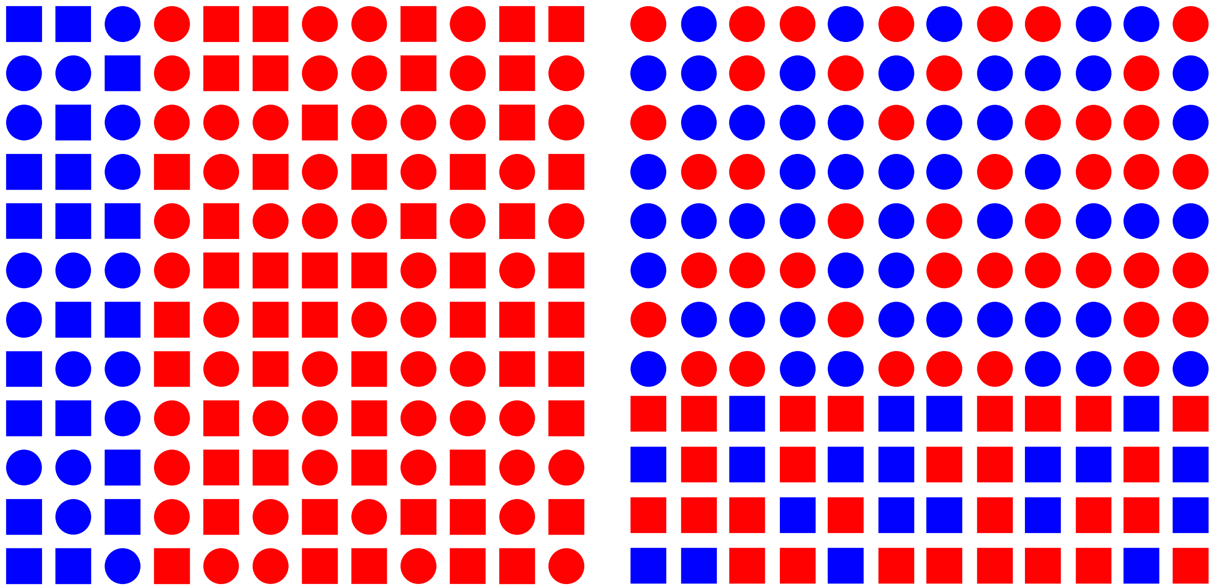

**Figure 3.9:** Orientation discrimination is processed preattentively [Ware, 2000]. In (a-c) the target is the vertical ellipse: various factors such as uniformity of distractors (a) and non-uniformity in (b), and random variations in background color (c), or random variations in two background dimensions (d) all influence how much the target pops out from the distractors. Local contrast is also important [Nothdurft, 1993]. Try finding the horizontal oval in (d).

***Preattentive Processing of Shape and Color in a Texture Segregation Task***

Although Healey et al. [1996] found no effect for changes in line orientation on estimation based on hue or vice-versa (Figure 3.3), other researchers have. Callaghan [1989, 1990] presents results from several experiments that investigated interference and dominance in texture segregation (texture segregation tasks involve both the perception of boundary and the estimation of proportional area based on texture features). She showed that when boundary judgments were based on shape differences, variation in color significantly increased participants' reaction times. However, when boundary determination was based on color, variation in texture had no effect. The textured arrays were either divided horizontally or vertically and were separated by shape (circle, square) or by color, Figure 3.10 shows two examples. The dimension not used for separation was randomly assigned across all elements. The results showed that color interfered with the perception of shape-defined boundaries, but shape did not interfere with color-defined boundaries. The asymmetric result differs from earlier work by Callaghan, Lasagn, and Garner [1986] that showed symmetric interference between color and texture. However in earlier work, textures were composed of line segments, instead of various shapes.

Treisman [1988] also investigated the effect of color on texture perception. In a study of visual search where the target element differs from the surround in orientation, she found that random color variation had no effect on detecting the presence or absence of a target element defined by orientation (similar to Figure 3.9c). One important difference between the work of Treisman and Callaghan, pointed out in a later investigation by Snowden [1998], is that the target in Treisman's study was a single element, whereas the target in Callaghan's work was an area, or group of elements. Examples of singleton search are shown in Figure 3.9(a-d), whereas examples of texture segregation, group search, are shown in Figure 3.10(a-b). A second difference was that the non-target elements in the work by Treisman were few and sparse, whereas Callaghan's elements were laid out on a grid.

Snowden [1998] investigated whether random color or stereo depth variation interfered with the detection of either a singleton target or a target region. He showed that detection and localization of a singleton target were not disrupted by background color or depth variations, but that a combination of both color and depth variation did interfere with the task. In a second experiment he showed that detection and orientation determination of a target area were significantly affected by background color variation, which is similar to Callaghan's findings.



**(a)** **(b)**

**Figure 3.10:** Boundary discrimination by hue (a) and shape (b), based on the work of [Callaghan, 1989]. The evidence suggests a dominance of hue over form, although others [Treisman, 1988; Snowden, 1998; Healey et al., 1996, 1998, 1999] have found conflicting evidence.

Snowden formulated a theory that background color or depth variations interfered only in tasks where the participant perceived the targets as a group, either because of close spatial proximity, or due to target elements forming notional shapes (such as when four individual targets form the shape of a square). With singleton targets participants had increased reaction times only when more than one background dimension varied (i.e. when both color and depth vary randomly). No increase in reaction time occurred when only one background dimension varied.

Healey and Enns [1998, 1999] further investigate the relationship of color and texture interference by defining textures along three perceptual categories: regularity, height, and density. They investigated the use of each texture dimension for the display of data values. They found that background texture variation in either height or density had no effect on the detection of the colored target. When background color varied randomly (blue and green or red and green) color interfered to a small but significant degree with the detection of a short target surrounded by tall texture elements but had insignificant effects on the tall and dense or sparse targets.

The work of Healey et al. [1996] and Callaghan [1989, 1990] are most closely related to the work presented in this chapter, as both consider texture segregation instead of target search. However, in all the studies discussed above, distractor elements surround the target, but do not overlap it. This is a key difference in design.

***Visualization with Combinations of Features: Conjunction Search***

Visualization techniques, such as DDS, that use texture to display data, can be thought of as falling along a continuum of visually separable or visually integrated. Ware defines an integral display as when two or more visual features of a single object are perceived holistically [Ware, 2000, p. 188]. Length and width combine to create the appearance of an ellipse, for example. In a separable display; each graphical dimension is perceived by the viewer as separate (pg. 188). The color and size of a Gaussian in DDS are examples of visually separate features. Chapter Four discusses several visualization techniques in terms of the integral-separable dimension. It is my opinion that the ideal technique should visually integrate only when the data values are highly correlated (for spatial variables this is when the data shows a high degree of spatial overlap). Where the data is uncorrelated, the display technique should be visually separable, so each individual variable can be clearly seen.

Integral displays can be thought of as involving what Treisman and Gelade [1980] call *conjunction search*, which is defined as the visual search for a target that is uniquely defined by the combination of two or more features that are also present, but not in combination, in the non-target elements. Examples of conjunction search are shown in Figures 3.11 and 3.12. When the target is a conjunction of separate visual elements also present in the background distractors, for example searching for a blue 'R' in a surround of blue 'B's and red 'R's, the target item does not pop out automatically and the search proceeds in a serial fashion. An explanation of conjunction search is presented in their paper [Treisman and Gelade, 1980]. They argue that although the separable features are processed early, that object identification and correlation of features occurs later and requires focused attention to be correctly perceived. They claim that without attention the *correct* relation of features is not perceived (pg. 98, their emphasis). Although color and some aspects of shape are processed preattentively, conjunctions are not.

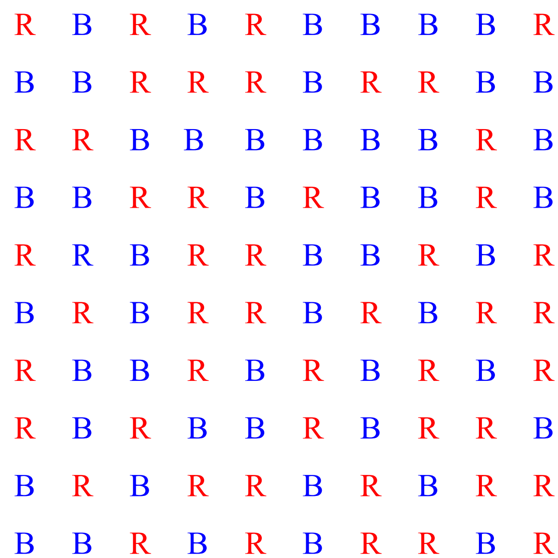



**Figure 3.11:** Conjunction search illustrated, based on [Treisman and Gelade, 1980]. The target is a blue 'R', displayed among red 'R' and blue 'B' distractors. The search is serial and depends on the number of distractor elements.

The literature on preattentive processing lends evidence for the visual discriminability of DDS alpha-blended layers distinguished by hue and size and for the visual discriminability of DDS bump-mapped layers distinguished by size and curvature. Data is displayed in DDS through one channel only per layer: through transparency in the DDS alpha-blended layers and through apparent height in the DDS bump-mapped layers, thus DDS layers fall into the category of separable displays. Because each layer is distinguished from the others by hue or size and not a combination – there are not two blue layers one with small spots and one with larger spots – visual search for a single target layer does not involve conjunction search and should not require focused attention to distinguish which layer is which. The literature suggests that both types of DDS layers will remain visually distinct in the presence of distractor layers; however the clear dominance of hue over shape suggests that the DDS alpha-blended layers will show less dependence on the number of distractors than the DDS bump-mapped layers. The results of the experiments below show both of these properties to be true.

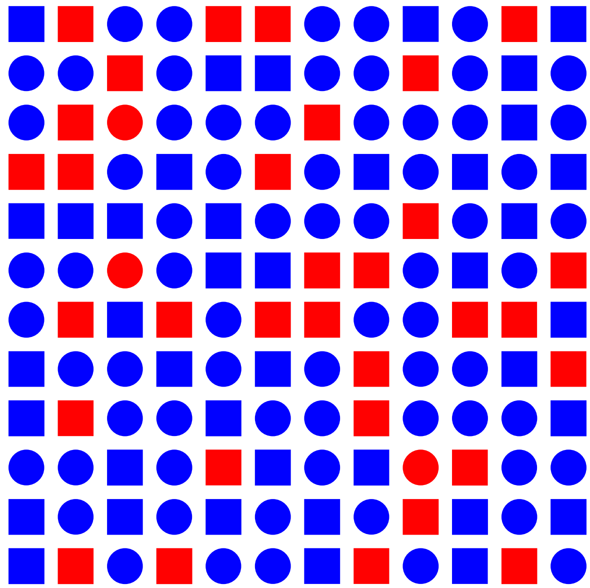


**Figure 3.12:** Another example of conjunction search. Three red circles are difficult to find among red and blue squares and blue circles.

***Visual Perception of Figure and Ground***

Another way to think about DDS layers is in terms of the Gestalt rules of visual perception of *figure* and *ground* described in [Hoffman, 1998]. The Gestalt laws predict the visual separation of objects into figure and ground based on characteristics such as proximity, similarity, and shared speed and direction of motion. Dividing the visual world into figure and ground is key to survival – consider the ability to see a leopard hiding in a patch of jungle – *The leopard you see won't be the one that kills you* [BBC, Big Cat Diary, 1996-2002]. Whereas the whole leopard is not visible, the parts of the leopard that are visible are interpreted as one partially-obscured object. This works because the parts of the leopard are self-consistent: the patterns of spots, the shininess of the coat, and the coherence of any motion, for example. The visual discrimination of DDS layers relates well to the formation of Gestalt figures. Within a DDS layer all the spots are consistent in size, hue, density, numerosity. The face-vase illusion is an interesting example of figure and ground. It is a bi-stable illusion: the faces or the vase are seen alternately as both figure and ground. Figure 3.13 shows an example with DDS alpha-blended layers.

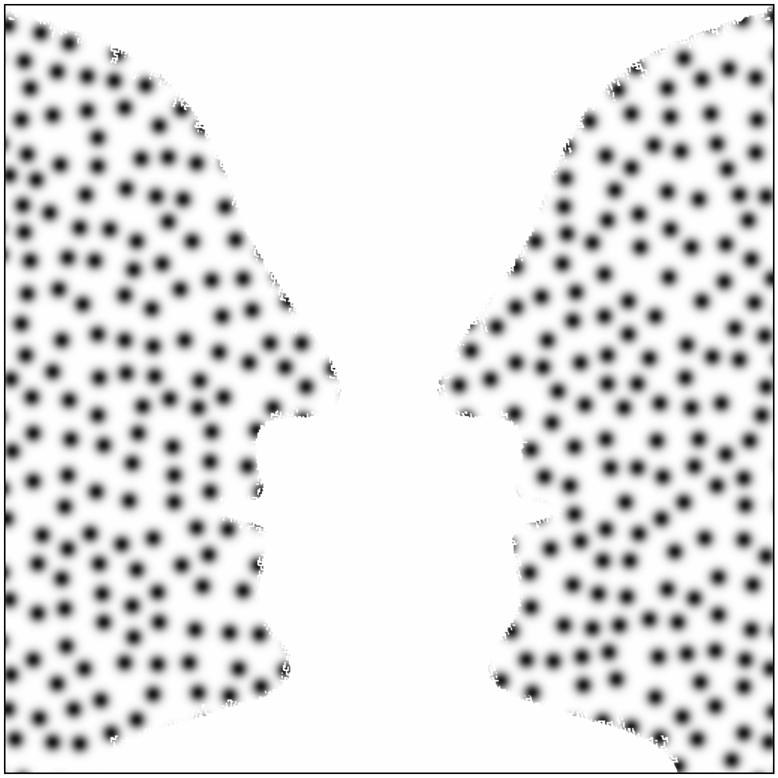


**Figure 3.13:** The face-vase illusion, displayed with DDS alpha-blended spots. Both the faces and the vase are seen alternately as figure and ground.