PERGAMON

Vision Research 39 (1999) 933–945

Vision Research

Long range interactions between oriented texture elements

S. Sabina Wolfson [a], Michael S. Landy [b,*]

[a] *Psychology Department, Columbia University, 1190 Amsterdam Avenue, New York, NY 10027, USA*
[b] *Psychology Department, New York University, 6 Washington Place, 8th Floor, New York, NY 10003, USA*

Received 16 January 1998; received in revised form 6 April 1998

Abstract

Long range interactions between texture elements (short, oriented line segments) were examined. Specifically, we studied the influence of a background array of texture elements on the detectability of a target element (separated from the background by an intermediate textured region) using textures like those of Caputo (Vis. Res. 1996, 36, 2815–2826). We found that, in general, when the background elements were oriented orthogonally to the target element, detection of the target element was better than when the background elements had the same orientation as the target element. We discuss these interactions in terms of inhibitory and excitatory connections between orientation and spatial frequency selective linear filters (e.g. filters which mimic V1 simple cells) which would respond to the individual texture elements. © 1998 Elsevier Science Ltd. All rights reserved.

Keywords: Texture; Long range interactions

1. Introduction

The visual system is designed to recognize, among other things, representations of objects which have long contours such as chairs, faces, etc. However, the 'building blocks' for these representations of objects, at a low-level (that is, V1 simple and complex cells), have receptive fields which necessarily view only a small part of any object. To recognize an object from isolated inputs such as these requires assembling the outputs. Thus, in order to further our understanding of visual processing beyond these individual samples of the world, we need to examine how these cells combine information across space in the form of long range interactions.

In this paper, we examine long range interactions between perceptual 'building blocks' (specifically, short line segments) in the context of texture segregation and pop-out. Exemplary stimuli for our experiments are shown in Fig. 1. Each stimulus/texture consists of three areas: the *target* element surrounded by a *patch* region surrounded by a *background* region. For example, in Fig. 1a, the target is a $-45°$ line element, the patch region is made of 90° line elements, and the background region is made of 45° line elements. In all of our experiments, we explore the relationship between the target element (or elements in one experiment), the patch region, and the background region. More specifically, we are interested in the effect of the background region on the detectability of the target element since such an influence would be indicative of long range interactions. As will be discussed in more detail below, past research (Caputo, 1996) found that when the target element and background elements had the same orientation (*iso-orientation*), the target element was harder to detect or identify than when the target element and background elements differed by 90° (*ortho-orientation*); we term this difference in performance the iso- *versus ortho-orientation effect*. Typical models of texture segregation (e.g., Malik & Perona, 1990; Landy & Bergen, 1991) do not consider long range interactions (between the target element and the background elements) and would predict that the target element should be equally detectable in the iso-orientation and ortho-orientation configurations. Thus, it is interesting to study these long range interactions since they are not accounted for by typical models of texture segregation.

There are different frameworks in which the perception of textures like those in Fig. 1 can be considered: (1) one can think of such textures in terms of occluded

* Corresponding author. Tel.: +1 212 998-7857; fax: +1 212 995-4349; e-mail: landy@nyu.edu.

PII: S0042-6989(98)00144-8

surfaces[1] (e.g. for the iso-orientation textures in Fig. 1, the target element and the background might be thought to form a surface which is occluded by the patch region as illustrated in Fig. 2); or (2) one can think of such textures at a low-level in terms of interacting filters selectively tuned for orientation and spatial frequency. We will refer to these general interpretations as the *occluded surface framework* and the *filter framework*. It may be that these two viewpoints are generally compatible; that is, the low-level filters may feed into a higher-level surface representation. However, there is some research which makes sense in terms of a filter framework but not in terms of an occluded surface framework, and vice versa. We will also consider physiological research regarding long range cortical interactions in V1; it may be that the interacting filters suggested in (2) are related to the context effects seen in single cell recordings.

1.1. Background research

Long range interactions have been examined physiologically. Using single cell recordings (in V1), researchers have examined how a stimulus presented outside of a cell's classical receptive field (CRF) can influence a cell's response. When a cell is presented with a stimulus in its CRF to which it is sensitive (say, a vertical grating), the cell will respond. When a cell is presented with a stimulus outside its CRF (say, a horizontal grating), it will not respond (if it did respond, then the region would be considered to be inside the CRF). However, there are cells that are sensitive to context. That is, there are cells that respond differentially to the central stimulus (the vertical grating) presented alone and the central stimulus presented in the context of the surround stimulus (the horizontal grating). In general, cells which are sensitive to context respond more when the central and surround stimuli are orthogonal than when they are of the same orientation (iso- versus ortho-orientation effect). This effect has been found using grating stimuli (Sillito, Grieve, Jones, Cudeiro & Davis, 1995; Levitt & Lund, 1997) and arrays of oriented line segments (Knierim & Van Essen, 1992).

Long range interactions have also been examined psychophysically. Caputo (1996) examined the effect of a background region of elements on an oriented target separated from the background by a patch region (as shown in Fig. 1). Caputo (1996) had three major findings. (1) Detection and identification of the target element are superior when the target and background are orthogonal rather than when they are of the same orientation (the iso- versus ortho-orientation effect). (2) The iso- versus ortho-orientation effect disappears if the patch region elements are erased (however, we found that the effect remains when there are no patch elements). (3) The iso- versus ortho-orientation effect diminishes as the distance between the target and background increases. Similar long range effects are seen in other tasks. The apparent contrast of a grating is reduced more when a surrounding grating has the same orientation than when it is oriented orthogonally (Cannon & Fullenkamp, 1991; Solomon, Sperling & Chubb, 1993).

The research presented here does not specifically consider element alignment. According to some psycho-

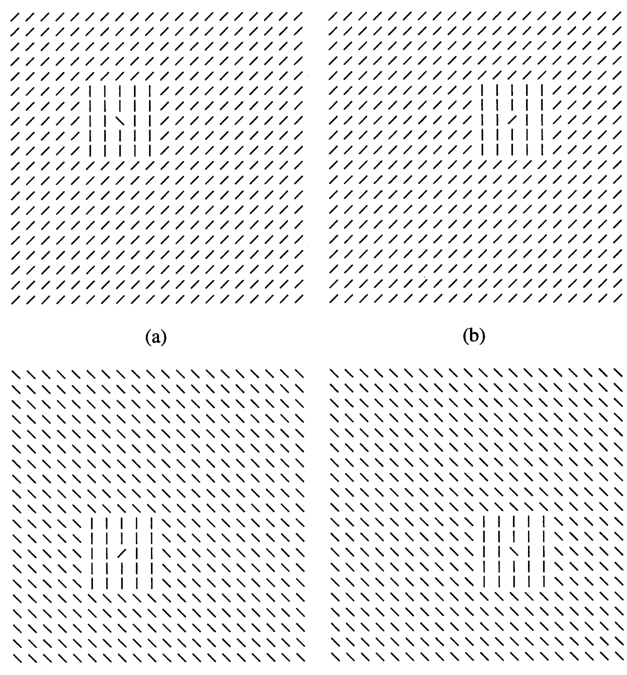


Fig. 1. Sample stimuli for Experiments 1 and 2. In all experiments, stimuli consisted of white line segments on a gray background. Each stimulus consisted of three regions: a *target region*, a *patch region* and a *background region*. (a) The target region consists of one element oriented at $-45°$, the patch region is a 5×5 region of 90° line segments, and the background region is a 20×20 region of 45° line segments. This stimulus is an example of an *ortho-orientation* texture with a 45° background. (b) An *iso-orientation* texture with a 45° background. (c) An ortho-orientation texture with a $-45°$ background. (d) An iso-orientation texture with a $-45°$ background. The target element was always (except in Experiment 4), oriented at either $-45°$ (a,d) or 45° (b,c). The patch region was always located in one of four possible positions: (a) upper-left; (b) upper-right; (c) lower-left; or (d) lower-right. The background region elements were always oriented at either 45° (a,b) or $-45°$ (c,d).

[1] For our purposes, we will consider a surface to be defined by an array of similar texture elements (i.e. similar in orientation and sign of contrast) which may include areas of smoothly varying texture elements (i.e. smoothly varying in orientation). That is, there will be some property which causes the 'pieces' of the scene to be grouped together as a surface (similar texture elements in our case), and a sudden change in this property would suggest a boundary/break in the surface. Finally, if there is evidence of occlusion, a surface may 'complete' behind the occluding surface.

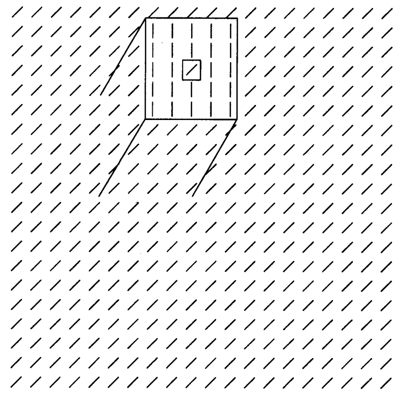


Fig. 2. Illustration of the percept of textures like those of Fig. 1 according to the occluded surface framework. The patch is seen as a textured surface that occludes the background. In the iso-orientation condition, the target is perceived as 'belonging' to the background surface, as if it were seen through a hole in the foreground patch surface.

physical and physiological research (Field, Hayes & Hess, 1993; Polat & Sagi, 1994; Kapadia, Ito, Gilbert & Westheimer, 1995; Saarinen, Levi & Shen, 1997), elements of the same orientation and aligned are better detected and grouped than orthogonal elements (orthogonal elements are not aligned by definition). Two of the experiments performed by Kapadia et al. (1995) elucidate the alignment issue. They examined the detectability of a line segment presented with a high contrast flanking line segment in humans, and the response rate of neurons (in V1) to a line segment presented in the CRF with a high contrast flanking line simultaneously presented outside the CRF (Fig. 3a). They found that (1) as the flanking element moved laterally (Fig. 3b), the detectability of the target element changed from being *enhanced* to being *suppressed* (at approximatley 20 min of arc), and (2) when an orthogonal element was placed between the aligned target and flanking elements (Fig. 3c), the detectability of the target element decreased (that is, the alignment was disrupted causing the facilitating effect to diminish).

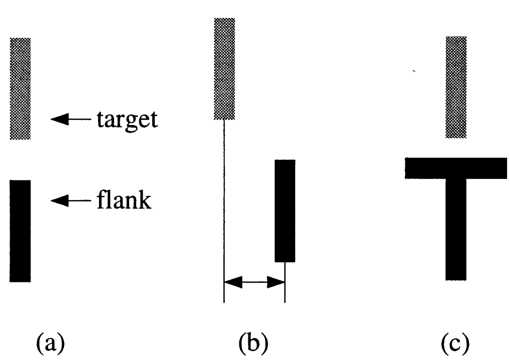


Fig. 3. Example stimuli used in experiments reviewed in the Introduction. (a) General stimulus setup for Kapadia et al. (1995) consisting of a target line segment (of varying intensity) and a flanking line segment. (b) Illustration of lateral movement of the flanking element in Kapadia et al. (1995). (c) Illustration of an orthogonal line segment placed between the target and flanking line segments in Kapadia et al. (1995).

The physiological and psychological findings can be summarized as follows: (1) ortho-oriented elements facilitate processing of the target; (2) iso-oriented, aligned elements facilitate processing of the target; (3) iso-oriented, non-aligned elements inhibit processing of the target.

This paper deals with the effects of an array of background elements on the detectability of a target element using textures like those shown in Fig. 1. Clearly, in such textures, elements in the background interact with one another, and further, some of these elements are aligned. However, the particulars of these interactions are beyond the scope of this paper, and the interactions within the background elements should not affect our results since they should be comparable in both the iso- and ortho-orientation conditions. We will focus on the effect of the background elements on the target element. As stated above, we believe such interactions can be interpreted in a low-level framework involving filter interplay (filters modeled after V1 cells) or in a higher-level framework involving occluded surfaces. We will argue for the former interpretation, but first the evidence for the latter interpretation will be presented.

1.2. Occluded surface framework and filter framework

Caputo (1996) argued that his work on textures like those of Fig. 1 suggests an occluded surface interpretation (Fig. 2). The logic of Caputo's argument is as follows. In iso-oriented stimuli (Fig. 1b,d), the target element and background are perceived as parts of a uniformly textured surface. The patch elements are seen as lying on a second surface that occludes the more distant surface. The target element is perceived as if seen through a hole in the patch surface. Because the target element is perceived as 'belonging' to the larger background surface, it no longer pops out (at least not as well) and hence is more difficult to detect or identify. For ortho-oriented stimuli (Fig. 1a,c), the target is no longer 'absorbed' into the background, and detection and identification are improved. This result is the iso- versus ortho-orientation effect. Caputo (1996) buttresses this argument with a series of experiments using simplified stimuli including manipulations of disparity-defined depth of the various image regions. These last results are reminiscent of the texture segregation results of He and Nakayama (1994) who find that a 'surface representation' created by a difference in disparity can have an effect on texture segregation performance under some circumstances.

We would like to interpret our results, and the other results involving long range interactions using stimuli like those of Fig. 1, in terms of a low-level filter representation (the filter framework). A standard, back pocket model[2] of texture can not account for such long range interactions. A generic version of the back pocket model consists of: (1) applying a set of orientation and spatial frequency tuned filters to the stimulus; (2) applying an even nonlinearity to these outputs, such as squaring; and (3) segmenting the image based on variations in the output over space. This basic model does not involve any interactions between the filters. However, consider an extension of this model with the addition of a stage between (2) and (3) in which like oriented filters inhibited one another and differently oriented filters excited one another over space, in the spirit of the physiological findings we have reviewed. Such a *modified* back pocket model could, in principle, account for the long range interactions found psychophysically.

A model like the one just described should show that (I) long range ortho-oriented elements facilitate target detection and iso-oriented elements inhibit target detection (note that we are not considering the alignment issue discussed earlier). Further, such a model predicts that (II) if we weaken the percept of the target element belonging to the same surface as the background elements, there should still be a performance difference between the iso- and ortho-oriented conditions, and (III) if the patch elements are removed, performance in the iso- and ortho-oriented conditions should still be different. To clarify points II and III, consider the influence of a background element (B) on an orthogonal target element (T). The simplest possible hypothesis is that the excitatory influence of B on T is static. That is, the influence of B on T should not change if some element is inserted (spatially) between B and T, or if an existing element between B and T is changed, or if an existing element between B and T is removed. Further, the influence of B on T should not change if the contrast sign of B or T is changed (assuming an even nonlinearity in stage (2) in the model). We performed experiments to examine each of these points and other exploratory experiments to learn more about the properties of long range interactions in texture segregation.

1.3. Preview of experiments

A list of the experiments we conducted is shown in Table 1. We found an iso- versus ortho-orientation effect in all of the experiments. The first six experiments were 'basic' experiments carried out to confirm Caputo's (1996) iso- versus ortho-orientation effect and further explore long range interactions. The last three experiments were carried out to distinguish between the occluded surface framework and the filter framework.

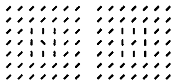
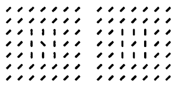
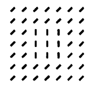
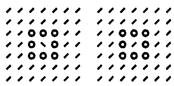
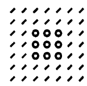
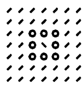
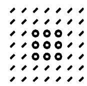
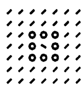
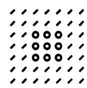
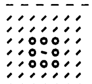
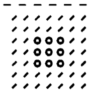
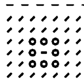
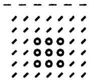
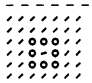
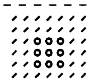
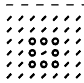
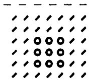
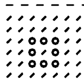
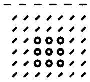
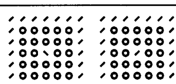
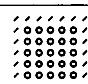
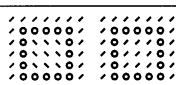
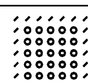
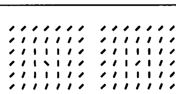
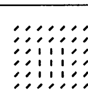
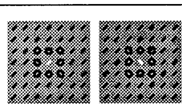
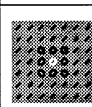
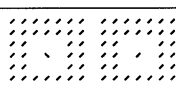
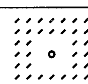
Experiments 1 and 2 (Fig. 1) were carried out to confirm Caputo's (1996) results[3]. In Experiment 3 we altered the patch element (Fig. 4a) to (1) see if the iso- versus ortho-orientation effect depended on the type of patch element and (2) to allow new manipulations of the target element like those of Experiment 4. In Experiment 4 we attempted to measure the 'orientation-bandwidth' of the iso- versus ortho-orientation effect by systematically altering the orientation of the target element. In Experiment 5 we drastically increased the size of the patch region (Fig. 4b) to see if the target and background elements would still interact over a greater region of space. In Experiment 6 we changed the single target element to an array (texture) of 9 target elements (Fig. 4c) to see if these findings truly apply to texture segregation or if they only apply to pop-out. Next, two experiments were run to examine point (II) raised above. In Experiment 7 (Fig. 4d) the orientation discontinuity between the patch and background was smoothed out so that the only discontinuity was between the target element and the patch elements[4]. Such a manipulation should diminish the surface qualities that could cause the target and background to form an occluded surface since the patch and background now form a smoothly varying surface (see our definition of surface in the first footnote). This manipulation should not alter the output from the sort of model described for the filter framework except for (slight) interactions between the smoothed elements and the target element if they are within the range of the iso- versus ortho-orientation effect. In Experiment 8 (Fig. 4e) the contrast sign of the target element was altered from that of the background elements. This manipulation should also break down the surface qualities that could cause the target and background to form an occluded surface since the target element is no longer 'similar' to the background elements with regards to brightness. This manipulation should not alter the output from the sort of model described for the filter framework since the iso- and ortho-orientation interactions are not affected

[2] These models are called 'back pocket models' of texture segregation, as researchers routinely pull these models out of their back pockets to explain new results in texture segregation (Chubb & Landy, 1991).

[3] Experiments 1, 2, 5 and 9 are similar to experiments run by Caputo (1996). The results for Experiments 1 and 2 agree with Caputo's (1996) results. The results for Experiment 5 may agree with Caputo's (1996) results depending on one's interpretation. The results for Experiment 9 do not agree with Caputo's (1996) results. All other experiments in this paper are original. Caputo (1996) used two different experimental procedures in his experiments, one of which is open to bias (as discussed in section 3). Caputo (1996) ran all of his experiments using both the biased and bias-free procedures except for the 'gap' condition (here Experiment 9) which he ran only using the biased procedure.

[4] This experiment was suggested by Bob Shapley and is reminiscent of Nothdurft (1992).

Table 1
Summary of the experiments. Each row corresponds to a block of trials in an experiment. That is, in Experiment 4 a block of trials included only a single stimulus type, whereas in all other experiments, blocks were mixed

Expt	Stimulus	Null	Task
1	 •white on gray •20x20 bg 5x5 patch 1x1 target	none	Is the target a "\\" or a "/"?
2	 •white on gray •20x20 bg 5x5 patch 1x1 target		Which interval has the target ("\\" or "/")?
3	 •white on gray •20x20 bg 5x5 patch 1x1 target		Which interval has the target ("\\" or "/")?
4	 •white on gray •20x20 bg 5x5 patch 1x1 target		Which interval has the target ("\\")?
	 •white on gray •20x20 bg 5x5 patch 1x1 target		Which interval has the target ("\\")?
	 •white on gray •20x20 bg 5x5 patch 1x1 target		Which interval has the target ("\\")?
	 •white on gray •20x20 bg 5x5 patch 1x1 target		Which interval has the target ("—")?
	 •white on gray •20x20 bg 5x5 patch 1x1 target		Which interval has the target ("/")?
	 •white on gray •20x20 bg 5x5 patch 1x1 target		Which interval has the target ("/")?
	 •white on gray •20x20 bg 5x5 patch 1x1 target		Which interval has the target ("/")?
5	 •white on gray •20x20 bg 11x11 patch 1x1 target		Which interval has the target ("\\" or "/")?
6	 •white on gray •20x20 bg 5x5 patch 3x3 target		Which interval has the target ("\\" or "/") region?
7	 •white on gray •20x20 bg 7x7 gradient 3x3 patch 1x1 target		Which interval has the target ("\\" or "/")?
8	 •white on gray w/ black target •20x20 bg 5x5 patch 1x1 target		Which interval has the target ("\\" or "/")?
9	 •white on gray •20x20 bg 5x5 blank patch 1x1 target		Which interval has the target ("\\" or "/")?

by the sign of contrast. Finally, in Experiment 9 (Fig. 4f) we examined the point (III) raised above by removing the patch elements, leaving a gap between the target element and the background elements. Overall, the results for these experiments agree with a filter interpretation rather than an occluded surface interpretation.

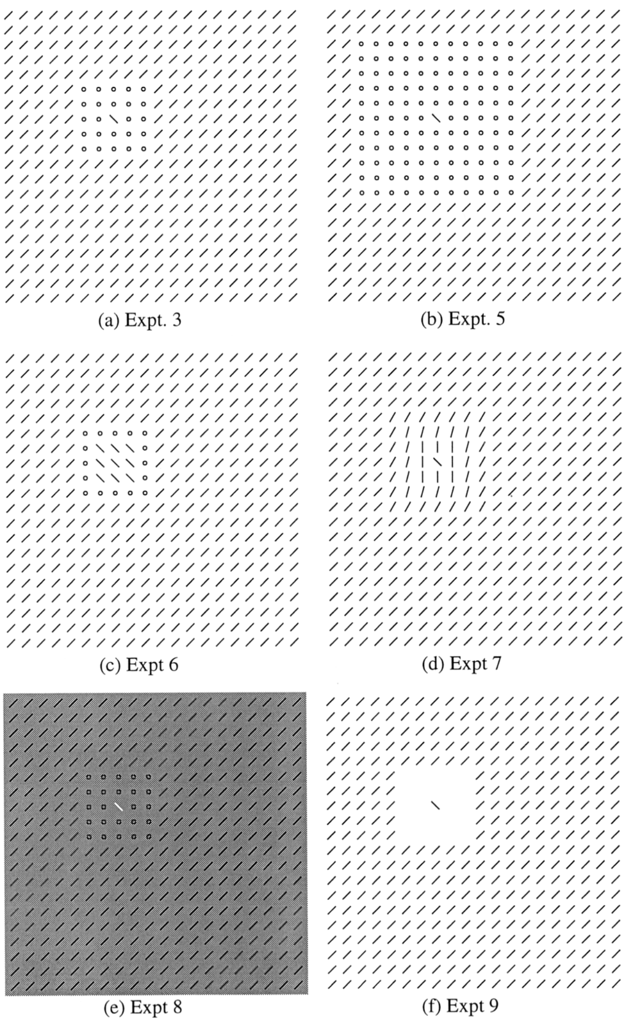


Fig. 4. (a) Sample stimulus for Experiment 3 (circular patch elements). (b) Sample stimulus for Experiment 5 (11×11 patch region). (c) Sample stimulus for Experiment 6 (3×3 target region). (d) Sample stimulus for Experiment 7. Line segments between the background region and the patch region varied smoothly in orientation in 15° steps. This smoothing causes the patch region of 90° elements and the background region of 45° elements to be smaller in size than in Experiments 1 and 2 since what was the outer ring of the patch elements and the inner ring of background elements are now part of the smoothed area. (e) Sample stimulus for Experiment 8. The sign of contrast of the target element was opposite that of the background elements. In the experiment, the patch and background elements were white line segments and the target element was a black line segment on a gray background. (f) Sample stimulus for Experiment 9 (patch elements removed).

2. Methods

2.1. Subjects

There were six subjects in all; different subjects ran in different experiments. Subjects JL, MP and SO were naive to the purposes of the experiments. Subject LC had some knowledge of the background literature pertaining to the experiments. Subjects ML and SW (the authors) had extensive knowledge of the experiments. All subjects had normal or corrected-to-normal vision.

2.2. Stimuli

Each stimulus consisted of a texture like those shown in Figs. 1 and 4. However, the actual stimuli consisted of white lines or circles (texture elements) on a gray background (except in Experiment 8 which used a black target element in addition to white elements). Stimuli were 400×400 pixels in size, viewed from 177 cm, resulting in a size of 5×5 deg[5]. Texture elements were 0.175 deg (14 pixels) in length (for line segments) or circumference (for circular patch elements). The background luminance was 35 cd/m^2. Texture elements had a nominal 100% white-on-gray Weber contrast, resulting in an incremental luminance of approximately 1.2×10^{-4} cd/texture element.

Each stimulus was a grid of 20×20 texture elements consisting of three regions: the background region, the patch region, and the target region/element. In all experiments: (1) the patch was randomly placed in one of four possible positions as shown in Fig. 1; (2) the target element/region was centered within the patch; (3) the center of the target element/region was always located at the same distance (0.89 deg) from the center of the image; (4) the background elements were oriented at either 45° or −45°. The particulars of the stimuli for each experiment are outlined in Table 1. In Experiment 4, the orientation of the target element was varied; the intensity of each target was calibrated using a photometer to be equal to that of a circular texture element (so that luminance and orientation did not covary).

The information presented above, in conjunction with Table 1, details the stimuli for each experiment. For example, consider Experiment 5. There were 16 unique target stimuli: two targets (45° and −45°) × two backgrounds (45° and −45°) × four patch locations. There were eight unique null stimuli: one 'target' (a circle texture element, that is, a patch texture element) × two backgrounds (45° and −45°) × four patch locations. As shown in Table 1 (and to be discussed further below) the task was to detect which of two

[5] To avoid confusion, 'deg' is used to denote measurements of stimulus size and '°' for angles within the stimulus.

temporal intervals contained the 45° or −45° target. In this experiment, the patch region was extended to be 11×11 elements rather than the usual 5×5 elements. However, as stated above, the target element was located 0.89 deg from the center of the image (as it was in all experiments). As can be seen in Fig. 4b, this causes the patch region in this experiment to extend through the center of the image.

A mask was used in all experiments, but the same mask was not used in all experiments. The mask consisted of a 'star' at each texture element location. For Experiments 1–3, the mask consisted of texture elements oriented at 90°, 65°, 45°, 25°, −25°, −45° and −65°. This mask would not be adequate for Experiment 4 in which some of the target elements were 0°. Thus, the mask was changed for Experiment 4 (and all subsequent experiments) to consist of texture elements oriented at 90°, 67.5°, 45°, 22.5°, 0°, −22.5°, −45° and −67.5°. This change to the mask should not affect the relative magnitude of the results between conditions but might change the absolute magnitude across conditions. One subject was tested with both masks in a control experiment and did not show any appreciable difference.

All images were generated prior to the experimental session. The images were computed using the HIPS image processing software (Landy, Cohen & Sperling, 1984a,b). Images were presented on a Nanao Flexscan 9070U color monitor. The lookup tables were set so that the relationship between pixel value and display luminance was linear.

2.3. Procedure

The experiments used a detection task with a two-interval forced-choice procedure except for Experiment 1 which used an identification task. The subject's task for each experiment is listed in Table 1. A trial in Experiment 1 consisted of: (a) 333 ms cue; (b) 333 ms blank; (c) 33 ms stimulus; (d) individually adjusted inter-stimulus interval (ISI) for each subject; (e) 150 ms mask; and (f) blank until the subject responded. The experimenter adjusted each subject's ISI[6] so that the percent correct in the iso- and ortho-orientation conditions would be between 50% and 100%.

A trial in Experiments 2–9 consisted of two repetitions of the single interval used in Experiment 1 (e.g. cue, blank, stimulus, ISI, mask, blank, cue, blank, stimulus, ISI, mask, blank). Which stimulus interval had the target stimulus and which interval had the null stimulus were chosen randomly. Null stimuli were the same as target stimuli except that in each null stimulus the target element was replaced with a patch element. The particular null and target stimulus to use on any given trial were chosen at random (and the choice of target stimulus was independent of the choice of null stimulus). A subject's response initiated the next trial. Auditory feedback was provided after each trial.

Each experiment started with at least 64 practice trials. Further trials were blocked as shown in Table 1, that is, a block of trials corresponds to a single row in the table. Thus, for all experiments, except for Experiment 4, trials for any given block were chosen at random from all possible stimuli for that experiment (combinations of target orientation, background orientation, and patch location). However, in Experiment 4, each target orientation was run in separate blocks. Each block consisted of 128 trials. When all the blocks for an experiment are combined, each combination of target orientation, background orientation, patch location and target interval had been shown the same number of times. In Experiment 5, each data point represents at least 128 trials; in all other experiments, each data point represents at least 256 trials.

3. Results

The results for Experiments 1–9 are shown in Figs. 5–13. Each figure has icons at the bottom of the figure representing the experimental conditions and stimuli. All icons illustrate textures with 45° line segments in the background, but in all experiments, backgrounds of both 45° and −45° were used. For further information about the experiments and icons, see Table 1. For all graphs, the error bars indicate ± 2 standard errors of the mean.

Experiment 1 was an identification task: a texture was presented (Fig. 1) followed by a mask and subjects had to indicate whether the target element was a right diagonal or a left diagonal. As shown in the results (Fig. 5), the target element was generally identified correctly more often when it was oriented orthogonally to the background elements (*ortho-orientation*) than when it had the same orientation as the background elements (*iso-orientation*). Caputo (1996) ran comparable experiments and found this same result.

The problem with this task is that it is open to alternative strategies. For example, suppose that a subject only saw and was able to identify the target on a subset of the trials (lets call these *seen trials* and the remaining trials *unseen trials*). On the seen trials, suppose the subject responded with the identity of the target they perceived. On the unseen trials, the subject should have to guess. However, suppose the subject

[6] Subject JL's ISI was 267 ms in Experiment 1, and 200 ms in all others. Subject LC's ISI was 50 ms in Experiments 1 and 5, and 17 ms in all others. Subject ML's ISI was 17 ms in Experiments 2 and 9, and 50 ms in all others. Subject MP's ISI was 267 in Experiment 4, and 33 ms in all others. Subject SO's ISI was 200 ms. Subject SW's ISI was 50 ms in Experiment 1, and 17 ms in all others.

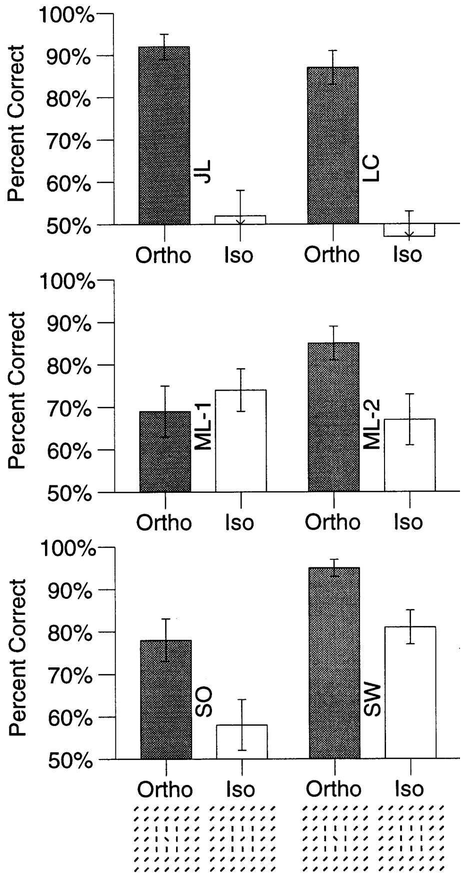


Fig. 5. Results for Experiment 1. The task was an identification task; the subject had to indicate whether the target element was a right or left diagonal. In this and all subsequent figures, the stimuli used in the experiment are illustrated with icons at the bottom of the graph. Most subjects in this experiment show superior performance in the ortho-orientation condition (see text for details on ML-1 versus ML-2). Error bars indicate ± 2 standard errors of the mean.

knows that if they did not see the target, it is likely that the target was an iso-orientation target (since an iso-orientation target, as shown in the experiments below, was harder to detect than an ortho-orientation target). Then, on unseen trials, the subject might respond that the target was of the same orientation as the background. Assuming that the background orientation was perceived correctly more often than not, this response strategy would produce results like those shown for ML (Fig. 5, ML-1). Such a strategy requires knowledge of the experimental design or extensive use of feedback, and produces little or no iso- versus ortho-orientation effect. ML was asked to run the experiment again and allocate the vast majority of his attention to the target element, not the background. When asked to do this, he did show the effect (ML-2). Thus, this task can produce or not produce an iso- versus ortho-orientation effect depending on the instructions and the subject's interpretation of the instructions. However, all subjects except ML (including the naive subjects) did show the effect. While it appears that there is an iso- versus ortho-orientation effect, this experimental design is not the best way to investigate it.

Experiment 2 was a detection task using a bias-free, two interval, forced-choice procedure: a texture with a target element (right or left diagonal) was shown in one interval and a texture without a target element (a patch element was placed in the target element location) was shown in the other interval; subjects had to indicate which interval contained the texture with the target element. All subjects, expect for subject SO, showed superior performance in the ortho-orientation condition than in the iso-orientation condition (Fig. 6). It is surprising that subject SO did not show the effect in this experiment but did show the effect in Experiment 1 since she was naive (and ran Experiment 1 before Experiment 2). Subject SO was not available to run any more experiments, so we do not know why she did show the effect once and did not show it the other

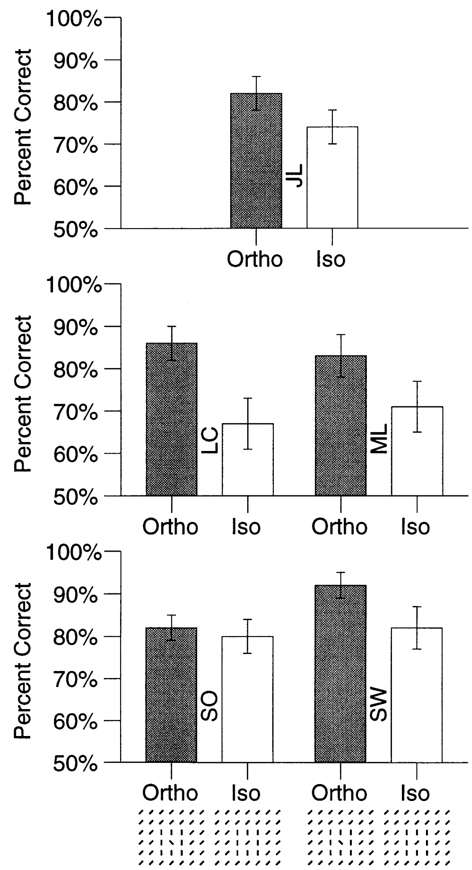


Fig. 6. Results for Experiment 2. In this and all subsequent experiments, the task was a detection task using a two interval forced-choice procedure; the subject had to indicate which interval consisted of a texture with a target element. Most subjects in this experiment show superior performance in the ortho-orientation condition (see text for details about subject SO).

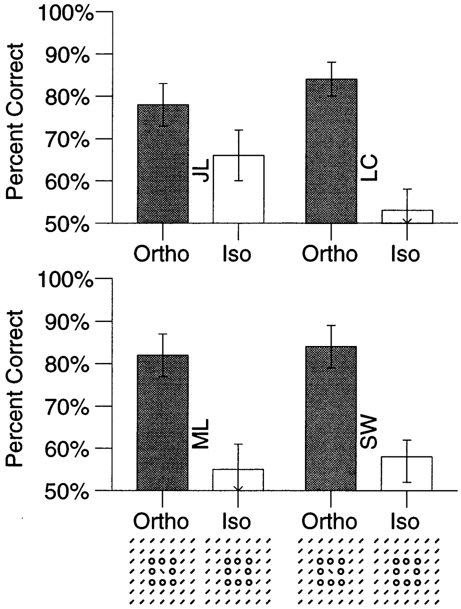


Fig. 7. Results for Experiment 3. All subjects show superior performance in the ortho-orientation condition.

time[7]. However, overall, subjects do show an iso- versus ortho-orientation effect in this experiment, as did subjects in Caputo's (1996) experiments that are comparable to this one. However, the iso- versus ortho-orientation effect is not as pronounced in this experiment as it was in Experiment 1.

Experiment 3 was the same as Experiment 2 except that the patch elements were changed. The patch elements were changed to (1) see if the type of patch element was important and (2) find a type of patch element which would not differentially interact with targets of different orientations (for use in Experiment 4 below). All subjects performed better in the ortho-orientation condition than in the iso-orientation condition (Fig. 7) indicating that this effect is not dependent on the use of vertical lines as patch elements. Further, the effect was generally larger in this experiment than in Experiment 2.

Experiment 4 was run to determine the 'orientation bandwidth' of the iso- versus ortho-orientation effect by systematically varying the target orientation in 15° steps. The task was the same as in Experiment 3 except that there was only one possible target in each block of trials (as shown in Table 1). When the target element was a left or right diagonal, subjects showed the usual iso- versus ortho-orientation effect (Fig. 8, far right data points). Further, for subjects MP and SW, there is still some effect when the target element has been rotated by 15° from exactly iso- and ortho-oriented (see the data points above a target orientation of |30°|). Thus, the target element does not have to be exactly the same orientation as or exactly orthogonal to the background elements to interact.

Subjects MP and SW ran the blocks of trials for this experiment in the same order (each block of trials had one target, the order of targets was: 45°, 30°, 15°, 0°,

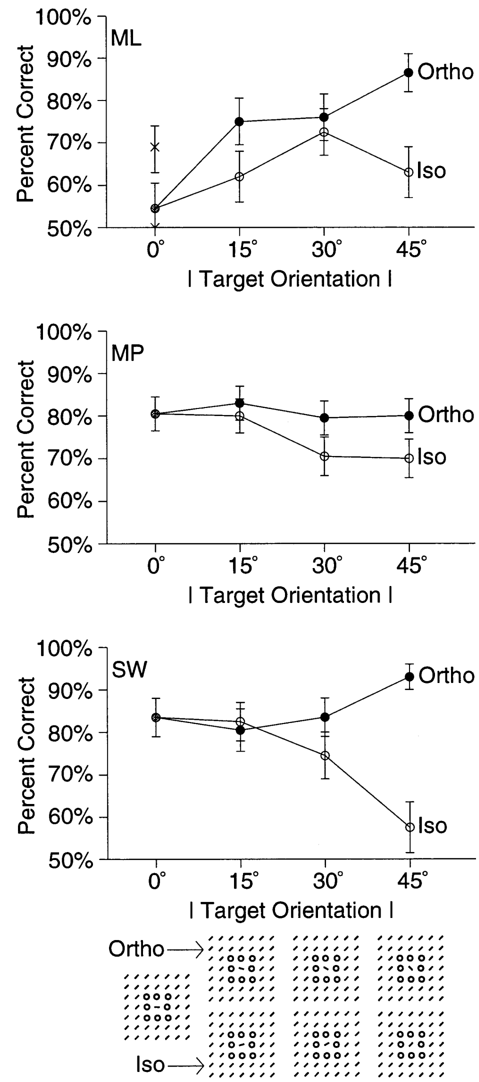


Fig. 8. Results for Experiment 4. All subjects show significantly better performance in the ortho-orientation condition than in the iso-orientation condition (as shown by the far right data points in each panel). In general, this performance difference diminishes as the orientation of the target element is altered by $\pm 15°$ steps until it is a horizontal line segment. Unlike all of the other two interval experiments, there was only one possible target orientation in each block of trials (Table 1).

[7] Subject SO, in general, performed poorly in both Experiments 1 and 2. To help her with the task, we increased her stimulus duration to 67 ms for both experiments. In addition, she required many practice trials to get her performance above chance in Experiment 2. We have no explanation for her difficulties with the task and her differential performance in Experiments 1 and 2.

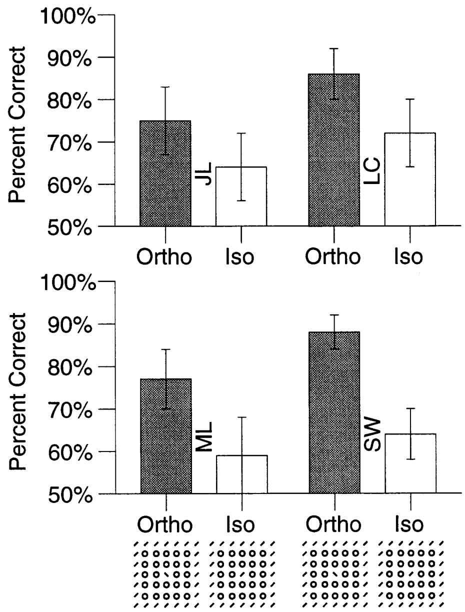


Fig. 9. Results for Experiment 5. All subjects show superior performance in the ortho-orientation condition (although JL's performance difference was not significant).

$-15°$, $-30°$, $-45°$)[8]. However, subject ML ran the blocks in a different order (0°, $-15°$, $-30°$, $-45°$, 15°, 30°, 45°). We thought ML's poor performance in the 0° target case might be due to the order in which he ran the trials, so after he had completed the experiment, we had him run the 0° target trials again; this data point is shown with an X on the left side of the plot. This data point is, as expected, between the performance levels in the $|45°|$ target conditions. Thus, all subjects show (1) performance in the 0° target case is in between performance in the iso- and ortho-orientation cases, (2) an iso- versus ortho-orientation effect which generally persists even when the texture elements are not exactly iso- or ortho-oriented.

Experiment 5 was run to get an idea of the spatial extent of the iso- versus ortho-orientation effect. The task in this and all subsequent experiments is the same as in Experiment 3. The stimuli were the same as in Experiment 3 except that the patch region was extended from 5×5 (1.25×1.25 deg) to 11×11 elements (2.75×2.75 deg). In general, even at this longer distance between the target element and the background elements, the iso- versus ortho-orientation effect still remains (Fig. 9). However, the effect is somewhat less pronounced than it was in Experiment 3. It would be useful to test even longer distances, but we could not do this with our experimental setup.

Experiment 6 was run to see if the iso- versus ortho-orientation effect was strictly a function of pop-out or if we would find the same effect with texture segregation. The stimuli were the same as those of Experiment 3 except that the target region was increased from 1 element to 3×3 elements. Subjects continued to perform better in the ortho-orientation than in the iso-orientation condition (Fig. 10). The terms texture segregation and pop-out cannot, in general, be used interchangeably. The results for segregation and visual search experiments do not always yield the same results (Wolfe, 1992). But, for our stimuli, either notion is apropos (the iso versus ortho-orientation effect applies in both cases).

In Experiment 7 we attempted to weaken the occluded surface percept. An occluded surface framework suggests that the iso- versus ortho-orientation effect is a function of the target element and the background region forming a surface, in the iso-orientation condition, which is perceived to be occluded by the patch region. There is an orientation discontinuity between each of these regions which helps to define them. If the discontinuity between the patch and background regions were smoothed, then the patch and background should group as a single surface, and the target should be seen as separate. The textures used in this experiment were like those used in Experiment 2 except that the orientation discontinuity between the patch and

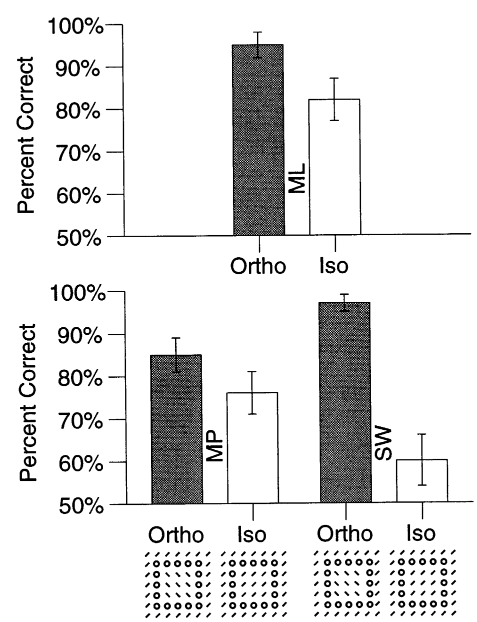


Fig. 10. Results for Experiment 6. All subjects show superior performance in the ortho-orientation condition.

[8] This ordering should minimize practice effects. To see why, consider the far right data points in Fig. 8. These data points represent the (standard) iso- and ortho-orientation conditions. Consider just the ortho-orientation data point. This point consists of the ortho-orientation trials from the 45° target blocks of trials and the ortho-orientation trials from the $-45°$ target blocks of trials. Thus, the first blocks of trials that were run (45°) and the last blocks of trials that were run ($-45°$) have been averaged together. Similarly the second set of blocks of trials and the second to last set of blocks of trials were averaged, etc.

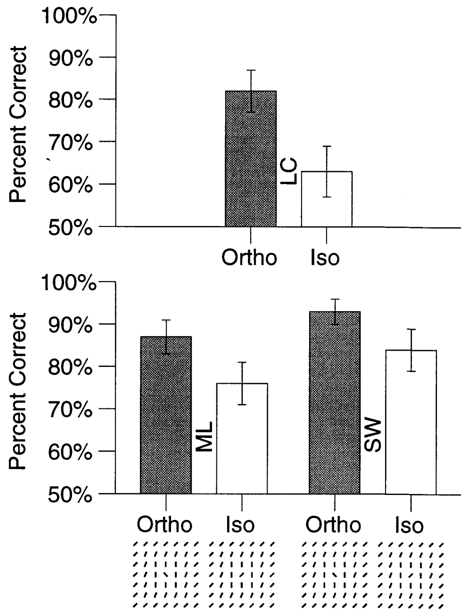


Fig. 11. Results for Experiment 7. All subjects show superior performance in the ortho-orientation condition.

background regions was smoothed (Fig. 4d). Subjects perform better in the ortho-orientation condition than in the iso-orientation condition (Fig. 11), suggesting that the effect is not (solely) mediated by the perception of occluded surfaces.

In Experiment 8 we again attempted to weaken the occluded surface percept. The textures were like those used in Experiment 3 except that the contrast of the target element was reversed (from white to black). This

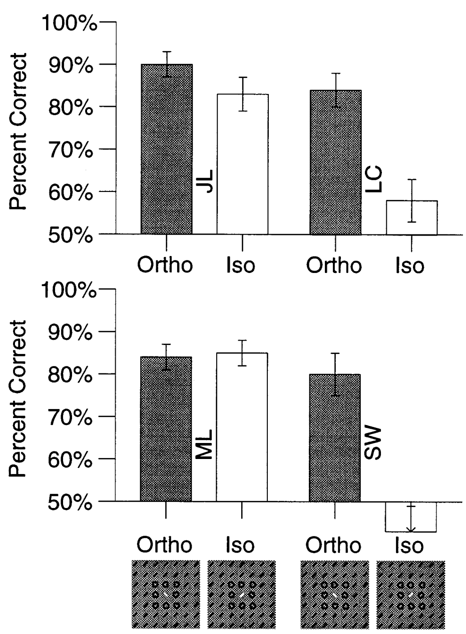


Fig. 12. Results for Experiment 8. Most subjects show superior performance in the ortho-orientation condition (see text for details on subject ML's performance).

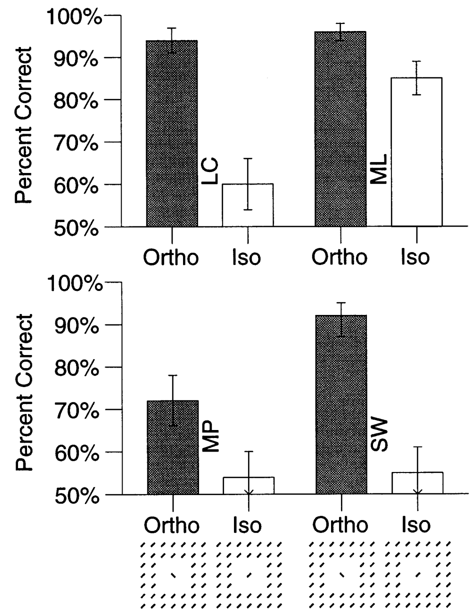


Fig. 13. Results for Experiment 9. All subjects show superior performance in the ortho-orientation condition than in the iso-orientation condition.

manipulation should interrupt the 'grouping' of the target element and the background elements since they are now perceptually quite different than each other. For a filter model, however, the change in polarity need have no effect as long as the nonlinearity has even components or interactions occur within and between ON and OFF channels. All subjects, except for ML, continue to perform better in the ortho-orientation condition than in the iso-orientation condition (Fig. 12). For this experiment only, subject ML noted and used an apparent brightness difference in the target elements to perform the task (that is, for ML, a circle element had a different brightness than an iso- or ortho-orientation target element, and the iso- and ortho-orientation targets had different brightnesses than one another). Other subjects did not comment on any brightness difference.

Experiment 9 was run to see if the patch elements are necessary. Caputo (1996) found that removing the patch elements eliminated the iso- versus ortho-orientation effect. Caputo (1996) used a biased procedure like that of Experiment 1; as noted previously, this procedure can eliminate the iso- versus ortho-orientation effect if the subject has knowledge of the experimental design or makes extensive use of feedback. However, removing the patch elements should not diminish the iso- versus ortho-orientation effect from the perspective of the filter framework. Any long range interactions between filters should continue to occur in the absence of the intervening patch elements. The stimuli in this experiment were the same as in Experiment 3 except that the patch region was blank. The results (Fig. 13) using this bias-free task show that performance is still better in the ortho-orientation condition than in the iso-orientation condition.

4. Discussion

The results show that there are long range interactions within textures. Specifically, a target element is better detected when it is oriented orthogonally to an array of background elements rather than oriented the same as an array of background elements (in addition, there may be effects of alignment, but these were not investigated here). This iso- versus ortho-orientation effect holds when the area between the target element and background elements is blank (Experiment 9), filled with vertical lines (Experiment 2), or filled with circular texture elements (Experiment 3). The effect, specifically, the difference in performance in the iso-orientation condition and the ortho-orientation condition, diminishes as the orientation of the target element changes from |45°| (right and left diagonal lines) to |0°| (horizontal line) (Experiment 4). The effect is shown when the distance between the target element and the nearest background element is between 0.5 deg (the shortest distance we examined, Experiment 3) and 1.25 deg (the longest distance we examined, Experiment 5). Furthermore, the effect holds when the target element is a single element and when the target is a group of elements, two cases which are generally treated as the separate phenomena of pop-out and texture segregation (Experiment 6). Finally, the effect is still in evidence when the textures are changed in ways that intuitively will make them less like occluded surfaces (Experiments 7 and 8).

The iso- versus ortho-orientation effect is clearly related to the notion of pop-out in visual search experiments e.g. Treisman and Gelade (1980). In the visual search literature, one is concerned with when a target item pops out from a background of distractor items, frequently using a yes-no paradigm, while varying the number of distractors. Here, a two interval forced-choice procedure is used and the layout of distractor (background and patch) items is manipulated. However, the phenomenology is the same: for ortho-orientation stimuli, the target often appears to pop out of the patch and background, and thus its form is easier to discern.

If we consider the data across experiments, we find that the iso- versus ortho-orientation effect is stronger in the one interval identification task than in the two interval detection task (compare Experiments 1 and 2), though this difference could be due to bias. We find that the iso- versus ortho-orientation effect is generally stronger when the patch elements are composed of circles rather than vertical lines (compare Experiments 2 and 3). Also, when the extent of the patch elements is increased, the iso- versus ortho-effect diminishes slightly (compare Experiments 3 and 5).

Our results can be thought of in the context of a filter framework or an occluded surface framework. These two frameworks might just be different levels of processing, where the low-level filter outputs feed into a higher-level surface representation. However, if this is the case, there is something else involved too since (1) there are texture segregation results which are inconsistent with a filter framework but can be accounted for by reference to an occluded surface representation (e.g., He and Nakayama, 1994); and (2) as we have shown in Experiments 7 and 8, there are texture segregation results which agree with a filter framework but cannot be easily explained by an occluded surface framework. All of our results are consistent with a filter framework interpretation. The filter framework, as we have defined it, can be conceptualized as a modified back pocket model of texture segregation; that is, between the second and third stage of a standard back pocket model we can add a stage in which oriented elements interact with one another. The model starts with a bank of orientation and spatial frequency tuned linear filters (like V1 simple cells); next, an even nonlinearity (such as squaring) is applied to these outputs; next, orthogonal elements excite one another and elements of the same orientation inhibit one another; finally, the texture is segmented based on changes in the output over space. Such a model is roughly consistent with the physiological literature on context effects discussed earlier.

Experiment 7 (Fig. 4d) tests the filter theory by smoothing the discontinuity between the patch elements and the background elements. Such a manipulation should not alter the output from a filter model very drastically. That is, as stated in the Introduction, the influence of the unrotated background elements (which are the majority of the background elements) on the target should be unaffected by the change in the element orientations at the background/patch boundary. The rotation of the elements near the boundary might have an effect, but they are relatively few in number and the effect should be small. However, the smoothed elements should have a drastic impact on the occluded surfaces interpretation. Since the background and patch regions should now form one surface, the target should be perceived as a separate object/surface, and no iso- versus ortho-orientation effect is predicted. In support of the filter framework, subjects in this experiment show the iso- versus ortho-orientation effect. The occluded surface and the filter frameworks also suggest different performance levels in Experiment 8 (Fig. 4e). In this experiment we changed the sign of the contrast of the target element relative to the contrast sign of the background elements. This manipulation should disrupt the formation of an occluded surface consisting of the target element and the background elements. However, this manipulation should not change the output from a filter model (with an even nonlinearity), and most subjects do indeed continue to show the iso- versus ortho-orientation effect in this experiment. Thus, our results are consistent with the filter framework but not with the occluded surface framework.

It may be that the orientation-tuned long range interactions seen here are a low-level trick intended to subserve a later computation of surfaces. In threshold vision with brief displays as studied here, the workings of these interacting filters are revealed. The full implications of surface representations are uncovered when the visual system is given adequate time to form such representations (as in the texture segregation results of He and Nakayama (1994), or in visual search experiments).

5. Conclusions

We have shown that there are long range interactions between the oriented line elements which compose some textures. In general, detection of a target element is better when it is embedded in a (distant) background of orthogonally oriented line elements rather than a background of similarly oriented line elements. These results are comparable to single cell recording experiments in V1 which examine the effects of stimuli placed outside a cell's classical receptive field on a cell's response. We believe our results can be accounted for by a model of texture segregation that allows for long range interactions among low-level filters across space and orientation.

Acknowledgements

The work described in this paper was supported in part by grant EY08266 from the National Institute of Health. We would like to thank Marisa Carrasco, Norma Graham, Larry Maloney, Brian McElree and two anonymous reviewers for helpful comments. We would like to thank our subjects, Jennifer Leong, Leanne Chukoskie, Melanie Palomares, and Shani Offen.

References

Cannon, M. W., & Fullenkamp, S. C. (1991). Spatial interactions in apparent contrast: inhibitory effects among grating patterns of different spatial frequencies, spatial positions and orientations. *Vision Research*, *31*, 1985–1998.

Caputo, G. (1996). The role of the background: texture segregation and figure-ground segmentation. *Vision Research*, *36*, 2815–2826.

Chubb, C., & Landy, M. S. (1991). Orthogonal distribution analysis: a new approach to the study of texture perception. In M. S. Landy, & J. A. Movshon (Eds.), *Computational models of visual processing*. Cambridge, MA: The MIT Press, 291–301.

Field, D. J., Hayes, A., & Hess, R. F. (1993). Contour integration by the human visual system: evidence for a local 'association field'. *Vision Research*, *33*, 173–193.

He, Z. J., & Nakayama, K. (1994). Perceiving textures: beyond filtering. *Vision Research*, *34*, 151–162.

Kapadia, M. K., Ito, M., Gilbert, C. D., & Westheimer, G. (1995). Improvement in visual sensitivity by changes in local context: parallel studies in human observers and in V1 of alert monkeys. *Neuron*, *15*, 843–856.

Knierim, J. J., & Van Essen, D. C. (1992). Neuronal responses to static texture patterns in area V1 of the alert macaque monkey. *Journal of Neurophysiology*, *67*, 961–980.

Landy, M. S., & Bergen, J. R. (1991). Texture segregation and orientation gradient. *Vision Research*, *31*, 679–691.

Landy, M. S., Cohen, Y., & Sperling, G. (1984a). HIPS: A UNIX-based image processing system. *Computer Vision, Graphics, and Image Processing*, *25*, 331–347.

Landy, M. S., Cohen, Y., & Sperling, G. (1984b). HIPS: Image processing under UNIX-Software and applications. *Behaviour Research Methods, Instruments & Computers*, *16*, 199–216.

Levitt, J. B., & Lund, J. S. (1997). Contrast dependence of contextual effects in primate visual cortex. *Nature*, *387*, 73–76.

Malik, J., & Perona, P. (1990). Preattentive texture discrimination with early vision mechanisms. *Journal of the Optical Society of America A*, *7*, 923–932.

Nothdurft, H. C. (1992). Feature analysis and the role of similarity in preattentive vision. *Perception and Psychophysics*, *52*, 355–375.

Polat, U., & Sagi, D. (1994). The architecture of perceptual spatial interactions. *Vision Research*, *34*, 73–78.

Saarinen, J., Levi, D. M., & Shen, B. (1997). Integrating of local pattern elements into a global shape in human vision. *Proceedings of the National Academy of Science USA*, *94*, 8267–8271.

Sillito, A. M., Grieve, K. L., Jones, H. E., Cudeiro, J., & Davis, J. (1995). Visual cortical mechanisms detecting focal orientation discontinuities. *Nature*, *378*, 492–496.

Solomon, J. A., Sperling, G., & Chubb, C. (1993). The lateral inhibition of perceived contrast is indifferent to on-center/off-center segregation, but specific to orientation. *Vision Research*, *18*, 2671–2683.

Treisman, A., & Gelade, G. (1980). A feature integration theory of attention. *Cognitive Psychology*, *12*, 97–136.

Wolfe, J. M. (1992). 'Effortless' texture segmentation and 'parallel' visual search are not the same thing. *Vision Research*, *32*, 757–763.