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Examining Edge- and Region-based Texture Analysis Mechanisms

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Instantaneous texture discrimination performance was examined for different texture stimuli to uncover the use of *edge-based* and *region-based* texture analysis mechanisms. Textures were composed of randomly placed, short, oriented line segments. Line segment orientation was chosen randomly using a Gaussian distribution (described by a mean and a standard deviation). One such distribution determined the orientations on the left side of the image, and a second distribution was used for the right side. The two textures either *abutted* to form an edge or were *separated* by a blank region. A texture difference in mean orientation led to superior discrimination performance when the textures abutted. On the other hand, when the textures differed in the standard deviation of the orientation distribution, performance was similar in the two conditions. These results suggest that edge-based texture analysis mechanisms were used (i.e. were the most sensitive) in the abutting *difference-in-mean* case, but region-based texture analysis mechanisms were used in the other three cases. © 1998 Elsevier Science Ltd. All rights reserved.

Texture Edge Region Segmentation Segregation

INTRODUCTION

Instantaneous texture segregation, also called effortless or preattentive texture segregation, is the "instantaneous" segregation of regions composed of different textures. An example of this can be seen in Fig. 1, where the region on the left side of the image and the region on the right are easily and quickly segregated. Texture segregation performance is affected by numerous texture attributes: density, orientation, size, and so on [Julesz (1981); Beck (1982); Nothdurft (1985a); for an excellent review of texture segregation see Bergen (1991)].

The terms *segregation* and *discrimination* cannot be used interchangeably. *Segregation* implies that the observer "instantaneously" perceives a distinct edge between abutting regions. This perceived edge can be used for tasks such as shape discrimination (e.g. Landy & Bergen, 1991; Wolfson & Landy, 1995a). On the other hand, *discrimination* is used to indicate the observer can distinguish between regions (using the appearance of each region's texture) regardless of whether a distinct edge is perceived where the textures abut. Many texture segregation experiments ask subjects whether the textures on either side of a border differ. Correct performance could result either from segregation (an edge is perceived) or discrimination (the two halves of texture appear to be different classes of texture). If two textures are separated in space or time, one might argue that only discrimination can be used to perform the task, as the region segregation is now obvious even if the two texture samples are physically identical. If a texture pair were easily discriminable but did not segregate well, then observers would be able to tell that there were two regions, but would be poor at tasks requiring precise localization or details of the texture border. Conversely, it is possible to make two texture regions that are not discriminable, but details at the border lead to good segregation. Examples of this include abutting, out-of-phase (but otherwise identical) grating or plaid patterns, or the textural Craik/O'Brien/Cornsweet illusion (Nothdurft, 1985b).

In this paper all textures are composed of short, oriented line segments. Textures such as these have been studied extensively (Nothdurft, 1985a,b; Sagi & Julesz, 1985; Wolfe, 1992; Wolfson & Landy, 1995a), since these textures allow the experimenter easy control of some important parameters:

- The mean *orientation difference* across the texture boundary: compare the large orientation difference in Fig. 1 to the small orientation difference in Fig. 2.
- The *texture gradient*, Δorientation/Δspace, between the textures: compare the abrupt gradient of the *abutting* textures in Fig. 1 to the gradual gradient in Fig. 3 or the *separated* textures in Fig. 4.

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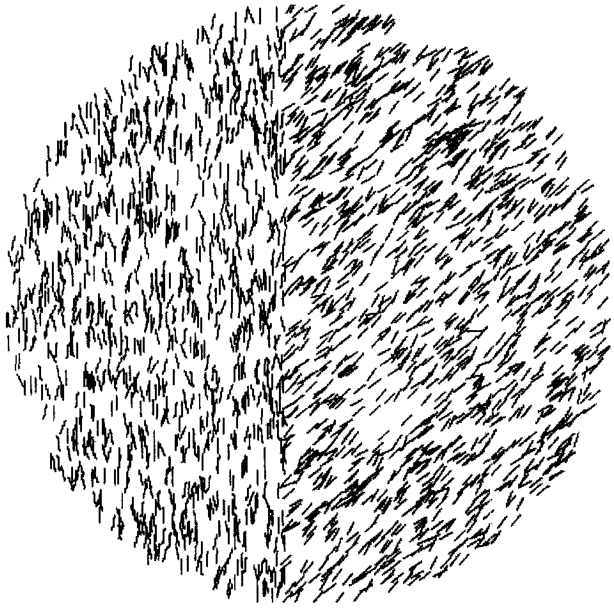

FIGURE 1. The texture on the left has a mean (μ) orientation of 0° while the texture on the right has a mean orientation of 45°. The textures quickly and effortlessly segregate. In the experiments, all stimuli consisted of white line segments on a gray background.

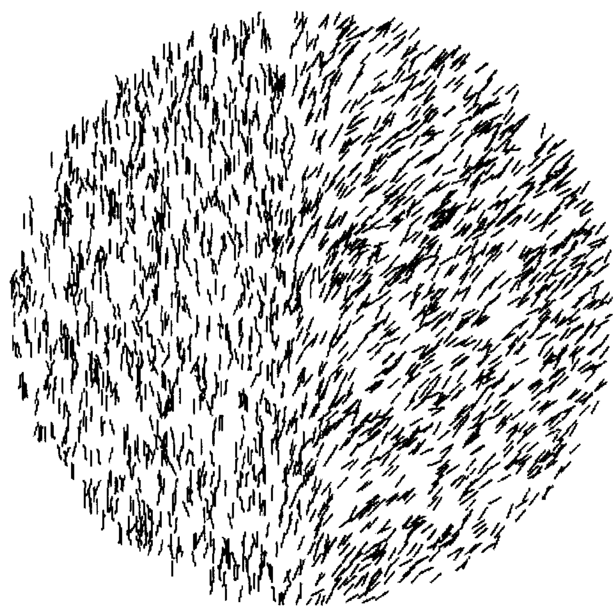

FIGURE 3. The textures differ in mean (μ) orientation by 45°, as in Fig. 1. While the textures in Fig. 1 abut to form an edge, between these textures there is a a smooth transition (a non-abrupt texture gradient) in mean orientation over a small distance, resulting in poorer texture segregation.

- The *variability* of a texture within a region: compare the small variance on the left side of Figs 5 and 6 with the large variance on the right side.

In general, the greater the mean orientation difference across the boundary, the better the segregation performance (Nothdurft, 1985b; Bergen & Landy, 1991; Landy & Bergen, 1991). However, the relationship between the individual line segment orientations and the edge they define can affect performance as well; for example, texture elements which align with the edge they define improve segregation (Nothdurft, 1992; Wolfson & Landy, 1995a). In general, the more abrupt the texture gradient between textures, the better the segregation performance (Nothdurft, 1985b; Landy & Bergen, 1991). However, Gurnsey and Laundry (1992) show that texture discrimination performance for abutted textures and separated textures of micropatterns can sometimes be

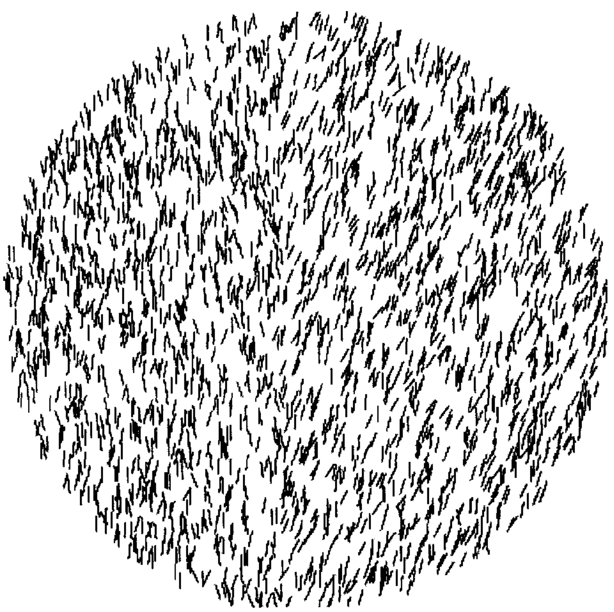

FIGURE 2. The texture on the left-hand side and the texture on the right-hand side differ in mean (μ) orientation, but the difference is small (15°). Segregation is much weaker than for the pair in Fig. 1.

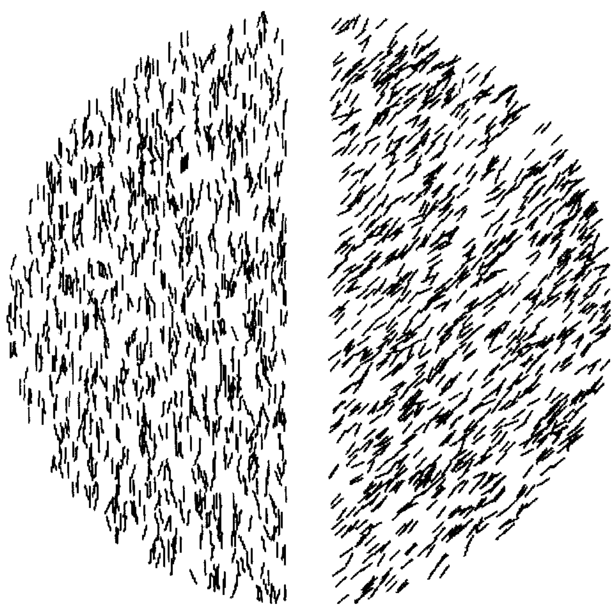

FIGURE 4. The textures differ in mean (μ) orientation by 45°, as in Fig. 1. While the textures in Fig. 1 abut to form an edge, these textures are separated, making discrimination of the two textures more difficult.

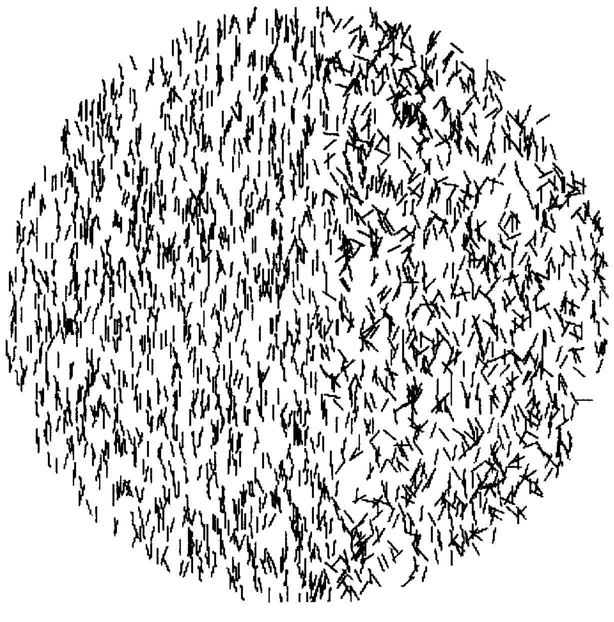

FIGURE 5. The texture on the left has a standard deviation (σ) of texture element orientation of 10° while the texture on the right has a standard deviation of 30°. The textures have the same mean (μ) orientation.

similar, stating: "If texture discrimination is a region-based rather than a boundary-based process then there may be little difference between the [abutting and separated] conditions".

Are there different types of texture analysis mechanisms? In the image analysis literature, a distinction is made between *edge-based* and *region-based* image segmentation methods. The typical "back-pocket model" of human texture segregation (Chubb & Landy, 1991) is an example of an edge-based scheme. It processes the image by:

1. convolving the image with a set of orientation-selective linear filters;
2. applying a nonlinearity (such as x^2, resulting in "texture energy"); and
3. segmenting based on changes in the local average output over space.

Stages 1 and 2 attempt to convert a textural difference to a difference in local response of a nonlinear filter. For example, a vertically oriented filter applied to the textures in Fig. 1 would result in an energy map (the output of stage 2) with high energy on the left and low energy on the right. It is stage 3 that makes this an edge-based segmentation method, since it calls for the stage 2 response map to be segmented using a local edge detection mechanism.

Alternative segmentation schemes are region-based (e.g. Caelli, 1985; Haralick, Shanmugam & Dinstein, 1973). In region-based schemes, the idea is to treat neighboring regions as belonging to the same image source (e.g. texture) if they are sufficiently similar (i.e. if they are classified as the same kind of texture). Such computational methods are called "region-growing", as each labeled region is allowed to grow until it bumps into a piece of image it no longer matches. Edges between regions are not explicitly detected, but rather are implicitly formed between the regions that are grown.

Is there any evidence for region-based texture analysis in human observers? When two textures abut, it is natural to consider their discrimination as resulting from some form of edge detection. At the other extreme, consider seeing a texture one day, and a different texture the next day. To discriminate these textures, it seem unlikely that

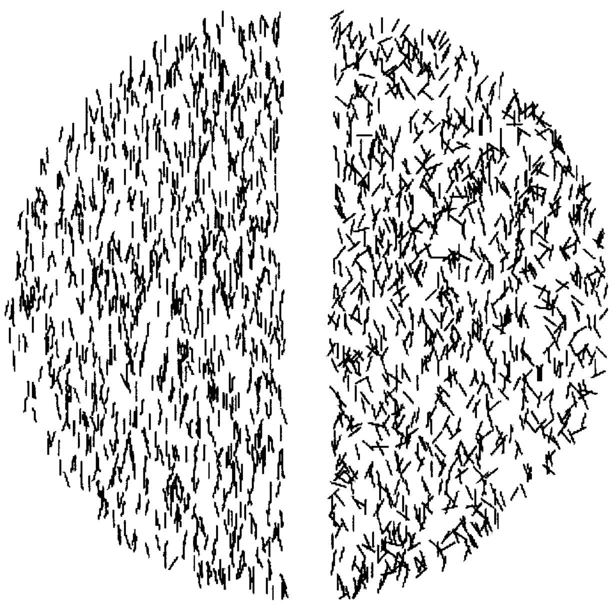

FIGURE 6. The texture on the left has a standard deviation (σ) of texture element orientation of 10° while the texture on the right has a standard deviation of 30°, as in Fig. 5. The textures have the same mean (μ) orientation. While the textures in Fig. 5 abut to form an edge, these textures are separated. Our results suggest it is likely that a region-based texture discrimination mechanism is used for these stimuli.

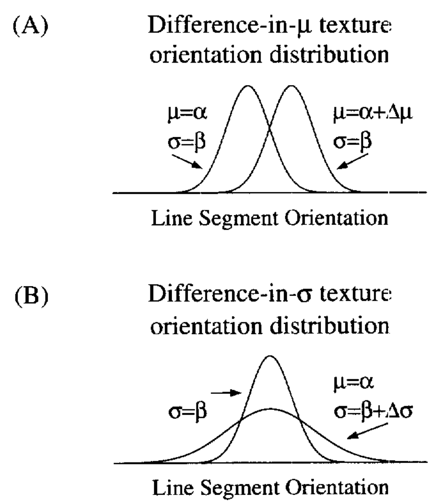

FIGURE 7. Schematic diagrams of the texture element orientation distributions for the (A) difference-in-μ textures (Figs 1 and 4) and (B) difference-in-σ textures (Figs 5 and 6).

the judgment is based on local (temporal) changes in some energy map. Rather, there must be some way to classify the appearance of each texture (using region-based mechanisms), and compare the stored classification of the first texture with that of the second. This region-based method would then be useful any time two textures were to be discriminated, especially in cases where edge-based mechanisms were ineffective.

Consider the two separated patches of texture shown in Fig. 4. If an observer tried to discriminate the two textures using an edge-based mechanism, performance would suffer due to the extraneous edge responses from the edges between each texture and the blank region. Thus, when edge-based mechanisms are the most sensitive ones for discriminating two textures, discrimination performance suffers when the textures are separated. However, suppose there was a pair of textures for which discrimination was more effectively accomplished using a region-based mechanism. In that case, separating the textures need not degrade performance. In fact, performance could improve as the extraneous edges now serve to clearly delineate the two regions to be discriminated.

Here, we examine whether we can psychophysically distinguish edge-based texture analysis mechanisms (which are based on the texture gradient) and region-based texture analysis mechanisms (which do not use the texture gradient). To do this, we have generated two types of texture pairs (shown schematically in Fig. 7). In each textured region, the line segment orientations are chosen randomly using a Gaussian distribution; thus, each textured region can be described in terms of a mean and standard deviation of line segment orientation. Our *difference-in-mean* (μ) textures vary the mean of the line segment orientation distribution across the boundary [Figs 1, 4 and 7(A)]. Our *difference-in-standard deviation* (σ) textures vary the standard deviation of the line segment orientation distribution across the boundary [Figs 5, 6 and 7(B)]. As argued above, we would expect that edge-based mechanisms will be effective in segregating textures differing in μ. Conversely, to discriminate textures differing in σ, the observer must first estimate σ in various image patches (using a region-based mechanism). Thus, we predict that:

- the abutting difference-in-μ textures should be easier to segment than the separated difference-in-μ textures; and

- the abutting difference-in-σ textures should be no easier to discriminate than those that are separated.

METHOD

Subjects

There were six subjects*: the two authors and four subjects naive to the purpose of the experiment. All subjects had normal or corrected-to-normal vision.

Stimuli

Each stimulus† was a circular (diameter = 9.6 deg) texture composed of white oriented line segments (texture elements) on a gray background. Initially, each stimulus was created as a square (9.6 deg × 9.6 deg) with 3000 texture elements, and then cut to be a circle. Texture elements were line segments of length 0.24 deg and density 33 texture elements/deg^2. Each image contained two textured regions (one on the left-hand side and one on the right-hand side). In each textured region, the texture element orientations were chosen randomly using a Gaussian distribution (described by a mean, μ, and a standard deviation, σ). The textured regions were either: (i) separated by 0.72 deg; or (ii) abutted at the left end or right end of that same region. The textures abutted at either extreme of the central 0.72 deg region of the image so that: (i) subjects would not know in advance where the edge was located; and (ii) eccentricity would not confound the results. The fact that subjects did not always perform better in the abutting condition than in the separated condition indicates that our effects are not simply the result of a difference in eccentricity‡.

Two different displays were used§: a Barco Calibrator color monitor viewed from a distance of 125 cm and a Nanao Flexscan 9070U color monitor viewed from a distance of 95 cm. These viewing distances resulted in the same visual angle. The lookup tables were set so that the relationship between pixel value and display luminance was linear. The stimuli were generated prior to the experiment using the HIPS image processing software (Landy, Cohen & Sperling, 1984a,b). The room was dark except for a small, diffuse light on the side.

Procedure

The task was texture discrimination using a two-alternative forced-choice procedure and interleaved staircases to place trials. In one interval (chosen randomly), the two textured regions had the same μ and

*One additional subject was run. He did not complete the experiments so his results are not shown.

†To avoid confusion, "deg" is used to denote measurements of stimulus size and "°" for line segment orientation.

‡Since the line segments are randomly located, line segments can intersect. Thus, an additional issue is whether our effects are based on detecting these intersections, either in the two regions (as a means of discriminating the regions) or at the boundary between the regions (as a means of detecting the texture edge). The former strategy would not differ substantially across the separated and abutting conditions and is not a concern. In the abutting difference-in-σ condition, the number of crossings is comparable across the image. In the abutting difference-in-μ condition, there are more crossings at the edge than elsewhere in the image. However, in the case of $\mu = 90°$ (of the abutting difference-in-μ condition), the probability (at threshold) of a texture element crossing another near the edge is no different from the probability elsewhere in the image. We analyzed the data for this case, and the effects discussed in the paper are still present. Thus, the effects discussed here cannot be accounted for by differences in the statistics of line crossings across the image.

§Subjects MSL, PDS, POD and SSW ran using the Barco monitor. Subjects LC and MAM ran using the Nanao monitor.

σ; in the other interval, the two textured regions differed in either μ or σ. In the interval with the two differently textured regions (the "target" interval), one of the textures (chosen randomly) could be described as $\mu = \alpha$, $\sigma = \beta$ (where α is 0°, 30°, 60°, 90°, 120° or 150°, and β is 10°); the other textured region could be described as: (I) $\mu = \alpha + \Delta\mu$, $\sigma = \beta$ for the difference-in-μ task; or (II) $\mu = \alpha$, $\sigma = \beta + \Delta\sigma$ for the difference-in-σ task. In the interval with the same texture on each side (the "blank" interval), both textures could be described as: (I) (i) $\mu = \alpha$, $\sigma = \beta$ or (ii) $\mu = \alpha + \Delta\mu$, $\sigma = \beta$ (chosen randomly) for the difference-in-μ task; or (II) (i) $\mu = \alpha$, $\sigma = \beta$ or (ii) $\mu = \alpha$, $\sigma = \beta + \Delta\beta$ (chosen randomly) for the difference-in-σ task. The subject's task was to identify the interval containing the two differently textured regions.

There were two types of texture pairs (difference-in-μ and difference-in-σ) and two stimulus layouts (separated and abutting), resulting in four conditions. Each block of trials contained a single condition, and consisted of two two-up-one-down interleaved staircases. Each subject ran at least two blocks of trials per data point, and there were 200 trials per block. Each trial consisted of a 750 msec cue followed by a 250 msec blank, a 250 msec stimulus, another 250 msec blank, and then a second 250 msec stimulus. The screen remained blank (at the same mean luminance) after the second stimulus interval until the subject responded. The subject's response initiated the subsequent trial. Auditory feedback was provided after each trial.

RESULTS

In the first experiment, the mean (μ) texture element orientation was varied across the boundary while the standard deviation (σ) of the texture element orientation distribution was held constant. The textures on the left and right hand sides were either abutting (as in Fig. 1) or separated (as in Fig. 4). The results in Fig. 8 show the increment threshold change in μ (that is, $\Delta\mu$) for six subjects in the two conditions. Error bars indicate 95%

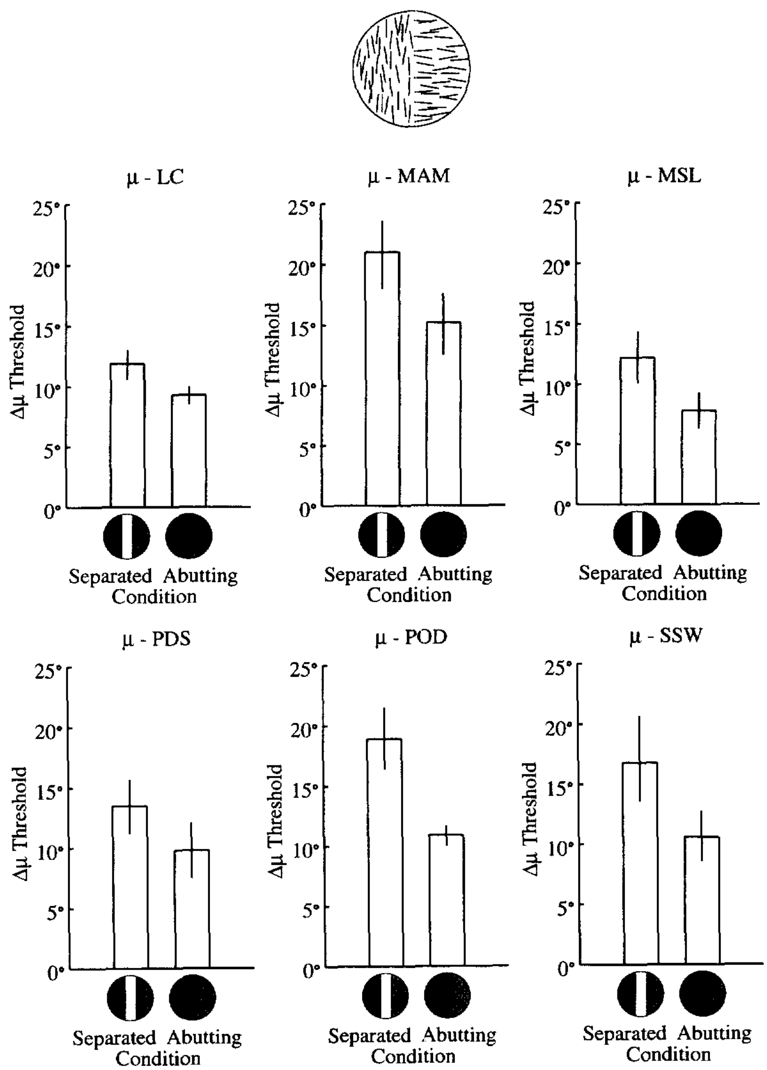

FIGURE 8. Results for six subjects for the difference-in-μ (the mean of the texture element orientation distribution) textures. The increment threshold change in μ is shown for each condition. Note that all subjects perform better in the abutting condition than in the separated condition.

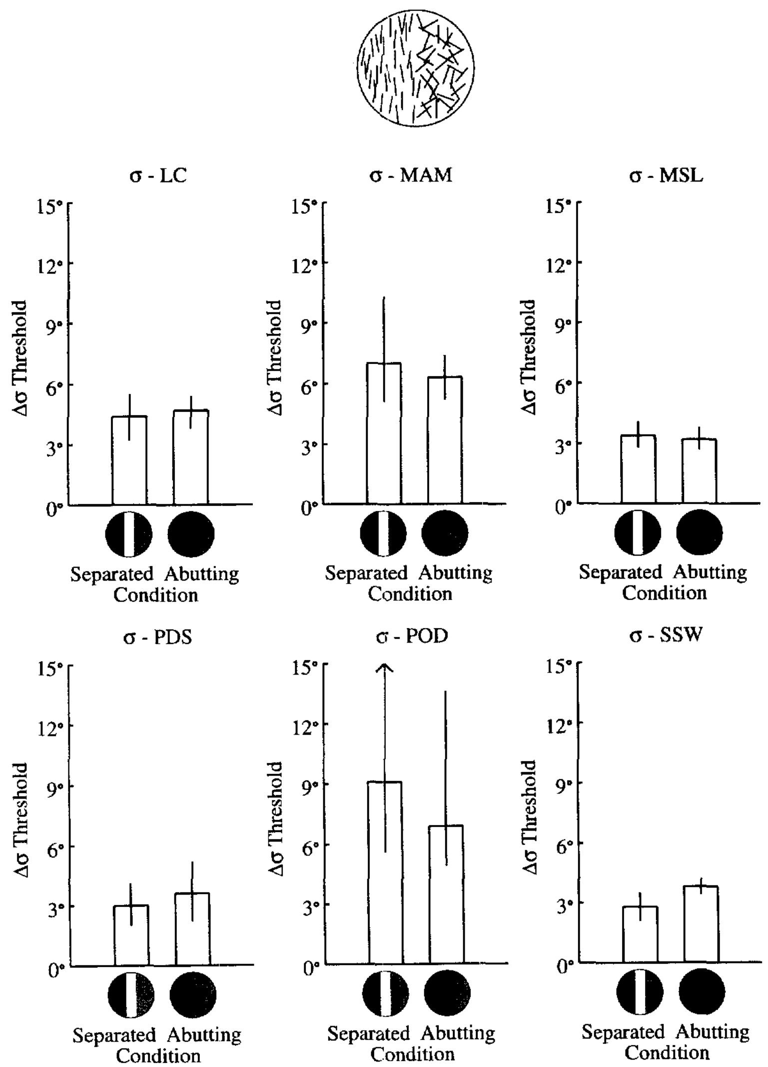

FIGURE 9. Results for six subjects for the difference-in-σ (the standard deviation of the texture element orientation distribution) textures. The increment threshold change in σ is shown for each condition. Note that subjects perform similarly in the abutting and separated conditions.

confidence intervals*. As predicted, subjects performed better in the abutting condition than in the separated condition†.

In the second experiment, σ was varied across the boundary while μ was held constant (as in Figs 5 and 6). The results in Fig. 9 show the increment threshold change in σ (that is, $\Delta\sigma$) for the six subjects in the two conditions. It was predicted that subjects would perform at least as well when the textures were separated as they did when they abutted. This was indeed the case for all subjects tested‡.

IDEAL OBSERVER

We have demonstrated that in some cases (difference-in-μ) separating textures results in decreased performance but not in other cases (difference-in-σ). One might argue that this effect was simply an aspect of the stimuli (the tasks that subjects found easier were, in fact, easier) rather than a demonstration of an aspect of observer abilities. To answer this objection, we computed the

*Data were fit with a Quick function using the maximum likelihood method, and then a bootstrap estimate of parameter variability was run (on the Quick parameters for the mean, α, and the slope, β). The resulting error bars represent 95% confidence intervals around the 75% correct points.

†Keeble, Kingdom, Moulden and Morgan (personal communication) have performed research similar to ours, examining texture discrimination for regions which differ in μ. They find that discrimination performance is comparable when the textures abut, are separated by a blank region, or are separated by a region filled with noise. We do not know how to account for the difference in the results. Keeble believes that the edge effect is more evident the poorer a subject is at the task.

‡To say that performance in two conditions is "similar" is most convincing when the error bars are small in addition to the data points being similar. The more trials a subject runs (and the smaller the variability in the subject's responses), the smaller the error bars. Thus, two subjects, SSW and PDS, were run extensively in the difference-in-σ task. These two subjects out of the six were chosen to run additional trials simply because they had the most time available in their schedules. PDS ran 2200 trials per point, and SSW ran 1600 trials per point. If anything, these subjects show a tendency to perform better in the separated condition (as was suggested in the Introduction).

performance of an ideal observer confronted with the same discrimination task. The ideal observer was given the trial type (difference-in-μ or difference-in-σ) and the stimuli in each of the two intervals coded as a list of texture elements (orientation and location). The ideal observer also was given the two possible edge locations (for the abutting case) and the base values of σ and μ (the α and β values discussed in the Procedure section). Because the prior probabilities of the target stimulus appearing in the two intervals were equal, as were the probabilities of each of the various kinds of stimuli (see the Procedure section for details), the *maximum a posteriori* and *maximum likelihood* strategies are identical. The ideal strategy is to respond that the target was in interval 1 if

$$\sum_j P(\text{stimulus}|\text{target interval} = 1, \text{case } j) > \sum_j P(\text{stimulus}|\text{target interval} = 2, \text{case } j).$$

The cases are the mutually exclusive, equally likely stimulus possibilities that were described in the Procedure section. A jth case consists of a specification of the value of μ and σ for each portion of the two images and of which texture elements belong to which side of the edge. Letting x be either μ or σ (depending on whether this is a difference-in-μ trial or a difference-in-σ trial), the cases range over:

1. the two types of "target" interval (x on the left or right side of the edge, and $x + \Delta x$ on the other side);
2. the two types of "blank interval" (either x or $x + \Delta x$ on both sides of the edge); and
3. the one or two possible edge locations (one edge location in the separated condition, two edge locations in the abutting condition).

Thus, there are four cases in the separated condition and eight in the abutting condition.

For the jth case in the ith interval, we can compute the likelihood:

$$P(\text{stimulus}|\text{interval} = i, \text{case } j) = \prod_{k=1}^{2}\prod_{l=1}^{2}\prod_{m} \frac{1}{\sigma_{ijkl}\sqrt{2\pi}} e^{-(\mu_{ijkl}-\theta_m)^2/2\sigma_{ijkl}^2}.$$

Here, k specifies the interval, l specifies the side of the edge being considered, m runs over the texture elements in that lth side of the edge in that kth interval (the texture elements are also constrained by the edge location which is determined by the case j), and θ_m is the orientation of texture element m. Once a particular case and portion of the stimulus is chosen, the ideal observer has a model of the distribution from which that texture element was drawn (μ_{ijkl} and σ_{ijkl}) and can calculate the probability of that texture element occurring. Finally, texture elements are treated as independent as was the case in the stimuli.

The ideal observer was run in all four conditions using 7000 trials to determine each threshold. For the difference-in-μ textures, the ideal observer's threshold was slightly (but insignificantly) lower in the abutting condition (0.379°) than in the separated condition (0.386°). For the difference-in-σ textures, the thresholds were comparable in the abutting (0.228°) and separated (0.226°) conditions. The small differences in the ideal observer's performance do not account for the differences in performance seen in the human observers, indicating that our effects are not due to intrinsic differences in task difficulty. The efficiency scores (i.e. ideal observer's threshold/human observer's threshold) for one subject (SSW) for the difference-in-μ textures are 0.036 (abutting) and 0.023 (separated), and for the difference-in-σ textures are 0.060 (abutting) and 0.082 (separated). Since the ideal's thresholds are comparable within a task (but not across the difference-in-μ and difference-in-σ tasks), the efficiencies within a task simply reflect the observer's data. However, the difference in efficiency across tasks is surprising, indicating that the subject was more efficient with the difference-in-σ textures than with the difference-in-μ textures. On the other hand, the efficiencies are so low overall that we can conclude that the observers are doing something quite different than the ideal*.

DISCUSSION

When the textured regions differ in μ (the mean of the texture element orientation distribution), we find that discrimination performance is better when the textures are abutting (rather than separated). On the other hand, when the textured regions differ in σ (the standard deviation of the texture element orientation distribution), we find that discrimination performance is comparable in both conditions.

The abutting textured regions which differed in μ are tailor-made for the edge-based texture analysis mechanisms of the "back-pocket model" of texture discrimination discussed in the Introduction: they produce strong orientation-defined edge responses. However, when these textures are separated, performance declines. There are at least three possible explanations for this decline.

1. If an edge-based texture analysis mechanism is employed when the textures are separated then the additional edge responses (produced at the edges of the blank region) make the task more difficult.
2. If region-based texture analysis mechanisms are employed when the textures are separated (and edge-based mechanisms are employed when the textures are abutting) then the results indicate these region-based mechanisms are simply not as sensitive as edge-based mechanisms.

*In the version of the ideal observer we are reporting, the ideal was given the value of $\Delta\mu$ or $\Delta\sigma$. Our observers did not have access to such information (as it was varied across trials by a staircase procedure). We also simulated an ideal observer with uncertainty as to the exact value of Δ (a flat distribution over several values, comparable to the range staircases achieved). The results were no different for this ideal observer.

3. If region-based texture analysis mechanisms are always employed and an edge-based mechanism is employed in addition when the textures are abutting, then the difference in performance indicates the usefulness of the edge-based mechanisms.

Regardless of which particular explanation is correct, the results indicate that edge-based texture analysis mechanisms are utilized effectively when these textures abut but not when they are separated.

The textured regions which differed in σ ill-suit the "back-pocket model" of texture discrimination. The textured regions yield little difference in average response from typical, linear, oriented mechanisms and hence are difficult to discriminate using edge-based mechanisms following linear filtering and energy computation. To discriminate these textures requires a region-based texture analysis mechanism (e.g. the estimation of local orientation variability, a kind of texture "appearance" measure) and the separation of the individual texture regions does not interfere with such mechanisms. The results also show that subjects are more efficient in the difference-in-σ task relative to the difference-in-μ task.

Thus, it appears that there are both edge-based and region-based texture analysis mechanisms. Either the edge-based mechanisms are more sensitive than the region-based mechanisms (within a particular task, for example, the difference-in-μ task), or edge-based mechanisms can be used in conjunction with region-based mechanisms to attain a greater sensitivity than the region-based mechanisms achieve in isolation. Either interpretation allows us to state that there are some pairs of textures (those with orientation differences lying between the abutting and separated thresholds for the difference-in-μ stimuli) which cannot be discriminated (separated condition), but can be segregated (abutting condition).

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