

# Texture segmentation influences the spatial profile of presaccadic attention

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Attention is important for selecting targets for action. Several studies have shown that attentional selection precedes eye movements to a target, and results in an enhanced sensitivity at the saccade goal. Typically these studies have used isolated targets on blank backgrounds, which are rare in real-world situations. Here, we examine the spatial profile of sensitivity around a saccade target on a textured background and how the influence of the surrounding context develops over time. We used two textured backgrounds: a uniform texture, and a concentric arrangement of an inner and an outer texture with orthogonal orientations. For comparison, we also measured sensitivity around the target on a blank background. The spatial profile of sensitivity was measured with a brief, dim, probe flashed around the saccade target. When the target was on a blank or a uniformly textured background, spatial sensitivity peaked near the target location around 350 ms after cue onset and declined with distance from the target. However, when the background was made up of an inner and outer texture, sensitivity to the inner texture was uniformly high, peaking at about 350 ms after cue onset, suggesting that the entire inner texture was selected along with the target. The enhancement of sensitivity on the inner texture was much smaller when observers attended the target covertly and performed the probe-detection task. Thus, our results suggest that the surface representation around the target is taken into account when an observer actively plans to interact with the target.

## Introduction

When we attend to a target, selective attention enhances the sensitivity at the target location. This is true whether attention is directed to a peripheral target covertly (Carrasco, Loula, & Ho, 2000; Eckstein, Shimozaki, & Abbey, 2002; Gandhi, Heeger, &

Boynton, 1999; Kim, Grabowecy, Paller, Muthu, & Suzuki, 2007; Lauritzen, Ales, & Wade, 2010; Martinez et al., 1999; Moran & Desimone, 1985; Motter, 1993; Müller, Teder-Sälejärvi, & Hillyard, 1998; Reynolds, Chelazzi, & Desimone 1999; Saenz, Buracas, & Boynton, 2002; Treue & Maunsell, 1996) or overtly with eye movements (Bahcall & Kowler, 1999; Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995; Kowler, Anderson, Doshier, & Blaser, 1995). Most of these studies have looked at sensitivity to a target on a blank background. However, in natural scenes, a target often lies on a textured surface, or among many similar objects. Here, we ask how a textured background affects the spatial pattern of sensitivity around the attended target. Our rationale is that texture segmentation processes likely occur before attention is directed to the background, and that these must influence how the profile of attention spreads around the target (see Chen, 2012).

Texture segmentation and grouping were regarded initially as bottom-up processes that occurred early and relatively independently of attention (Graham, 1991; Landy & Bergen, 1991). Landy and Bergen (1991) measured observers' ability to judge the shape of a foveal texture as a function of the presentation time of the texture (duration from stimulus onset to the onset of a subsequent mask). They found that performance improved with presentation times, and then reached an asymptote at about 80 to 130 ms. More recent studies using evoked responses (electroencephalography/EEG) show that attention modulates later aspects of texture segregation. Specifically, while early texture-specific responses at about 100 ms after stimulus onset appear to be independent of attention demands, evoked responses that occur after 250 ms are much more susceptible to the demands of attention (Heinrich, Andres, & Bach, 2007; Schubo, Meinecke, & Schroger, 2001). As we are interested in the interaction between

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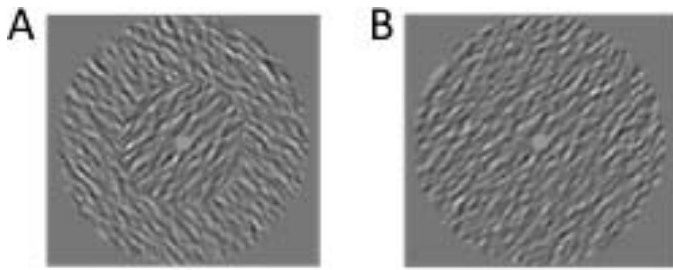


Figure 1. The target on circular textured backgrounds composed of orientation-filtered Gaussian noise, subtending  $4^\circ$  in diameter. Panel (A) shows the two-texture background with an inner texture (diameter  $2^\circ$ ) that is oriented orthogonally to the outer texture and (B) shows a single uniform-texture background.

attention and texture segregation, we chose to examine the effect of texture segmentation on sensitivity at these later times.

The goal of our study was to map out the spatial spread of attention around a target depending on the underlying texture on which the target rests. To this end, we asked observers to detect a small dim probe that was presented at various distances from a peripheral target located on a textured background (see Figure 1) following a central cue to attend to the target. Sensitivity was measured when observers were instructed to make a saccade to the target and when observers fixated a central marker (Experiments 1 and 3, respectively). To determine how sensitivity evolved as a function of latency from the cue, we probed the profile of sensitivity at a range of temporal onsets following the cue. The target appeared on one of two textured backgrounds: a single uniform texture (Figure 1B), or a concentric arrangement of two textures with orthogonal orientations (Figure 1A). For comparison to earlier work, we also determined sensitivity around a saccade target on a blank background in Experiment 2.

Attention to a target is known to increase sensitivity at that location (Carrasco et al., 2000; Doshier & Lu, 2000a, b). Thus, when the background is blank, we expect that the profile of sensitivity will become more selective for the target over time (Castet, Jeanjean, Montagnini, Laugier, & Masson, 2006; Montagnini & Castet, 2007; Rolfs & Carrasco, 2012; White, Rolfs, & Carrasco, 2013). For the textured backgrounds, we predict that texture segmentation will influence the spatial spread of attention around the target. Thus, we expect that the profile of sensitivity will depend on how much of the textured background is selected with the target. One possibility is that sensitivity on the textured background falls off smoothly with distance from the target as in the case of a blank background (Deubel & Schneider, 1996; Kowler et al., 1995). A second possibility is that the surface on which the target rests is selected along with the target. In this case, we would

expect the whole textured disc to be selected when the target rests on a uniform-texture disc (Figure 1B) and only the inner texture to be selected when the target rests on a two-texture disc (Figure 1A). A third possibility is that larger discs are more likely to be seen as background, so the larger disc in the uniform-texture disc is not selected, but the inner texture in the two-texture disc is selected. In this case, sensitivity will be high for locations within the inner texture, regardless of their distance from the target. We expect this effect to emerge for probes occurring later in the trial as it takes about 300 ms for cueing effects from a central cue to be most effective (Cheal, Lyon, & Gottlob, 1994).

## Methods

### Participants

Seven observers (six female, one male) whose ages ranged from 27 to 52 years participated in this study. All had normal or corrected-to-normal vision. All observers had prior experience with psychophysics studies. Two observers were authors; the remaining five were naïve to the purpose of the study and were not informed that there were two different textured backgrounds. For the texture–background conditions with overt attention (Experiment 1), the authors and two naïve observers participated in the study involving four probe onset times; additional data were collected on three naïve observers with the two critical probe onset times (250 and 350 ms). For the blank background condition (Experiment 2), the authors and three naïve observers took part with measurements at these two probe onset times. For the texture background conditions with covert attention (Experiment 3), the authors and four naïve observers took part with probe delays of 250 and 350 ms. All observers gave informed consent to participate in the study. The Smith-Kettlewell Institutional Review Board approved the protocol for the experiments. All experiments were carried out in accordance with the Code of Ethics of the Declaration of Helsinki.

### Apparatus

The stimuli were presented on a 21-inch ViewSonic G225f monitor (ViewSonic, Walnut, CA), with a mean luminance of  $37.9 \text{ cd/m}^2$ . Viewing was binocular at a viewing distance of 1 meter. Each pixel subtended  $0.02^\circ$ . Participants' eye movements (left eye) were recorded using the EyeLink 1000 in the tower mount configuration. EyeLink (SR Research, Toronto, Ottawa, Canada) calibration was performed at the begin-

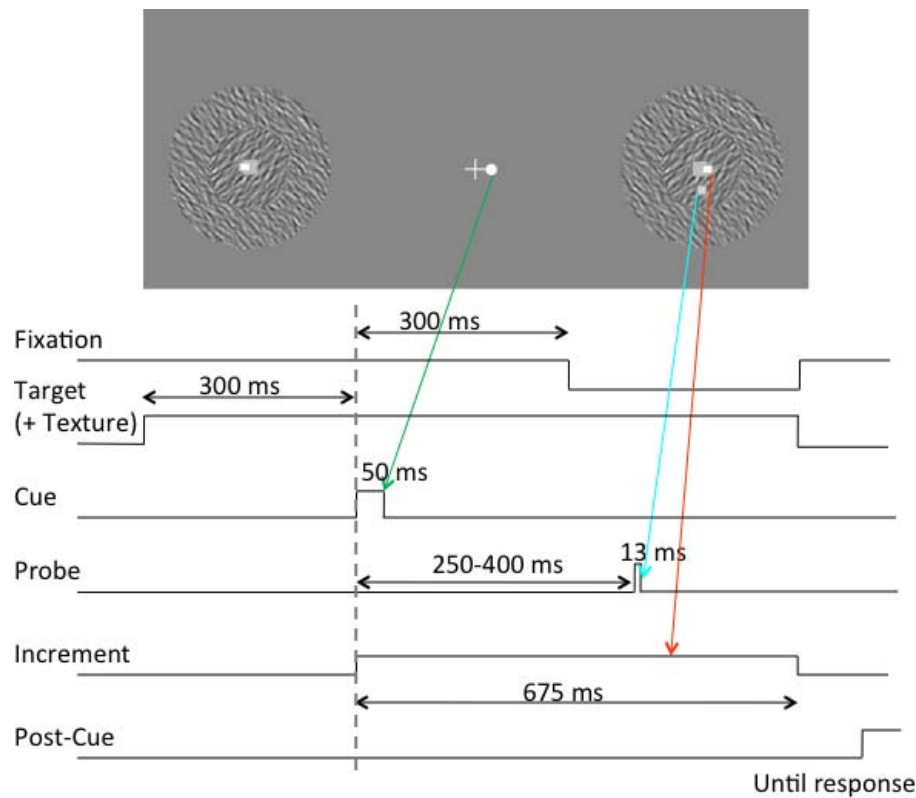


Figure 2. Schematic timeline of a trial in Experiments 1 and 3. The figure illustrates a central fixation marker, a central cue indicating the side to be attended, and the texture background with the target at its center. The timeline of the increment on the target and the brief probe are also shown. The textured patch appeared with the target. Experiment 2 had a similar timeline, except that there was no textured background.

ning of each block. Participants responded either to the target or the probe by pressing either the left/right-arrow key or the upper/lower-arrow key.

## Procedure

Figure 2 illustrates the temporal sequence of a trial in Experiment 1. The spatial details of the various elements in the display are provided as follows. Each trial started with the appearance of a fixation cross at the center of the screen. Participants fixated the cross and initiated the trial by pressing the space bar when ready. To ensure fixation, the trial started only if the gaze was within  $1^\circ$  of visual angle (dva) of fixation for 500 ms after the space bar was pressed. Then background textures (either single- or two-texture) with a square target at the center were presented at an eccentricity of 5 dva on the left and right of fixation. After a delay of 300 ms, a central cue indicated whether the observer should saccade to the target on the left or right. The cue lasted for 50 ms. The fixation cross turned off 300 ms after cue onset and served as the go signal for the saccade. Observers had 675 ms from cue onset to make a saccade, or equivalently, 375 ms after

fixation offset. Trials in which saccades occurred before fixation offset or at latency greater than 375 ms after fixation offset were discarded online, as were trials in which the saccade landed more than 2 dva from the target. Experiment 2 had a similar temporal sequence except that no texture was presented. Experiment 3 was similar to Experiment 1, except that observers were required to maintain fixation throughout the trial and attend to the target covertly.

In addition to the saccade, observers also performed either a probe-detection task *or* a target contrast-increment task on each trial, depending on a post cue. The probe task was intended to measure spatiotemporal sensitivity around the target and observers were asked to report the location of a probe flashed briefly (13 ms) above or below the target (cyan arrow in Figure 2) on the cued side. The purpose of the contrast increment task on the target was to ensure that attention was centered on the target, and thus on the center of the texture. Observers were asked to report the location of an increment (left/right) on the target. The luminance increment occurred on both the cued and uncued targets, but the side with the increment was picked at random, such that the location of the increment on the uncued side was not informative

about the increment on the cued target. The increment is shown with a red arrow in Figure 2, but only on the cued side.

A postcue presented in the center of the screen 875 ms after cue onset informed the observer whether he or she should respond to the location of the increment on the target or to the location of the probe. If the postcue indicated the target–increment task, the observer used the left or right arrow keys to indicate whether the increment was on the left or right side of the target. On the other hand, if the post cue indicated the probe detection task, the observer used the upper or the lower arrow keys to indicate whether the probe appeared above or below the target. Two kinds of feedback were provided: Audio feedback indicated the correctness of the target/probe response, and visual feedback at fixation indicated the timing (too early, acceptable, or too late) and accuracy of the saccade (acceptable or too far from cued target). Each experimental block lasted until 100 good trials (in terms of saccade latency and saccade accuracy) were collected. Between five and 20 trials (depending on observer) were discarded online because saccade latency was outside the 375 ms window after fixation offset, or because saccades landed more than 2 dva away from the target.

## Stimuli

### Texture backgrounds

The texture consisted of circular discs made up of Gaussian noise filtered with oriented Gabor filters (Landy & Bergen, 1991) of the form

$$w(x, y, \theta) = \sin[2\Pi f(x \cos \theta + y \sin \theta)] e^{-(x^2 + y^2)/s^2} \quad (1)$$

$\theta$  refers to the center orientation of the texture (either  $45^\circ$  or  $135^\circ$ ),  $f$  the spatial frequency (set to  $5.7 \text{ c/}^\circ$ ), and  $s$  the spatial spread of the Gaussian envelope (set to 1.4 cycles of the frequency  $f$ ). The single texture was 4 dva in diameter, centered on the target location and composed of an oriented texture tilted  $45^\circ$  with respect to the horizontal. The two-texture background had an inner circular region, similar to the single texture and a concentric outer circular region made up of an oriented texture tilted  $135^\circ$ , perpendicular to the outer texture. The diameter of the inner and outer regions was 2 and 4 dva, respectively. Texture discs were centered 5 dva to the left and right of fixation. The luminance of the gray background was  $37.9 \text{ cd/m}^2$ . Identical texture configurations appeared on the right or left sides of fixation in each trial. The target (see the following material) had the same temporal onset and offset as the textured background. The two textured backgrounds were interleaved within a session.

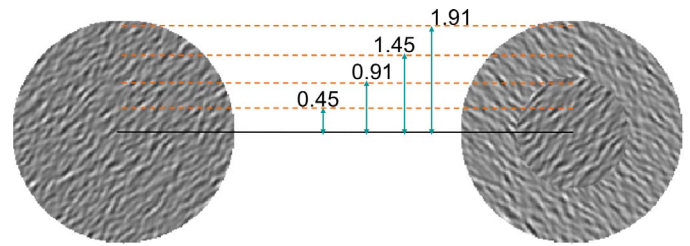


Figure 3. Probe locations. Probes with a distance of 0.45 or 0.91 dva occurred on the inner texture in the two-texture condition.

### Cue

The cue appeared on the left or right side of the fixation cross and lasted 50 ms. The cue was a filled circle of diameter 0.16 dva at the left or right end of the fixation cross. The cue was always 100% valid, as the probe appeared only on the cued side.

### Target

The target was a square ( $0.22 \text{ dva} \times 0.22 \text{ dva}$ ) located on the horizontal meridian 5 dva to the left and the right side of central fixation, with a luminance of  $63 \text{ cd/m}^2$ . It was centered on the texture in the textured-background conditions. Upon cue onset, a smaller increment rectangle ( $0.13 \text{ dva} \times 0.22 \text{ dva}$ ) was superimposed randomly on the left or right edge of the cued target, and remained on for 675 ms. Prior to the start of the experiments we measured the increment contrast on the target on the textured backgrounds for each observer so that it was detected with about 85% accuracy when a saccade was made to the target on a textured background, and about 70% accuracy when no saccade was made. The contrast increment ranged from 5% to 58% depending on observer. The increment contrast on the target was set to this value for each observer for both texture background conditions, which were interleaved within a block. These contrast increment values were also used in the blank background condition with one exception: One observer needed a 40% higher increment in the blank background conditions to keep increment detection on the target at 85%.

### Probe

The probe subtended  $0.13 \text{ dva} \times 0.13 \text{ dva}$  and was presented for 13 ms. The probe could appear randomly at one of four positions either above or below the target, at a distance of 0.45, 0.91, 1.45, or 1.91 dva from the target (Figure 3) and at a temporal onset of 250, 300, 350, or 400 ms from the cue onset. The probe location closest to the target fell within the inner texture, and the probe at a distance of  $0.91^\circ$  from the target fell within the inner texture, near the texture

boundary of the two-texture background (Figure 3). The outer two probes fell on the outer texture in the two-texture background, with the farthest probe, close to the boundary with the blank screen. Prior to the start of the main experiment, we determined the contrast of the probe that yielded about 75% accuracy across all four probe locations. Probe contrast was defined as the ratio of the luminance increment of the probe to the mean luminance of the texture/background (Weber contrast). We measured the detectability of the probe as a function of contrast under the following conditions: central fixation, a temporal onset of 300 ms, no concurrent target task, and with both texture backgrounds interleaved. The value of probe contrast corresponding to 75% correct for each observer in this condition was used for at all probe locations and texture background configurations in Experiments 1 and 3. These values of probe contrast were also used in the blank background condition (Experiment 2) with one exception: The probe contrast on the blank background had to be decreased by 7% for one observer to keep probe detection at 75%.

## Data

Four observers were tested with all four temporal onsets, interleaved. For each observer, we repeated blocks until there were, on average, 40 accepted trials for each condition. Trials were discarded if the saccades were too early or too late, and if they failed to land within 2 dva of the target. On average, there were about 12 discarded trials for each condition, yielding a total of 52 trials per condition. As there were 64 conditions: 2 (texture backgrounds)  $\times$  2 (tasks: probe detection/target contrast increment detection)  $\times$  4 (probe stimulus onset synchronies/SOAs from cue onset)  $\times$  4 (probe locations); this amounted to a total of 3,328 accepted trials per observer. About half this number of trials was required in conditions where only two temporal onsets were tested (three additional observers).

## Analysis

To avoid the period of poor visibility immediately preceding a saccade, we only included trials in which saccade onset occurred at least 50 ms after probe onset (the visibility of probes that occurred less than 50 ms from saccade onset was almost at chance). This criterion resulted in the removal of about 30% of the trials, so that on average we were left with about 40 accepted trials per condition for a given participant. We measured the proportion of correct trials, at each spatial position and temporal onset of the probe, and

calculated the corresponding discriminability,  $d'$ . We normalized each observer's data based on their maximum sensitivity. The normalization was done separately for the textured background and the blank background.

To determine whether the type of background texture had a significant effect on the spatial profile of attention, we performed statistical tests on the spatial pattern of probe sensitivity in the single- and two-texture conditions. We used a within-subject planned linear contrast analysis to characterize the shape of the sensitivity profile as a function of distance from the target. The contrast analysis was performed at the probe temporal onset at which sensitivity to the probe was maximum. We used both a "segmented" and a "graded" contrast analysis as described in Kim and Verghese (2012; see also Cardinal & Aitken, 2006; Howell, 1997; Myers & Well, 2003).

A linear contrast is a linear combination of the sensitivity for each configuration. The sensitivity at each location  $j$ ,  $\mu_j$  is weighted by a weight  $w_j$ :

$$L = \sum_j w_j \mu_j$$

such that

$$\sum_j w_j = 0 \quad (2)$$

One set of linear contrast values was used to compute "segmented versus unsegmented" contrast. In the case of the two-texture background, we hypothesized that if the inner texture is selected with the target, then the segmentation should result in two surfaces as in Kim and Verghese (2012). To quantitatively test our hypothesis that a segmented texture differentially modulates the profile of sensitivity, we fit the sensitivity using weight values +1 for each of the inner probes (0.45 and 0.91 dva), and  $-1$  for the outer probes (1.45 and 1.91 dva), to satisfy the constraint that they summed to zero.

$$L_{segmented} = \mu_1 + \mu_2 - \mu_3 - \mu_4 \quad (3)$$

We expected that this segmented contrast would be significant for the two-texture (as in Kim & Verghese, 2012). For the single texture, we expected that the profile of sensitivity would depend on whether the entire texture was perceived as background, or whether the entire texture was selected with the target. A decline in sensitivity with distance from the target would be a graded profile, and be consistent with the perception of the single texture as a background, as in the case of targets on a blank background (Castet et al., 2006; Deubel & Schneider, 1996; Kowler et al., 1995; Montagnini et al., 2007).

To evaluate the trend for a "graded" decline in sensitivity with distance from the target, we chose a set

of linear contrast weights: +3, +1, -1, and -3 for the four probe locations in order of distance from the target. Equivalently,

$$L_{\text{graded}} = 3\mu_1 + \mu_2 - \mu_3 - 3\mu_4 \quad (4)$$

As we are interested in whether the texture background affects the profile of sensitivity, the overall shape of the sensitivity profile on a particular texture for each participant is more important than whether the sensitivity at every location is different across the two textures. Within-subject contrast analysis is ideally suited to determine whether the sensitivity profile follows the two hypothesized trends. Because we hypothesize two different profiles a priori and consider two corresponding contrast analyses, an omnibus analysis of variance for main effects of interaction is not necessary (Keppel & Wickens, 2004).

As the segmented contrast and graded contrast analyses are not mutually exclusive, it is possible that a given set of data can generate a significant effect for both the analyses. Specifically, because the segmented contrast analysis pools the sensitivities of the inner probes and compares this to the pooled sensitivity of the outer probes, any sensitivity pattern that yields an antisymmetric profile (around the mean sensitivity across all positions) will have a significant segmented contrast. This includes the step function (segmented profile) that we hypothesize for the two-texture background, but also includes a straight line of any slope. Thus, both the segmented contrast and graded contrast will be significant for a linear falloff in sensitivity.

To address this ambiguity in the contrast analysis, we also fit the average sensitivity profile in each condition with a linear and a step function (each with two parameters) to determine which of these provides a better fit to the data.

## Results

### Experiment 1: Sensitivity around a saccade target on a textured background

Initially four observers (two authors and two naïve) performed the task on the textured backgrounds with four probe locations and four temporal onsets: 250, 300, 350, and 400 ms. Figure 4 plots a heat map of average spatio-temporal sensitivity ( $d'$ ) to the probe (accuracy for probe locations above and below the target were combined because they were not significantly different). Sensitivity across space was highest at probe locations closest to the target and then declined typically with distance from the target.

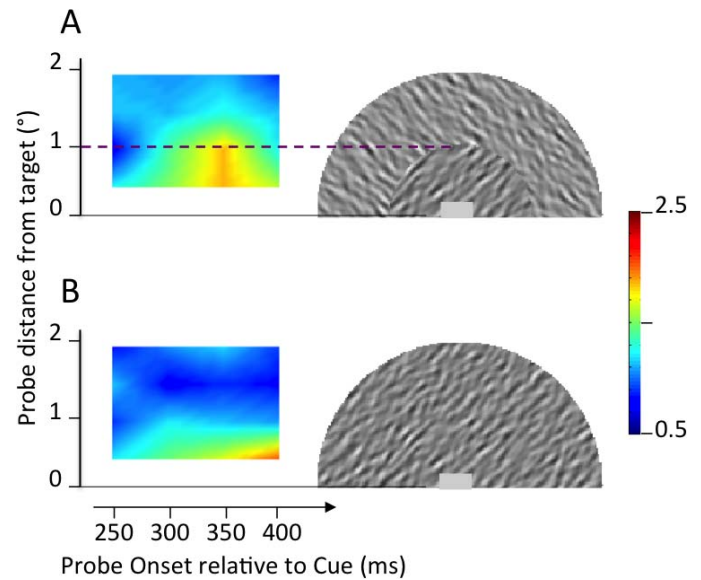


Figure 4. Sensitivity around the target on a textured background. Mean heat maps smoothed across probe positions and temporal onsets. Sensitivity for a two-texture (A) and uniform-texture (B) background, for four probe distances (vertical axis) and at four different probe onsets relative to the cue (horizontal axis). Sensitivity values are interpolated between measurements. The dashed line in (A) indicates the texture-defined border for the two-texture background. The heat maps are based on the average  $d'$  of the four observers who were tested with all four probe temporal onsets.

The profile of spatial sensitivity seemed to depend on the texture background. Sensitivity for the two-texture background was high across the inner texture, whereas sensitivity on the single-texture background appeared to decline in a graded fashion, except for a slight increase at the border of the large texture with the blank screen for probe onsets of 300 and 350 ms. For both backgrounds, sensitivity across time was low for probe onsets of 250 ms and increased to a maximum at 350 ms before declining at longer probe delays of 400 ms. The falloff in sensitivity at later temporal onsets is presumably because of saccadic suppression as saccades, on average, occurred at 428 ms ( $SEM = 9$ ) and 432 ms ( $SEM = 10$ ) after the cue for the two-texture and single texture backgrounds, respectively. In terms of latency relative to fixation offset, these values are 128 and 132 ms (see Supplementary Figure S1 for saccade latency distributions). Given that sensitivity peaked at 350 ms, we ran three more observers at a probe onset of 350 ms, as well as a probe onset of 250 ms, for comparison.

Normalized sensitivity was computed for each observer relative to each observer's maximum sensitivity across space and time across both texture backgrounds). Figure 5A and B compares the normalized sensitivity profile on the two-texture and single

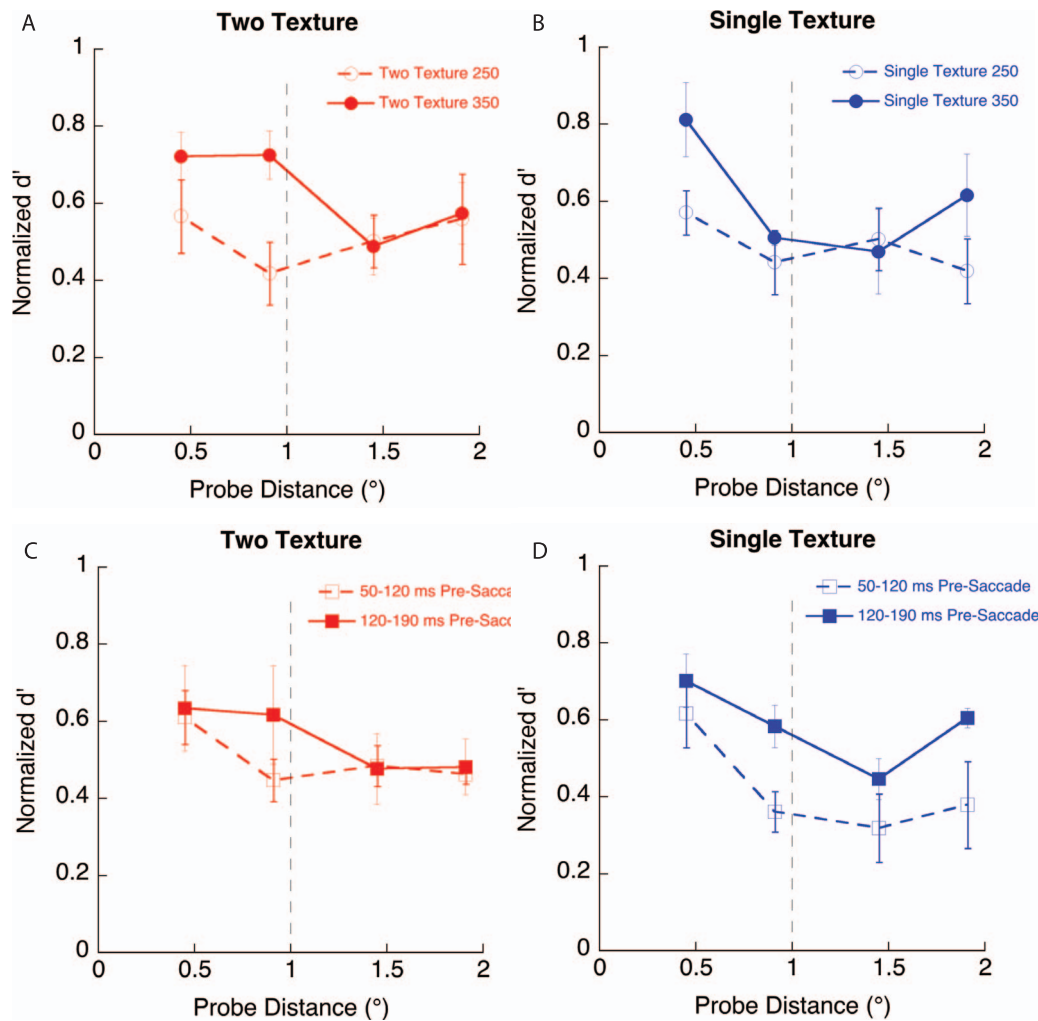


Figure 5. Normalized sensitivity around target for texture backgrounds in Experiment 1. (A) and (B) plot data for two-texture and single-texture background conditions in red and blue, respectively. Normalized sensitivity is plotted for probes occurring 250 ms (dashed) or 350 ms (continuous) from cue onset. The dashed gray vertical line indicates the location of the border of the inner and outer texture on the two-texture background. Seven observers participated in the texture background conditions (Experiment 1). (C) and (D) plot sensitivity relative to saccade onset in intervals 50–120 ms (dashed) and 120–190 ms (continuous), for the two-texture and single-texture backgrounds. Error bars show one standard error of mean.

texture background, respectively, for seven observers. The solid and open symbols plot average normalized sensitivity probe onsets of 250 and 350 ms, respectively. Figure 6 shows a direct comparison of the sensitivity profiles across the two-texture and single-texture backgrounds for a probe onset delay of 350 ms. We analyzed the profile of sensitivity as a function of distance using planned contrast analysis described in the Methods section for temporal onset of 350 ms where sensitivity was highest (Table 1). The segmented contrast analysis is significant for the two-texture condition; the graded contrast analysis is not significant. Notably, neither contrast analysis is significant for the single texture; this is perhaps due to the increased sensitivity for the farthest probe close to the texture border (we return to this issue in the Discussion). These analyses, taken together, suggest

that there is a difference between sensitivity to probes that lie on the inner texture as opposed to the outer texture, supporting our conjecture that the inner texture is selected with the saccade target.

### Sensitivity around the target relative to the saccade onset

We show that as attention orients toward the target over time, the textured background influences the profile of sensitivity around the target. If the enhancement in sensitivity is indeed due to attention preceding eye movements, we should observe a similar texture-specific pattern of enhancement if we plot sensitivity relative to saccade onset. Figure 5C and D plot normalized sensitivity relative to saccade onset for two-

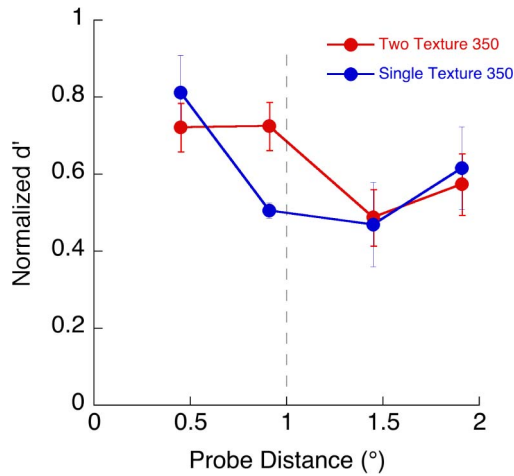


Figure 6. Comparison of normalized sensitivity profiles for the different background conditions in Experiment 1. Data are shown for a temporal onset of 350 ms, where temporal sensitivity is maximum. Sensitivity is plotted versus probe distance from the target, for the single-texture (blue) and two-texture (red) backgrounds.

texture and single texture backgrounds. We exclude all trials in which the saccade occurred within 50 ms of the probe because sensitivity in this interval was close to chance, and plot our data in two 70-ms intervals: 50–120 ms, and 120–190 ms. For each observer, sensitivity is normalized relative to their highest sensitivity across these time bins. Sensitivity was higher for probes occurring in the interval 120–190 ms compared with the interval 50–120 ms prior to the saccade, for both texture background conditions,  $F(1, 6) = 10.63, p = 0.017$ . As can be seen, the interval 120–190 ms shows a similar profile of sensitivity to the data for probe onsets of 350 ms, with higher sensitivity on the inner texture for the two-texture background and a more graded profile of sensitivity for the one-texture background. The higher sensitivity at the 120–190 ms interval before the saccade (compared with the 50–120 ms interval) for probe locations around the saccade target is in contrast to previous studies where sensitivity for probes at the saccade target location increased monotonically until 50 ms before saccade onset (Rolfs, Jonikaitis, Deubel, & Cavanagh, 2011). Perhaps this is because sensitivity

350 ms SOA	Segmented contrast	Graded contrast
Two-texture	$F(1, 6) = 6.06$ $p = 0.049$	$F(1, 6) = 3.63$ $p = 0.105$
Single-texture	$F(1, 6) = 1.21$ $p = 0.312$	$F(1, 6) = 1.66$ $p = 0.245$
Blank	$F(1, 6) = 9.83$ $p = 0.035$	$F(1, 4) = 18.68$ $p = 0.012$

Table 1. Results for planned contrasts for temporal onset of 350 ms. Significant results with  $p$  values  $\leq 0.05$  are in bold.

350 ms SOA	Segmented contrast	Graded contrast
Two-texture	$F(1, 5) = 6.78$ $p = 0.048$	$F(1, 5) = 3.46$ $p = 0.112$
Single-texture	$F(1, 5) = 6.19$ $p = 0.055$	$F(1, 5) = 4.88$ $p = 0.078$

Table 2. Results for planned contrasts for temporal onset of 350 ms in Experiment 3 (covert attention). Significant results with  $p$  values  $\leq 0.05$  are in bold.

at the saccade goal was becoming more selective: increasing at the target location and decreasing at probe locations away from the goal. The data in Figures 5C and D are indeed consistent with sensitivity decreasing at probe locations away from the target at intervals closer to saccade onset (see dashed lines corresponding with data for the 50–120 ms interval).

Figure 6 compares the data for the two-texture and uniform texture backgrounds at 350 ms from Figures 5A and B. A direct statistical comparison of sensitivity for the two probe locations closest to the target (two left red vs. blue symbols in Figure 6) shows a significant interaction between probe distance and texture type,  $F(1, 6) = 9.14, p = 0.023$ . The interaction comes from a significant effect of texture at the inner border,  $t(6) = -3.21, p = 0.018$ ; two-tailed, with the higher sensitivity for the probe on the two-texture background. Thus, our results suggest that when the background is made up of an inner and outer texture, the inner texture is selected along with the target but not the outer texture (Figure 6). Perhaps this discrepancy is due to the scale of texture that is preferred at this eccentricity (Gurnsey, Pearson, & Day, 1996). Studies by Yeshurun, Montagna, and Carrasco (2008) have shown that sustained attention improves the quality of texture representation. On the other hand, sensitivity for the large uniform texture is clearly not constant and in general appears to decline with distance from the target, with the exception of sensitivity to the farthest probe locations.

It is possible that the uniform texture affected the spatial profile of sensitivity so that the fall in sensitivity would have been sharper in the absence of the textured background. To address this issue we measured the profile of sensitivity on a blank background in Experiment 2. Given that sensitivity around the target was at its highest for probes occurring with a temporal onset of 350 ms, we only probed the profile of sensitivity at this onset, as well as at 250 ms for comparison.

### Experiment 2: Sensitivity around a saccade target on a blank background

All stimulus parameters were similar to the texture background except that the target was on a blank



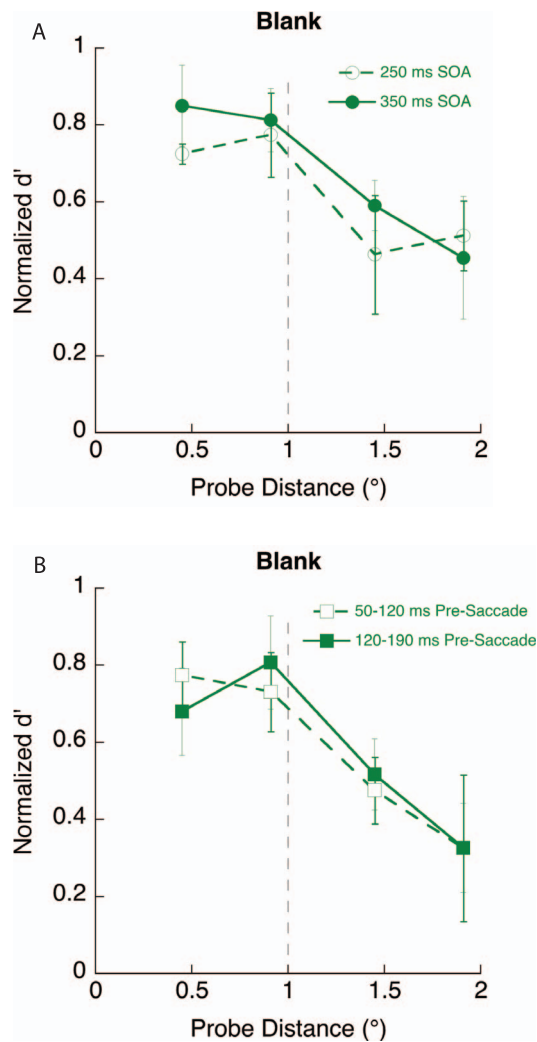


Figure 7. Normalized sensitivity around target for blank background in Experiment 2. (A) plots sensitivity in terms of probe onset relative to the cue. The filled and open symbols are for probe delays of 350 and 250 ms. (B) plots sensitivity relative to saccade onset. The filled and open symbols plot sensitivity for intervals 50–120 ms and 120–190 ms before the saccade. Error bars show one standard error of mean. The dashed gray vertical line indicates the location of the texture-defined border in the two-texture background.

background. Five observers performed the task. For four observers the contrast of the probe was the same as in the texture background. For the fifth observer, the contrast of the probe was reduced by 7% to achieve around 75% accuracy across probe locations.

Figure 7A illustrates the average normalized  $d'$  over probe distance for probes occurring with temporal onsets of either 250 ms or 350 ms on a blank background. For a temporal onset of 350 ms, there is a clear monotonic decline in sensitivity with distance from the saccade target. Our planned contrast analysis shows that both the segmented contrast and graded contrast (which are not mutually exclusive) are

significant for the blank background (see Table 1). Therefore we fit the data using both a step function and a line (with the same number of parameters) and show that a graded rather than a segmented trend is a better fit to the data (Supplementary Figure S3).

If we look at the profile of sensitivity relative to saccade onset (Figure 7B), the sensitivity profile on the blank background declines with distance, especially for the outer three probe locations. This finding is consistent with previous studies that have examined the spatial profile of attention around a saccade target on a blank background (Castet et al., 2006; Deubel & Schneider, 1996; Kowler et al., 1995; Montagnini et al., 2007). The pattern of results relative to saccade onset is in agreement with the pattern of results based on probe onset delay (Table 1). Both suggest that the texture background affects the profile of sensitivity around the saccadic target before the saccade. Thus, sensitivity profiles across all the different background conditions support a segmented profile for the two-texture background, and a graded profile for the blank background but show no support for either the segmented or the linear profile for the single-texture background.

Our data (whether based on probe onset relative to cue or saccade-onset) together with our contrast analyses support a clear pattern for the two-texture background and the blank background. For the two-texture background, the segmented contrast analysis shows a sensitivity profile consistent with the segmentation of the two-texture background. For the blank background, the sensitivity profile declines slightly for the second probe location and more markedly for the outer two probe locations, and is most consistent with the graded trend analysis. However, our planned analysis does not readily capture the trend of sensitivity in the single-texture background condition (see also Supplementary Figure S3).

The patterns of sensitivity across these three backgrounds are quite different. Supplementary Figure S4 in the supplement compares the sensitivity for the five observers who took part in both the texture- and blank-background experiments. Supplementary Figure S4A plots normalized data for these three different backgrounds. The normalization is done just as for Figures 5 and 7: separately for the textured (both textures combined) and the blank background. Apart from the different patterns across the three backgrounds, it is also clear that the blank background has relatively higher sensitivity. Recall that data on the texture backgrounds were obtained in the same block, whereas data on the blank background were obtained in a separate block. To compare the shape of the sensitivity profiles across the different backgrounds, we scaled the texture background data by the sensitivity for the nearest probe in the blank background.

Supplementary Figure S4B shows that the three backgrounds have different sensitivity profiles. The two-texture background has a sensitivity profile that is a step function, with flat sensitivity for the inner and outer textures, respectively. The blank background has sensitivity that falls very slightly for the inner two probe locations and more dramatically for the outer two probe locations. The single-texture background has a sensitivity profile that falls dramatically for the nearest probe locations, but increases at the outer boundary of the texture.

### Potential tradeoff between target and probe sensitivity?

Recall that to keep attention centered on the target, observers detected a contrast increment on the target on half the trials. Although observers made only one judgment at the end of the trial (probe location or contrast increment), they were likely preparing both responses during the trial until the appearance of the post cue specifying the task. To determine whether there was a tradeoff between target and probe sensitivity for any condition, we ran regression analyses. The regression analyses shows that there is no correlation between sensitivity in the probe and target tasks ( $R^2 = 0.003$ ;  $p = 0.643$ ), indicating no tradeoff between these two tasks. In addition, saccade latency was not correlated with probe sensitivity ( $R^2 = 0.001$ ;  $p = 0.961$ ), nor with target sensitivity ( $R^2 = 0.106$ ;  $p = 0.098$ ). Indeed, distributions of saccade latency and landing position in both experiments were not affected by the experimental manipulations (see Supplementary Figures S1 and S2). Thus, it is unlikely that the changes in probe sensitivity are due to tradeoffs with target sensitivity.

### Experiment 3: Is a saccade necessary?

Is covert attention alone sufficient for the textured background to affect the profile of sensitivity? If the observed effect of texture background on the profile of sensitivity around the target is due to covert attention only, then the same profile should occur in the absence of a saccade to the target. To address this issue, six out of seven participants (including the authors) performed the probe detection and target increment tasks while maintaining gaze at fixation (saccades were not permitted). Probe distances were the same as Experiment 1 and temporal offsets of 250 and 350 ms were used. For each participant, we normalized their sensitivity for probe discrimination based on their maximum sensitivity across probe distance (four distances), temporal onset (250 ms and 350 ms) and

textured background (single texture and two-texture). Figure 8 illustrates the average normalized sensitivity. Figure 8A and B shows the normalized sensitivity for the two-texture and single texture backgrounds, respectively. Figure 8C compares sensitivity for the two-texture and single texture background at a probe onset of 350 ms.

For probes occurring at 350 ms on the two-texture background, the segmented contrast reaches significance, even though the sensitivity for the probes on both sides of the border does not appear to be different; the graded contrast is not significant. For the single texture background, both contrasts are marginally significant. These results suggest that the segmentation of the two-texture background affects the profile of sensitivity around the target even when a saccade is not being planned (covert attention). To directly compare sensitivity profiles for the six participants who participated in both Experiments 1 and 3, we normalized their individual sensitivity by their maximum sensitivity in the two experiments (attending overtly or covertly to the target), across texture background (single and two-texture), probe distance (four distances), and temporal onset (250 ms and 350 ms). This common normalization factor is reasonable as the probe eccentricity was the same in the two conditions: Only trials where the probe occurred before the saccade in the overt-attention condition were accepted. Figure 9 plots the average normalized sensitivity for the two-texture (Figure 9A) and single texture (Figure 9B) backgrounds, for a temporal onset of 350 ms. For the single texture background, making a saccade does not affect the profile. For the two-texture background, sensitivity appears to be elevated on the inner texture when attending overtly compared with attending covertly. To investigate this further, we calculated the relative increase in sensitivity on the inner texture relative to the outer texture for each participant for the overt and covert condition. Sensitivity on the inner texture relative to the outer texture was larger on average by 48 % ( $SEM = 24\%$ ) in the overt and 19% ( $SEM = 7\%$ ) in the covert condition. Thus, when a saccade was planned to the target, sensitivity on the inner texture was a factor of 3.02 ( $SEM = 1.26$ ) higher compared with when the target was attended covertly, without eye movements. This enhancement ratio for the overt relative to the covert condition was marginally larger than 1,  $t(5) = 1.61$ ,  $p = 0.085$ .

## Discussion

Using a spatial cueing paradigm (Posner, 1980), we probed the effect of textured backgrounds on the spatio-temporal profile of attention around the cued

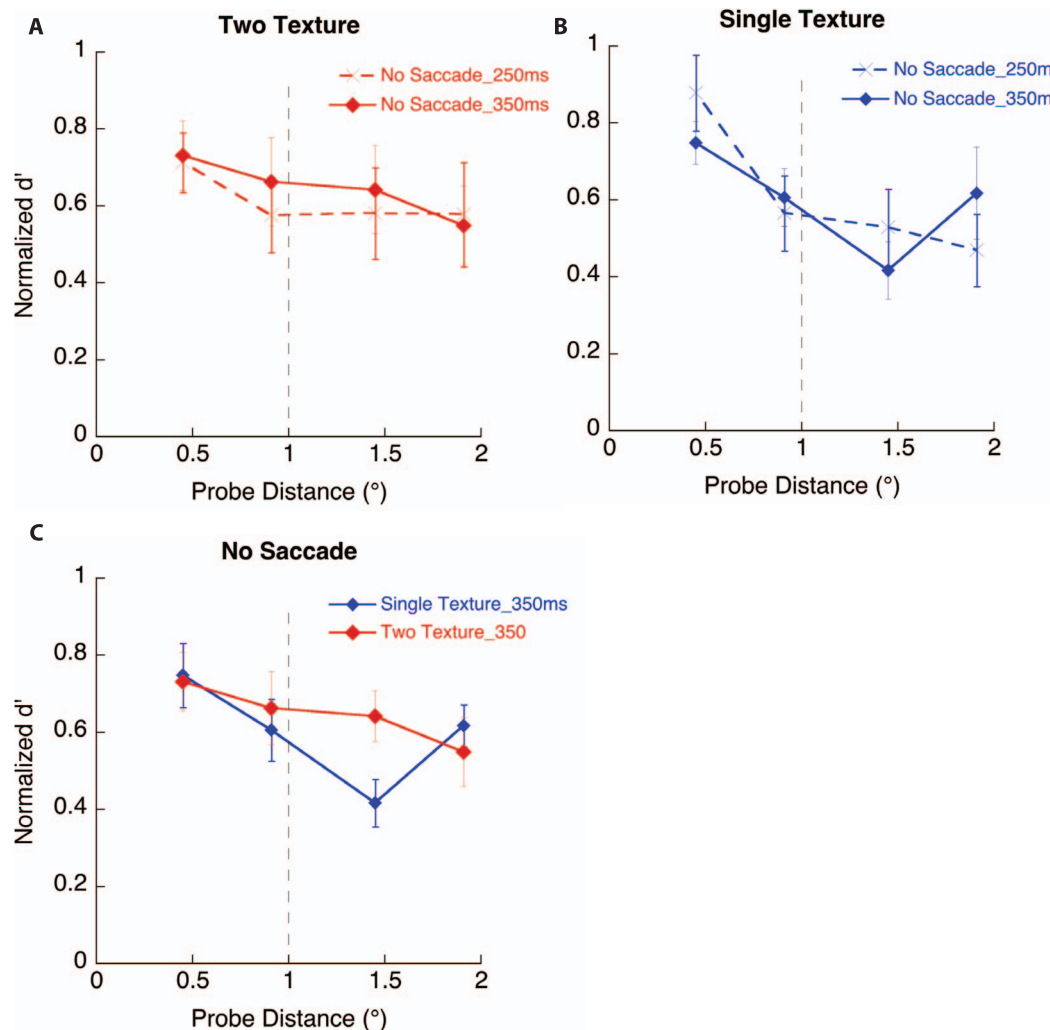


Figure 8. Normalized sensitivity around target, averaged across six observers, during covert attention (Experiment 3). Panels (A) and (B) plot data for the two-texture and single-texture background conditions in red and blue, respectively. Normalized sensitivity is plotted for probes occurring 250 ms (dashed) or 350 ms (continuous) from cue onset. The dashed gray vertical line indicates the location of the border of the inner and outer texture on the two-texture background. Panel (C) compares profiles of normalized sensitivity for the two-texture and single texture backgrounds at a temporal onset of 350 ms. Error bars show one standard error of mean.

target. Our results show that when observers prepare to saccade to a target on a textured background made up of two concentric textures, the sensitivity profile followed the segmentation, with higher sensitivity on the inner texture. When the background was a blank texture, sensitivity decreased in a graded fashion with distance from the target. When the background was a single uniform texture, the profile of sensitivity followed neither a graded decline nor a flat profile consistent with the selection of the whole background (Feldmann-Wüstefeld & Schubö, 2013). Instead the profile showed a nonmonotonic profile decreasing in sensitivity for probes near the target and then increasing at the border with the blank background suggesting perhaps a border effect. As follows,

we discuss our results in the context of other studies on the interaction of attention and segmentation.

### Time course of attention on a segmented background

The effect of textured background on the profile of attention in our study was at its highest 350 ms from cue onset, when a saccade was being planned to the target. At this latency, the inner texture in the two-texture background was selected with the target, although this less clear when attention is directed covertly to the target. This latency for attentional modulation of sensitivity on a segmented background

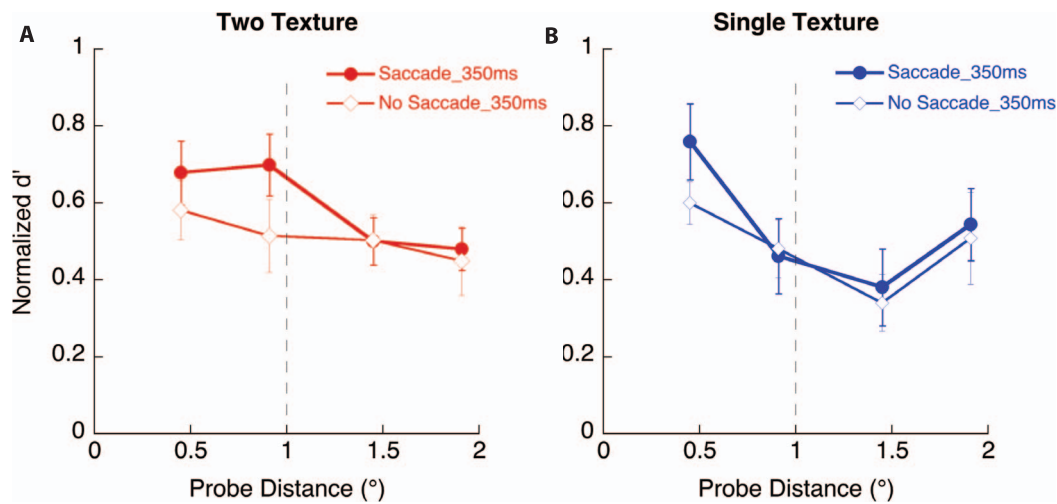


Figure 9. Effect of saccade on profile of sensitivity around a target on a textured background. Panels (A) and (B) plot normalized sensitivity for two-texture and single-texture background conditions in Experiment 1 (with saccade) and Experiment 3 (no saccade), respectively, for probes 350 ms from cue onset. The dashed gray vertical line indicates the location of the border of the inner and outer texture on the two-texture background.

is consistent with previous studies of voluntary covert attention to a peripheral target in response to a central cue (Cheal et al., 1994; Koenig-Robert & VanRullen, 2011). In fact, Koenig-Robert and VanRullen (2011) showed that effects of covert attention peak at 350 ms after cue onset for a target located 5 dva from the central cue, which is the distance between the saccadic target and the fixation point in our study. In addition, the time course is in line with attention modulating later aspects of texture segregation: Texture-specific evoked responses that occur after 250 ms are much more susceptible to the demands of attention (Heinrich et al., 2007; Schubo, Meinecke, & Schroger, 2001).

## Segmentation and attention

Other studies report that segmentation appears to be an early process that occurs preattentively. For example, Landy and Bergen (1991) have shown that it occurs at latencies as short as 84 ms, while others have shown that segmentation occurs at a latency of less than 100 ms (Casco, Grieco, Campana, Corvino, & Caputo, 2005; Lamme, 1995; Schubo et al., 2001; Zipser, Lamme, & Schiller, 1996) and is not affected when performed concurrently with another task (i.e., letter identification) that requires attention (Braun & Sagi, 1991). Interestingly the texture-based modulation of the attention profile in our study is most evident at longer latencies. Furthermore, the profile of sensitivity on a segmented background depends on the kind of attention—it is most evident under conditions of overt attention when saccades are being planned to a target on a segmented background.

In our study, the sensitivity profile that reflects the segmentation into two surfaces is most evident at longer latencies (350 ms) and appears to depend on attention. Evidence for presaccadic attention modulating later stages of segmentation comes from Poort et al. (2012) study. They recorded from neurons in areas V1 and V4 when monkeys were required either to make a saccade to a textured-defined object or to make a saccade to another target. Thus, texture segmentation was either behaviorally related to the selection of a target in texture (the attended condition) or not (the unattended condition). This study showed that neurons in area V1 responded early at a latency of 60 ms to the texture boundary regardless of whether texture-defined object was behaviorally relevant. The increased responses to the interior of the texture (filling in) when the monkey was planning eye movements to the texture occurred at a latency of 159 and 205 ms in V4 and V1 neurons, respectively, suggesting a role for feedback modulation of early responses. Our experiment is similar to that of Poort et al. (2012) in that participants made a saccade to the target at the center of the textured disc. In line with their results, our study supports texture filling-in of the inner texture at 350 ms from cue onset, when the observers were planning a saccade to a target on the texture. Our results, in addition to those of Poort et al. (2012), suggest that attention to the texture-defined object in conjunction with an active eye-movement plan enhances the representation of the object. We speculate that the enhanced sensitivity for the inner texture that occurs in conjunction with a saccade represents a selection of a surface that is relevant for active interaction with the target.

Visual sensitivity is highest at the probe location closest to the saccade target (Deubel & Schneider, 1996; Kowler et al., 1995). At further probe locations, the profile of sensitivity depends on the background. On the two-texture background, we see a clear increase in sensitivity for probes on the inner texture compared with the outer texture, when a saccade is directed to the target. This enhancement of sensitivity on the inner texture is much smaller when attention is directed covertly. This is true in our study and in related studies as well. For example, in a study that compared the benefit of detecting probes presented on the same or different object while maintaining fixation on a central marker, Hollingworth, Maxcey-Richard, and Vecera (2012) showed that the probe was detected better when it was on the same object, even when the probe-to-cue distance was matched in the two cases. The same-object advantage was small but significant (4% improvement in accuracy, Figure 2; Hollingworth et al., 2012). The increased sensitivity on the inner texture in the two-texture background mirrors this same-object advantage, suggesting that the inner texture is considered the “same surface” as the target.

Our study shows that the texture background influences the profile of attention even when the segmentation of the background is irrelevant to the probe detection task, similar to the same-object advantage in object attention studies where the probe is as likely to occur on the same object as a different object (Chen, 2012; Shomstein & Yantis, 2004). The irrelevance of a texture background in our study is similar to a study by Ben-Shahar, Scholl, and Zucker (2007) that showed that an irrelevant texture background did indeed influence the spread of attention. Observers were better able to compare two probes when they occurred within a texture-defined region, than when they were on opposite sides of a texture boundary. But fixation was not controlled in their study and observers may have made multiple saccades during the course of the 700 ms display (the background was presented alone for 500 ms, followed by a 200-ms presentation of the probe).

How do our results relate to other studies investigating the effect of attention on texture segmentation? Yeshurun and colleagues (Anton-Erxleben & Carrasco, 2013; Yeshurun et al., 2008) showed that a central cue improved the performance at all eccentricities, with performance peaking at an eccentricity of 5 dva. In their study participants were required to detect a  $2 \times 2$  dva texture-defined square that differed in orientation from the surrounding texture). It is possible that the characteristics of our stimulus—the 2 dva diameter inner texture at an eccentricity of 5 dva—were optimally suited to obtaining attention effects on the inner texture. The outer disc was much larger at 4 dva

in diameter, which may explain why the inner, but not the outer, disc was selected with the target.

Why is sensitivity uniform on the smaller inner texture of the two-texture background, but non-monotonic for the larger single texture? It could be that the inner texture has the optimal size (2 dva) for texture segmentation at 5° eccentricity, as discussed already. It could also be that smaller textures are typically seen as the figure in figure-ground segmentation, and that the inner texture is segmented as the figure. But by the same analogy, the larger single texture should be seen as figure against the blank backdrop of the screen. However, we see that sensitivity on the single texture drops off for probe locations closest to the target, but increases again at the edge. Thus it appears that the large single texture has a dual role: It is treated as ground over most of its extent, but at the boundary with the blank screen it is treated as figure, or at least as a region boundary.

Some previous studies have suggested different mechanisms for edge detection and region-growing (Grossberg & Mingolla, 1985; Mumford, Kosslyn, Hillger, & Herrnstein, 1987; Wolfson & Landy, 1998). However, other studies suggest that the segmentation of the figure from the background depends mostly on boundary detection mechanisms (Li, 1999; Rossi, Desimone, & Ungerleider, 2001). Poort et al. (2012) attempted to explain this discrepancy by proposing that filling in occurs only if the texture detection is task-relevant. Our results suggest that filling-in can occur before a saccade, even when texture detection is not relevant to the task. An alternate possibility is the suggestion from Zipser et al. (1996) that figure-ground modulation occurs in neuronal responses in V1 only if the texture-defined region is perceived as figure, rather than as background. Participants in our study were not required to report whether they perceived the inner texture as figure. However, six of the seven participants (one author, and five naïve) reported subjectively that they were unaware whether a particular trial had a uniform or two-textured background. These subjective reports suggest that when a saccade is planned to a target on a textured background, filling in occurs even when the inner texture is not perceived as figure, and the background is not task relevant.

In sum, we have shown for the first time that a textured background affects the spatial profile of selectivity around a peripheral target when a saccade is planned toward it. When the texture background is made of a single uniform texture, sensitivity declines with distance as with a blank background; but it increases at the edge of the texture. However, when the background is made up of two concentric textures, sensitivity is uniformly high on the inner texture,

suggesting that the inner texture is selected with the target.

*Keywords:* texture segmentation, eye movements, saccades, attention

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