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Texture Brightness Filling-in

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The masking procedure by Paradiso and Nakayama (1991) (*Vision Research*, *31*, 1221–1236) was used to investigate brightness filling-in within textures made of line elements: a texture stimulus was masked by a second stimulus containing a square contour. When a uniform texture was presented, the texture region inside the masking square appeared darkened and a small number of texture elements were perceived with a degenerated shape, appearing as dim dots or shorter line elements; it is as if the line element expanded from a bright point to fill the entire region defined by its contour. If the texture stimulus was a texture patch segregating from the surrounding texture by an orientation gradient and this patch was inside the square mask, darkening was not as strong as in the previous condition, and masked line elements preserved their elongated shape. Brightness spreading was measured in two experiments using dichoptic presentations. Experiment 1 used an adjustment task and showed that the brightness of texture line elements spread from equiluminant borders between segregating textures. Experiment 2 used a matching task and demonstrated that spreading was blocked by segregation borders dependent on the orientation gradient between texture line elements. The selectivity for line orientation began 40–80 msec after texture onset and maximal spreading occurred at ~120 msec. These findings may indicate that two processes subserve filling-in within textures: the first spreads isotropically the mean stimulus luminance at an initial processing stage of image analysis; at a later stage, the second spreads a texture flow (both brightness and shape of line elements) directed along the orientation of texture line elements. The texture flow mechanism fills in with a texture surface the region bounded by segregation contours. © 1998 Elsevier Science Ltd. All rights reserved.

Boundary contours Masking Surface representation Texture flow Texture segregation

INTRODUCTION

A conspicuous phenomenon involved in the perception of our everyday world is exemplified by the ability of the visual system to produce, even in monocular viewing, a representation of the visual field without a hole which should correspond to the blind spot resulting from the lack of photoreceptors at the optic disk. This region appears to have the same surface pattern as the surrounding visual field. The same ability is also present in patients when retinal scotoma prevents input to the cortex.

Similar phenomena have been observed in experimental settings with stabilized images. In the case of a stabilized small spot surrounded by a uniformly colored background, the perceptual result is described as a "filling-in" of the surrounding color into the central spot (Gerrits, de Haan & Vendrik, 1966; Yarbus, 1967). Other studies have found that when the border of a disk surrounded by a differently colored annulus is stabilized, the color of the annulus fills in the disk and the stimulus appears to have uniformly the same color of the annulus (Krauskopf, 1963; Yarbus, 1967).

More recently, powerful demonstrations of filling-in have been shown with texture patterns. Ramachandran and Gregory (1991) presented a computer monitor filled with twinkling two-dimensional noise. A gray square (1.5 deg side) of the same mean luminance as the noise was displayed 6 deg from a fixation point. Following steady fixation, the border of the gray square faded first, then the twinkle filled in slowly from outside to inside. The entire process took approx. 5 sec. These findings can be explained by the fact that the unstimulated gray square is like an "artificial scotoma" which is filled in by the texture pattern of the surround. In another experiment, the authors were able to show that filling-in by color and by texture may be based on two different mechanisms, the first occurring earlier and the second later. They used twinkling black spots on a pink background, and horizontally moving black spots on the gray square. First, the gray region in the artificial scotoma was filled in by the pink surround. Once this occurred, the moving spots in the artificial scotoma also faded and were replaced a few seconds later by the twinkling spots of the background.

The time course of the filling-in of artificial scotoma is approx. 5–10 sec depending on the size of the gray square (De Weerd, Gattass, Desimone & Ungerleider, 1995) and on its eccentricity (Ramachandran, Gregory, & Aiken,

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1993). Instead, filling-in of the natural scotoma at the blind spot occurs without delay with respect to the rest of the visual scene. Since no direct stimulation is present at the blind spot, it is possible that the delay for filling-in an artificial scotoma is due to the initial segmentation of the gray square that has to be overwhelmed by the massive stimulation from the surrounding texture.

Such a conclusion can also be drawn from neurophysiological studies which employed artificial scotoma (a gray rectangle) within a background of twinkling texture made of line elements. Pettet and Gilbert (1992) found a 5-fold expansion in receptive field sizes of cells located in the supragranular layers of cat's area 17 after 10 min of stimulation. De Weerd *et al.* (1995) recorded cells of monkey's cortex: the response to the scotoma was initially low, then sharply climbed and joined the response level of the cell when directly stimulated by the twinkling texture. A comparison of the climbing activity between different areas indicated that filling-in occurs most commonly in V3, to a minor extent in V2, and not in V1. A different conclusion can nevertheless be drawn from results concerning the blind spot. Fiorani, Rosa, Gattass and Rocha-Miranda (1992) showed that, at locations corresponding to the blind spot, some neurons of monkey's V1 were able to accurately interpolate the position of a long sweeping bar or a drifting grating when only the contralateral eye was stimulated. These results suggest that filling-in of the natural scotoma at the blind spot can occur at the level of V1, whereas filling-in of an artificial scotoma requires cortical areas with receptive fields large enough to span the artificial scotoma.

To clarify the role of filling-in in normal perception (that is, without steady fixation) it would be helpful to devise an experimental procedure that can reveal filling-in at a similar time course of visual processing. Paradiso and Nakayama (1991) masked a bright disk of uniform luminance with a second stimulus containing contours of various shapes. In the case of masking by a circular contour having a smaller diameter than the disk, they found that the region of the disk inside the circle appeared strongly darkened so that the disk was perceived as an annulus. Moreover, when gaps in the circular masking were progressively increased, the perceived darkening of the disk region inside the mask was progressively reduced. The authors hypothesized that brightness perception is based on a mechanism of lateral spreading. Disk edges produce a brightness signal that spreads inward toward the disk center. If the circular contour is presented before spreading has completed to fill-in the disk, then this spreading is blocked and the disk region inside the contour will appear dark. Therefore, in this interpretation luminance edges are relevant in producing boundary conditions that constrain both starting and blocking of lateral spreading, subserving brightness perception.

In the experiments reported in the present paper the masking procedure was used with texture stimuli (Fig. 1). There are several reasons for this. First, the use of textures allows us to investigate the spreading mechanism on which filling-in is based. In fact, a simple mechanism based on lateral spreading cannot explain filling-in within textures because spreading should be blocked by the contours of each texture line element. Therefore, filling-in within textures had to be hypothesized to occur at a processing level in which a texture constituted by physically discontinuous elements is represented as a continuous surface.

Second, the use of textures allows us to investigate the boundary conditions that are responsible for the spreading starting in the filling-in process. In fact, edges in the visual image are defined not only by discontinuities in luminance, but also by differences in texture. Since texture borders can be produced within equiluminant stimuli by exploiting texture segregation, it is possible to disentangle the role of texture edges from the effect of luminance edges. This manipulation allows us to investigate whether filling-in occurs at a representational level in which a texture segregates into figure and ground.

Third, from a computational viewpoint, detection of luminance edges requires a single stage of filtering of the image. In contrast, detection of edges due to texture segregation requires two subsequent filtering stages and an intermediate non-linearity (Malik & Perona, 1990). In other words, a luminance discontinuity is a first-order edge, whereas a texture discontinuity (i.e., a segregation contour) is a second-order edge (Lu & Sperling, 1996). Therefore, it is interesting to investigate whether texture perception involves a second-order filling-in.

In the following sections, after a preliminary description of the perceptual phenomena that suggest the involvement of a process of texture filling-in, two experiments investigate the spatial and the temporal characteristics of such a process.

PRELIMINARY OBSERVATIONS

The masking procedure used is illustrated in Fig. 1(A). A uniform texture made of equally oriented line elements is briefly displayed and followed, in a different frame, by a square contour. This contour sorts the effect of masking the texture patch located within it.

The basic paradigm we used consists of confronting this condition with a second condition in which a texture patch segregates inside the masking contour [Fig. 1(B)]. This comparison seems appropriate if we hypothesize that if there is a filling-in process specific to textures, then it should start its spreading from texture-specific borders (i.e., segregation borders).

Within this framework, the spatial distance between the segregation border and the masking contour is relevant for disclosing a spreading activity that depends on the distance to be covered. In our display this distance is chosen between two extrema corresponding to the location of the texture boundary. In the first case, texture boundary corresponds to the overall texture border (maximal texture-to-mask distance). In the second case, the segregation border is placed at the same location of the masking contour (null texture-to-mask distance). It can be hypothesized that in the first condition the filling-

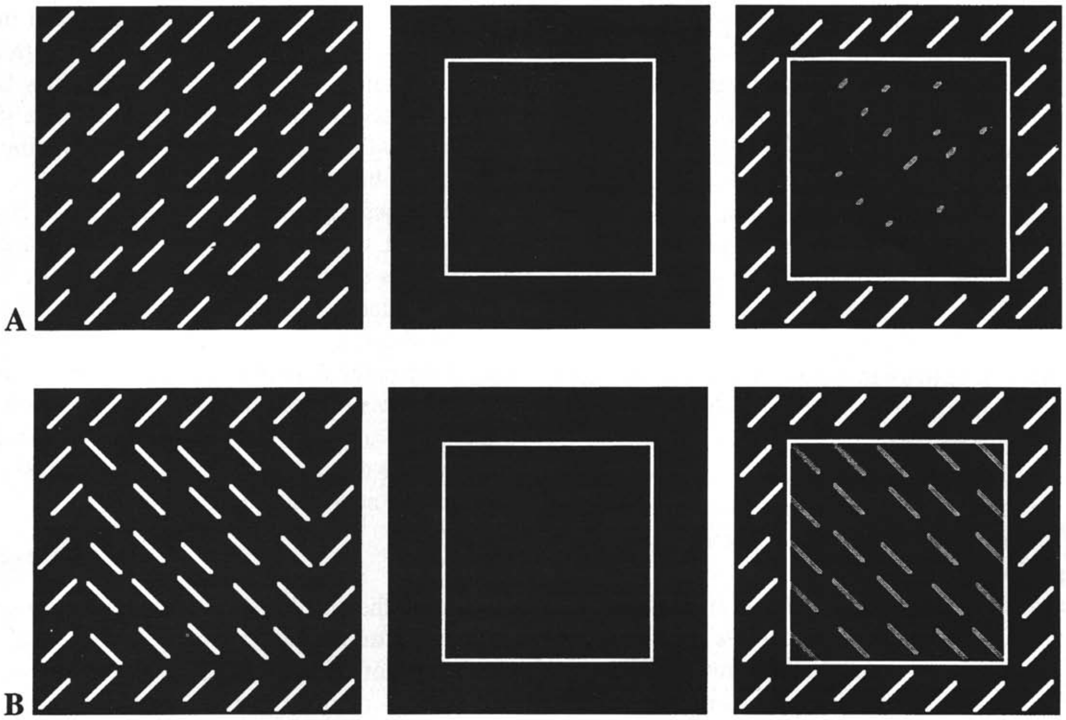

FIGURE 1. The dichoptic masking procedure used in the preliminary observations and the perceptual results. This figure displays only the portion of the texture in correspondence to the location of the masking square contour. (A) The uniform condition in which the texture (left panel) was presented to a randomly chosen eye, and was followed by a masking square (middle panel) presented to both eyes. This produces (right panel) the perceptual result sketched out. (B) The segregation condition in which a 5 × 5 texture patch segregated from the surrounding texture by an orientation gradient (left panel); the perceptual result is also sketched out (right panel). These observations were made with a texture-to-mask ISI = 0 msec. Similar findings can be obtained in monocular masking (texture and square contour presented to the same eye) when an ISI approx. 60 msec is used.

in process specific to textures should spread across the entire texture and should be blocked by the masking contour; hence we expect a very strong masking effect. In the second condition, the border generated by texture segregation should block filling-in coming from the surrounding texture and should restart filling-in inside the segregating texture patch. Since in this second condition the segregation boundary is located inside the masking square, then the masking square should have a very limited effect on the filling-in process within the segregating texture patch. As a consequence, a filling-in process specific to the texture pattern should be blocked by the masking contour in the first [Fig. 1(A)], but not in the second [Fig. 1(B)] condition.

In the experimental procedure we used a dichoptic presentation of texture stimulus and masking contour to avoid temporal integration between the two frames. In fact, Paradiso and Nakayama (1991) showed that dichoptic masking of their bright disk produced the strongest darkening when the masking circle immediately followed the stimulus (0–60 msec interval between disk and masking circle). With monocular masking the results were qualitatively similar but were delayed in time, the strongest darkening being present when the masking circle was presented 50–100 msec after disk onset. Therefore, the dichoptic presentation is more appropriate for characterizing the time course of the filling-in process. In other experiments not shown here, I found that monocular presentations led to results comparable with the ones reported here.

Methods

Apparatus. Stimuli were generated by a PC, displayed on a color monitor (640 × 480 resolution, 70 Hz vertical refresh), and viewed in a dark room at a distance of 57 cm. The PC also controlled the opening and closing of two liquid crystal shutters mounted on spectacles through which the subject viewed the monitor screen.

Stimuli. A trial (Fig. 1) was made by two subsequent frames: the first was the texture stimulus, the second the masking contour. A fixation cross appeared on the monitor center shortly before and during the texture–mask presentation.

The texture stimuli were displayed on the monitor center. They consisted of line elements arranged on a 40 × 40 raster subtending 17 × 17 deg visual angle. The spatial position of each line element was not exactly in the center of its raster cell but was in a random location (jittered) 0–5 min arc around. A line element measured 24 × 2.5 min arc.

The mask was a square contour (2.1 deg side, 2.5 min arc thickness) which appeared at 4.5 deg around the fixation cross, in randomly chosen eccentric positions. The mask isolated two regions in the texture: a texture patch (inside the mask) containing 5×5 line elements, and a surrounding texture outside the mask.

Texture line elements slanted randomly 45 deg either to the left or to the right at each presentation. Two conditions were examined: in the uniform condition [Fig. 1(A)], line elements of both patch and surrounding textures had the same orientation; in the segregation condition [Fig. 1(B)] they had 90 deg reciprocal orientations.

Line elements of both texture surround and target patch had the same luminance (12 cd/m^2). The background screen was dark (0.08 cd/m^2).

Procedure. The observers had to describe their perception of the texture in correspondence to the location of the masking square. In particular, they were told to describe the appearance of the texture line elements inside the mask. The subject started the trial by pressing a key and could repeat the texture–mask sequence an unlimited number of times. The two experimental conditions (uniform vs segregation) ran separately.

In each trial the stimulus sequence was the following. The fixation cross appeared in the center of the monitor. After a random interval of 500–1000 msec, the surrounding texture and the target patch were displayed for 14 msec to a randomly chosen eye. Then the texture stimulus disappeared and was replaced (stimulus-to-mask interval $\text{ISI} = 0$ msec) by the masking square presented for 14 msec to both eyes. After this the fixation cross disappeared.

Subjects. Two psychophysically experienced observers (CC, FC), who were unaware of the purposes of this research, participated. Informal observations were also made by two naïve subjects. All observers had normal or corrected-to-normal acuity and normal stereo vision, as tested in a depth discrimination task with stereoscopic presentations.

Results

The phenomenological observations made by subjects (and by the author as well) are sketched in Fig. 1. The two patch–surround conditions produce very different perceptual results. In the uniform condition [Fig. 1(A)] the texture patch is strongly darkened by the masking square and the appearance of its line elements can be described in the following three points: (1) the number of line elements that can be perceived inside the masking square seems reduced to only 5–10 instead of the actual 25; they are randomly distributed across the patch and they change at each repetition of the trial. (2) Shape of patch line elements is degenerated: they are described as dots or blobs lightening over the dark screen inside the mask. Some line elements can become slightly visible; in this case they often appear of shorter length* than line elements outside the masking square. (3) These dots make their appearance with a delay after the texture outside the mask, as if they are segregated in time, and the perceptual result is much like an aftereffect.

These findings with uniform textures may be summarized in the words of a naïve subject about a single patch line element that is like "a dot that is beginning to become a short line but then extinguishes".

In the segregation condition [Fig. 1(B)] the line elements of the target patch are not so darkened as in the previous condition. The textural pattern of the target patch is intact in both line element number and line element shape. Line elements appear brighter in the outer ring of the patch than in its center. Within the target patch the brightness of each line element appears uniform.

In both uniform and segregation conditions, the surrounding texture is not affected by masking, neither at positions near the square contour.

Discussion

Mainly, the results show that: (1) the masking of a uniform texture influences perception of both brightness and shape of its line elements; (2) the masking of a segregating texture patch influences only brightness, while the shape of its line elements is preserved.

On the basis of these findings, two effects produced on the texture patch by the masking contour can be distinguished. The first effect concerns the brightness of the masked texture patch: it is reduced in both uniform and segregation conditions. The second effect concerns the appearance of the texture patch: its textural pattern is degenerated when a uniform texture is masked, whereas it is maintained intact when a segregation border is at the same location of the masking contour. Therefore, the first effect is independent from texture line element orientation, whereas the second effect is orientation selective.

In relation to the filling-in hypothesis, two mechanisms can be proposed for explaining these two masking effects. The first filling-in mechanism spreads isotropically the mean stimulus luminance independently of the orientation of texture line elements.

The second filling-in mechanism spreads the texture pattern anisotropically in the direction of the orientation of the texture line elements. This second filling-in component concerns both texture element brightness and texture element shape. The selectivity of this second filling-in component for the orientation of the line elements and its involvement in spreading the textural pattern suggests that it can be characterized as a "texture flow". This flow spreads both the brightness and the shape of texture line elements in the direction of their orientation.

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*This expansion of line length in the uniform condition is more easily visible when target patch elements have a greater luminance than line elements of the surrounding texture. Another finding that is not investigated here is the effect of eccentricity: masking in the uniform condition is stronger at large eccentricities, whereas at fixation point target patch elements preserve their shape and appear to have different degrees of darkening in a randomly distributed manner.

In relation to the present observations, the masking contour blocks both filling-in components in the uniform condition. In the segregation condition the masking contour blocks only the first filling-in component, while the second component is not involved, owing to the orientation difference in correspondence to the texture patch. This interpretation will be tested more carefully in the two following experiments.

Another comment concerns the appearance of the texture patch in the segregation condition. Some results can be explained by previous findings on texture segregation (Nothdurft, 1985b). For example, the brighter appearance of the line elements of the outer ring of the segregating texture patch depends on their greater saliency produced by the different orientation with respect to the neighboring line elements of the surrounding texture.

EXPERIMENT 1

The aim of this experiment is to demonstrate that the masking effects observed above depend on a filling-in process that is in progress before being interrupted by the square contour. Apart from phenomenological observations, the strongest foundation for a filling-in process resides in demonstrating a spreading mechanism. For this purpose it is necessary to investigate the masking effects in both their spatial and temporal aspects. Spatial characterization can be made by manipulating the distance between the texture segregation border and the square contour. Temporal characterization of the masking effects can be made by manipulating the stimulus-to-mask delay (ISI).

These two aspects of brightness spreading were investigated by Paradiso and Nakayama (1991, Experiment 2) in the case of bright disks masked by a circular contour. They manipulated the diameter of a bright disk while the diameter of a circular contour remained constant. The darkening of the disk region inside the circular contour was measured for different stimulus-to-mask ISIs. The results indicated that the larger the disk size, the longer was the stimulus-to-mask ISI at which darkening was still present. This result was interpreted as evidence that activity caused by disk edges spreads towards the disk center. The farther the disk edges are from the masking contour the larger the space that the spreading activity has to cover and the later the time at which the masking contour can continue to interfere in the spreading process.

In the case of textures, the spatial characteristics of brightness spreading can be investigated by using a texture stimulus of constant size and producing within it an equiluminant border due to texture segregation. In the case of textures made of line elements, a segregation border is produced by an orientation gradient between the line elements (Fig. 2). In this manner it is possible to maintain the same stimulus luminance, while the size of the segregating texture patch is manipulated. The hypothesized second filling-in component specific to the texture pattern should start spreading from the segregation border. Thus, the larger the size of the segregating texture patch, the larger the space that spreading has to fill in with the textural pattern. Therefore, we expect that the longer the distance is between segregation border and masking contour, the later the time at which the masking contour can still block spreading.

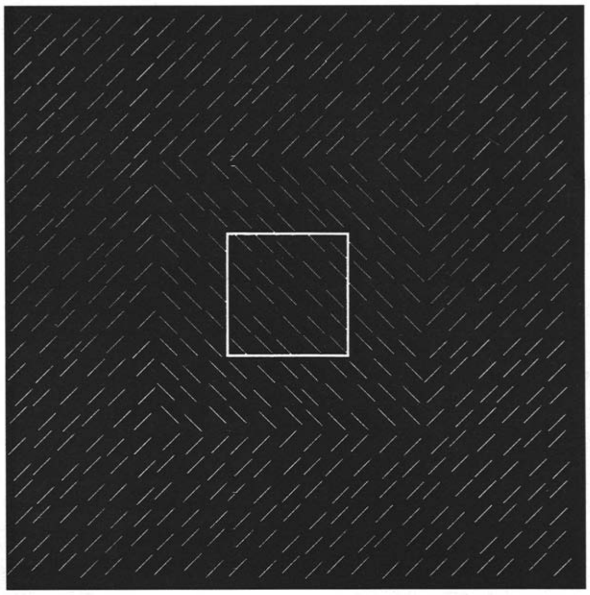

FIGURE 2. An example of the stimuli used in Experiment 1. A surrounding texture measuring 23 × 23 line elements contains a segregating texture in its center. In this example the segregating texture has 11 × 11 line elements size, whereas in the experiment it could take the sizes 5 × 5, 7 × 7, 11 × 11, or 15 × 15. The masking square contour was displayed in the texture center (in the actual presentation, texture and mask were displayed separately in two different frames). The 5 × 5 texture region inside the masking square was the target patch in the psychophysical adjustment task: its luminance was regulated by the subject in such a way that the line elements of the target patch had the same brightness of the line elements outside the masking square. The luminance of the line elements of the surrounding texture and of the portion of the segregating texture outside the masking square was constant. The center of the stimulus was displayed in random positions 4.5 deg around a fixation cross presented in the center of the monitor.

Methods

Apparatus and stimuli. The same apparatus as before was used. The texture stimulus was arranged on a 23 × 23 raster subtending a 9 × 9 deg visual angle. The raster had its center displayed in randomly chosen positions at an eccentricity of 4.5 deg around the fixation cross presented in the center of the monitor. The geometrical characteristics of the raster and of the line elements were the same as used in the preliminary observations: a line element measured 24 × 2.5 min arc; its position was jittered by 0–5 min arc. In the stimulus a segregating texture segregated from a surrounding texture by an orientation gradient. The surrounding texture had its line elements uniformly oriented at 45 deg either to the left or to the right at random. The segregating texture was centered in the surrounding texture, and its line elements were orthogonal to the orientation of surrounding line elements. The first experimental factor was the size of the segregating texture that could be made of 5 × 5, 7 × 7, 11 × 11, or 15 × 15 line elements (subtending 2.1 × 2.1, 3 × 3, 4.6 × 4.6, or 6.3 × 6.3 deg, respectively). In Fig. 2 an example is shown in which the segregating texture measures 11 × 11 line elements.

The masking square was the same as in the preliminary observations (2.1 deg side, 2.5 min arc thickness) and it isolated a 5 × 5 texture patch from the segregating texture that was the target in the psychophysical task. In the 5 × 5 size condition the segregating texture was entirely inside the masking square; in the other size conditions the segregating texture extended beyond the masking square.

The line elements of the surrounding texture and of the portion of the segregating texture outside the masking square had the same luminance (12 cd/m^2) throughout the experiment. The background screen was dark (0.08 cd/m^2). The luminance of the line elements of the 5 × 5 target patch inside the mask could be regulated within a 0.08–82 cd/m^2 range during the adjustment task; the starting level was set randomly at the beginning of each trial.

Procedure. An adjustment task was used. The subject had to regulate the luminance of the line elements of the texture patch inside the masking square so that they appeared to have the same brightness as the line elements in the texture outside the masking square. The subjects were informed to pay no attention to the shape of patch line elements.

The stimulus sequence was the following for each trial. A fixation cross appeared in the center of the monitor. After a 500–1000 msec random interval, the surrounding texture and the target patch were displayed for 14 msec to a randomly chosen eye. This was followed by an interval (ISI) in which the monitor was blank. Then the masking square was presented for 14 msec to both eyes. Finally, the fixation cross disappeared.

Each trial could be repeated an unlimited number of times throughout which the adjustment could be made more and more accurate by preserving the luminance value of the adjustment in progress across repetitions. When the subject was sure of his/her brightness adjustment, he/she ended the current trial and the next trial started. At each trial repetition, new texture and mask stimuli were generated. Repetitions were separated by a 1000–1500 msec blank interval. The subject used two keys to regulate (up or down) the luminance of the texture patch; two other keys served to repeat the trial and to end the trial.

Two factors were intermixed within a block of trials: the size of the segregating texture and the ISI between texture and mask. Four ISIs were used, 0, 42, 85, or 128 msec. A session comprised a block of 16 trials (one trial per condition) and its phases were under computer control. The subjects ran some training sessions before they had 3–4 experimental sessions.

Subjects. Two psychophysically experienced subjects who were unaware of the purposes of the experiment participated. They had normal or corrected-to-normal acuity and normal stereo vision.

Results

The results are plotted in Fig. 3. In these graphs, because of the adjustment task used, a larger increase in the adjusted luminance can be taken as a measure of a stronger masking produced by the square contour. In the graphs the actual luminance of surround line elements is indicated by the dotted horizontal line.

A repeated-measure analysis of variance (ANOVA) was carried out on the subjects' sessions with size of the segregating texture and texture-to-mask ISI as factors. Both the effects of size ($F_{3,12} = 82.7$, $P < 0.001$) and of

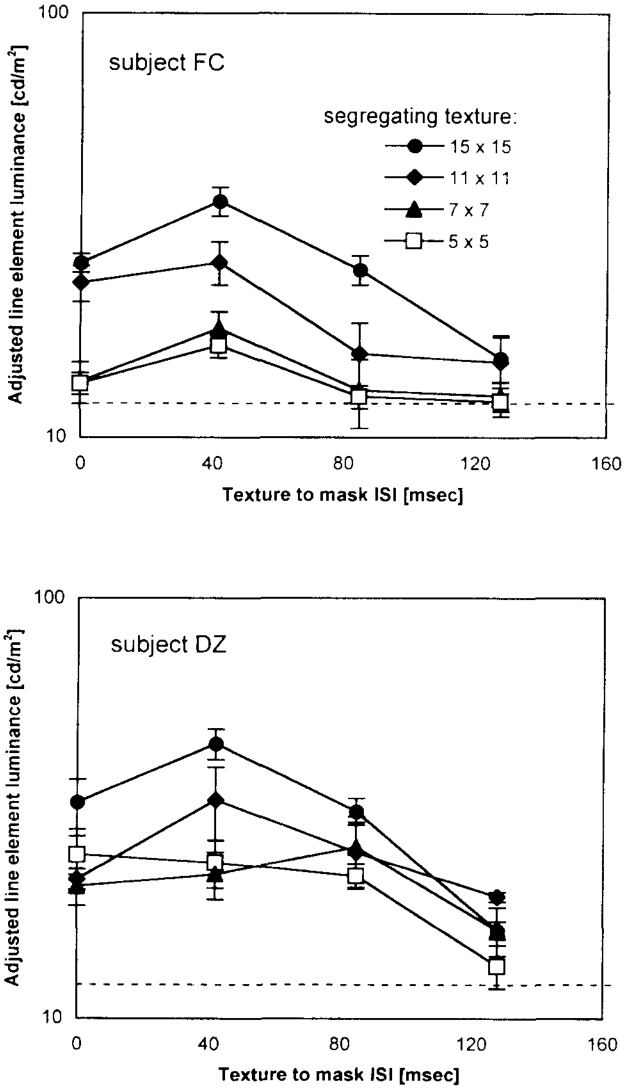

FIGURE 3. Results of Experiment 1 by two subjects. Adjusted target patch luminance as a function of texture-to-mask ISI for different sizes of the segregating texture. The actual luminance of the line elements of the texture outside the masking square is indicated by the dotted horizontal line. A larger adjusted luminance corresponds to a stronger masking effect. Error bars represent SEM.

ISI ($F_{3,12} = 25.3$, $P < 0.001$) were significant; their interaction ($F_{9,36} = 3.0$, $P < 0.01$) was significant.

Discussion

The results show that: (1) the square contour produces a masking effect that is stronger with large segregating texture sizes. (2) For 11 × 11 and 15 × 15 sizes the masking effect increases for short ISIs, with maximal masking around 40 msec; then, it decreases for longer ISIs. (3) The ISI required to attain the same brightness level becomes more and more protracted in time, as long as the size of the segregating texture is increased.

The first finding extends the preliminary observations concerning a difference in masking effects between uniform and segregation conditions to conditions in which distances between the segregation border and the masking contour has intermediate values. In fact, increasing the size of the segregating texture produces an increasingly larger uniform texture (without changing overall stimulus luminance). Two inter-related variables change when the size of the segregating texture is increased: one is the distance between the segregation border and the masking contour; the second is the amount of equally oriented line elements displayed in the segregating texture. The relevance of the first variable will be further investigated in Experiment 2.

The second finding shows that the masking effect (for texture sizes 11 × 11 and 15 × 15) is characterized by a non-monotonic function peaking at approx. 40 msec. This is different from the monotonic functions obtained with luminance stimuli, which are characterized by a maximal masking for ISI = 0 msec (Paradiso & Nakayama, 1991). Therefore, we can hypothesize that texture stimuli and luminance stimuli involve different filling-in mechanisms.

The third finding is the most important, as evidence for a spreading process. A large size segregating texture attains the same level of masking of a small size segregating texture at later ISIs. For example, the 15 × 15 segregating texture presented with ISI = 85 msec requires the same luminance level as the 11 × 11 texture presented with ISI = 42 msec, in order that both texture patches achieve the same brightness. This finding can be interpreted as a consequence of a spreading process that starts from the segregation border. The larger the distance between the segregation border and the masking contour, the later the time at which the masking contour can continue to interfere with this spreading process.

The comparison of the masking functions across different sizes is relevant in relation to our hypothesis of two filling-in components in textures. The plots show that a masking effect is present when the segregating texture is inside the square contour (size 5 × 5). This is most evident in subject DZ, who shows a monotonic function for this condition, whereas only a slight masking effect is present in subject FC. Sizes larger than 5 × 5 add further masking with respect to this condition. Our interpretation is that the masking effect in the 5 × 5 condition gives a basic function that corresponds to the non-orientation specific component of filling-in. The second filling-in component is increasingly involved for sizes larger than 5 × 5, because texture spreading entails the parts of the segregating texture that are outside the masking contour. Therefore, the intervention of the second filling-in component is represented by the difference with respect to the basic function in the 5 × 5 condition. This difference is characterized by the peak at approx. 40 msec, which can represent the latency of the second filling-in component.

Another interesting finding concerns the adjusted luminance at the longest ISI used, where, as the graphs for size 5 × 5 show, the masking effect is exhausted. A residual elevation in adjusted luminance is nevertheless present for the other conditions, at least larger than size 7 × 7. This residual elevation can be explained by a lower saliency of segregating textures larger than size 7 × 7. In fact, increasing the size of the segregating texture decreases the ratio of the length of its boundary contour to its area, thus decreasing its saliency.

EXPERIMENT 2

The hypothesized texture flow component involved in brightness filling-in within textures is orientation selec-

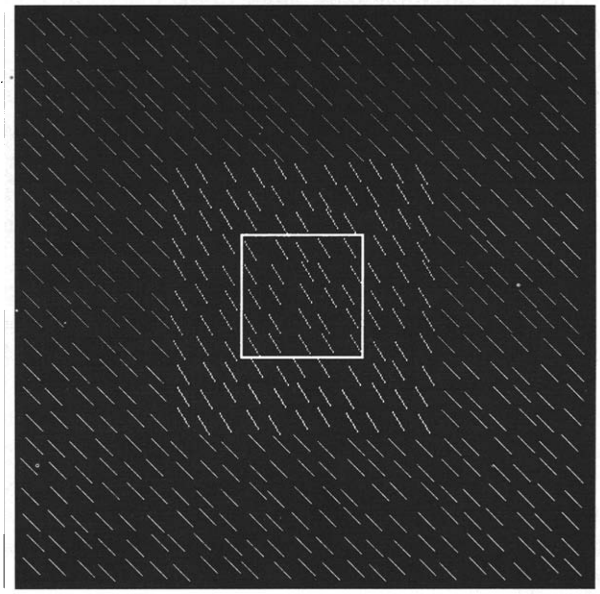

FIGURE 4. An example of the stimuli used in Experiment 2. A surrounding texture having a 23 × 23 line elements size contains in its center an 11 × 11 segregating texture. The orientation gradient between the line elements of the two textures was the segregation angle that could take three values (0, 9, or 18 deg) with the 0 deg condition producing no-segregation and with increasing segregation strength as the angle increased (in this example the angle is 9 deg). The masking square contour (actually presented in a different frame) isolated a 5 × 5 target patch. The center of the stimulus was displayed in random positions 4.5 deg around a fixation cross presented in the monitor center. In Experiment 2, the luminance of the line elements of the entire texture stimulus (surrounding, segregating, and patch textures) was constant and the subject's task was a matching of the brightness of the target patch with a comparison stimulus (displayed after the texture–mask sequence) that consisted of a 5 × 5 texture.

tive. In this experiment the angle difference between surrounding texture elements and segregating texture elements is manipulated, while the size of the segregating texture remains constant (11 × 11 line elements, see Fig. 4). The basic condition is when no orientation gradient is present (angle difference = 0 deg) and no segregation occurs. In this case the masking square should produce the strongest effect because the texture flow spreads across the entire texture. Instead, as long as the orientation gradient is increased, the segregation border that progressively emerges should block more and more strongly the texture flow from the surrounding texture and should restart spreading from this segregation border. As a consequence, the masking effect produced by the square contour should be progressively reduced as the orientation gradient is increased.

In the previous experiment, non-monotonic masking functions were found which differ from monotonic masking functions obtained by Paradiso and Nakayama (1991). This difference may depend on the adjustment task used in Experiment 1. Therefore, in this second experiment a comparison task was used similar to the matching task employed by Paradiso and Nakayama.

Methods

Apparatus and stimuli. The same apparatus as before was used at a higher resolution (1152 × 864) in order to obtain a fine variation in the angle of the line elements of the segregating texture. An example of the texture stimulus is shown in Fig. 4. Texture line elements were arranged on a 23 × 23 raster subtending 9.6 × 9.6 deg visual angle. The stimulus center appeared at 4.5 deg around the fixation cross, in randomly chosen eccentric positions. A line element measured 25 × 1.4 min arc; its position was jittered by 0–4.2 min arc around its raster cell.

The texture stimulus was subdivided in a larger surrounding texture that occupied the outer raster rings, and in a segregating texture that occupied the 11 × 11 central raster positions and subtended a 4.6 × 4.6 deg visual angle. Line elements of the surrounding texture slanted 45 deg either to the left or to the right at random. The line elements of the segregating texture were tilted toward vertical with respect to the line elements of the surrounding texture: the difference between the two angles was the first experimental factor, the segregation angle, that could take three values (0, 9, or 18 deg) with 0 deg condition producing no segregation and with increasing segregation strength as the angle increased.

The masking square contour was similar to the one used previously (2.1 deg side, 2.8 min arc thickness), centered on the texture, and isolating a 5 × 5 texture patch.

Line elements of surrounding, segregating, and texture patches had the same luminance (70 cd/m^2) which was constant throughout the experiment. The background screen was dark (0.08 cd/m^2).

The comparison stimulus used in the matching task was a 5 × 5 texture patch that was spatially identical (both in the arrangement of its line elements and in its position with respect to the fixation cross) to the previous presented texture patch inside the masking square. The luminance of the line elements of the comparison texture could be regulated within a 0.08–82 cd/m^2 range during the matching task; the starting level was randomized for each trial.

Procedure. A comparison procedure between two temporal intervals was used. In a trial the texture–mask presentation was followed by the comparison texture patch. The subject's task was to match the luminance of the line elements of the comparison texture patch with the just-perceived brightness of the line elements of the texture patch inside the masking square. The subject could view unlimited repetitions of each trial; the luminance value of the comparison texture was preserved across repetitions in order to achieve a more and more accurate match. When the subject was sure of the match performed, he/she ended the current trial and the next trial started.

The texture–mask dichoptic presentation was the same as that used in Experiment 1. This was followed after a 1000 msec blank by the comparison texture patch that was presented continuously during the matching task. When a new repetition or a new trial was requested by the subject, the comparison texture disappeared and was followed by the new texture–mask sequence after a random 500–1000 msec blank interval. At each repetition new stimuli were generated.

Two experimental factors were used. The first was the segregation angle. The second was the texture-to-mask ISI (0, 42, 85, 128, or 171 msec). A session comprised a block of 15 intermixed trials (one trial per condition). The subjects ran four experimental sessions after a large number of training sessions.

Subjects. Participation was by two psychophysically experienced subjects who were unaware of the purposes of the experiment; they had normal acuity and normal stereo vision.

Results

The results are plotted in Fig. 5, which represents perceived brightness of the texture patch inside the masking square as a function of texture-to-mask ISI. The use of a matching procedure produces plots that are up–down rotated with respect to the plots obtained in the previous experiment that used an adjustment task. The actual luminance of line elements of the texture stimulus is shown by the dotted line.

There are some differences between the subjects that may be attributed to their different sensitivities for orientation gradients. For subject LM the 9 deg orientation gradient already produces a texture segregation, whereas for subject CC only the 18 deg gradient shows a relevant effect. Moreover, in subject LM there is an interaction between angle and ISI: with a 18 deg gradient the brightness has its minimum around 80 msec, with 9 deg around 100 msec, and with no-gradient around 120 msec; in subject CC this interaction is not so evident,

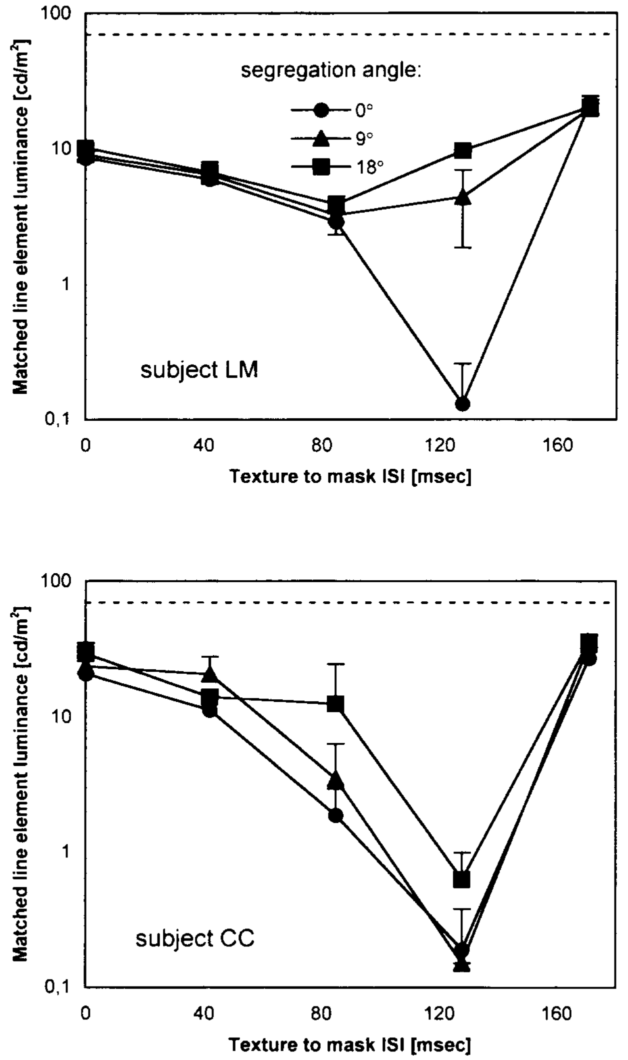

FIGURE 5. Results of Experiment 2 for two subjects. Perceived brightness of the texture patch inside the masking square contour as a function of texture-to-mask ISI. The plots are parametrized for different angles between surrounding and segregating textures. The actual luminance of the texture line elements is indicated by the dotted horizontal line. A stronger effect of masking corresponds to a lower matched luminance. Error bars represent SEM.

with condition 18 deg probably peaking before the two other conditions.

A repeated-measure ANOVA was carried out on the subjects' sessions with segregation angle and ISI as factors. The effect of angle was significant ($F_{2,16} = 5.1$, $P < 0.02$) as well as the effect of ISI ($F_{4,32} = 25.5$, $P < 0.001$); their interaction was non-significant ($F_{8,64} = 1.1$, $P > 0.3$). However, an ANOVA on LM's sessions showed a significant interaction between angle and ISI ($F_{6,18} = 5.7$, $P < 0.005$).

Discussion

The results show that: (1) the masking contour produces a perceptual darkening that decreases as the segregation angle increases. (2) This darkening is approx. constant for short ISIs; then it increases for intermediate ISIs, with maximal darkening around 80–120 msec, depending on the segregation angle; finally, for longer ISIs, darkening steeply decreases. (3) The three angle conditions are not different up to ISIs of 40–80 msec, then they diverge for ISIs of 40–120 msec.

The first finding of a dependence of darkening on the orientation of texture line elements sustains our hypothesis that a filling-in component, specifically involved in the perception of textures, spreads a texture flow in the direction of the orientation of the texture line elements.

The second experimental finding of a different shape of the masking function for texture stimuli, with respect to the monotonic functions found by Paradiso and Nakayama (1991) for luminance stimuli, replicates the results of Experiment 1 with a different psychophysical procedure. Therefore, luminance and texture stimuli involve two different filling-in mechanisms that are characterized by different masking functions.

The third experimental finding details this interpretation further. Indeed, before 40–80 msec, darkening does not depend on the angle of line elements and remains approx. constant across these short ISIs. Therefore, the intervention of the isotropic component of filling-in is represented by the constant and orientation-independent darkening at these short ISIs.

Instead, after 40–80 msec, darkening depends on the angle of texture line elements, so that the orientation-selective flow component of filling-in is involved. This second filling-in component intervenes with a delay after texture onset, hence suggesting that it operates at a processing stage later than the isotropic mechanism. Moreover, as the results in the 0 deg condition show, there is a further delay between the onset of orientation selectivity (40–80 msec) and the latency of maximal darkening (approx. 120 msec). This finding can be explained by the involvement of two processes: first, boundary contours are extracted at the texture discontinuity points, then texture surface fills-in the bounded region. This processing sequence extends the filling-in hypothesis, which states that spreading starts from contours, and that contours provide compartments (boundary conditions) for filling-in, to texture stimuli.

The strength of brightness spreading produced by the flow component of filling-in (see 0 deg condition at ISI approx. 120 msec) is two orders of magnitude stronger than brightness spreading produced by the first filling-in component (same condition at ISIs approx. 0 msec). Therefore, we are facing a mechanism selective for texture pattern that is much more powerful than the low-level isotropic mechanism.

GENERAL DISCUSSION

In the experiments presented in this paper, filling-in was studied within textures made of line elements. Phenomenological observations showed that texture filling-in is a process that concerns both brightness and shape of texture line elements.

Experimental investigations led us to hypothesize that two mechanisms subserve filling-in in textures. The first filling-in component is involved in spreading isotropically the mean stimulus luminance independently of the orientation of the texture line elements. This component starts spreading from luminance edges of the overall texture stimulus. It is an early process as it operates with a short latency (0–40 msec).

The second filling-in component consists of a texture flow directed along the orientation of texture line elements. This texture flow involves spreading of the textural pattern* in what concerns both brightness and shape of texture line elements. This component starts spreading from segregation borders. Segregation contours are first extracted with a latency of 40–80 msec after texture onset. Then the texture surface fills-in the bounded region with maximal spreading at a latency of approx. 120 msec.

This dissociation between processing of segregation contours and filling-in of the texture surface, can be explained by hypothesizing that two stages subserve texture filling-in. The first stage produces a continuous surface representation from textures made of physically discontinuous elements through inhibition of the segmentation of individual texture elements. At this first stage, only texture discontinuities (i.e., segregation contours) are extracted from the image. The second stage spreads and smoothes a texture surface representation inside the segregation borders. Its mechanism can be based on lateral excitatory connections between grossly aligned detectors.

In a previous paper, I have discussed the possible neurophysiological machinery on which the first inhibitory stage can be based (Caputo, 1996). Briefly, the results of this mechanism arise from regulatory feedback driven by infragranular layers, and are represented in the response of supragranular layers of V1. The second stage of spreading of the texture flow can tentatively be localized in the extensive set of lateral excitatory connections that are present in supragranular layers of V1 (Rockland & Lund, 1983; Kisvarday, Cowey, Smith & Somogyi, 1989).

The present results can be considered in relation to some neurophysiological studies. Firstly, selectivity to texture line element orientation begins at a similar latency (40–80 msec) as that required in V1 neurons of macaque monkey for selectively responding to texture segregation (approx. 59 msec, Knierim & Van Essen, 1992; 60–70 msec, Lamme, 1995). Secondly, our finding that maximal spreading of the flow component of filling-in develops at a further latency (approx. 120 msec), can be in relation to the component (peaking at approx. 160 msec) found in human visual evoked potentials in response to texture segregation (Bach & Meigen, 1992; Lamme, Van Dijk & Spekreijse, 1992).

The present results can be considered in relation to computational models of brightness filling-in. These models (Grossberg & Todorovic, 1988; Arrington, 1994) propose that boundary contours gate lateral spreading within a neural network that receives activity from an initial filtering stage of the image with circular symmetric center–surround kernels. Brightness perception would be "isomorphistic" to the activity present in this neural network (Pessoa, Mingolla & Neumann, 1995).

These models can explain our finding of a first component of filling-in. In the case of textures the image is low-pass filtered with non-oriented kernels having a larger size than line element length. High spatial frequencies are irrelevant because the overwhelming number of contours makes spreading impossible.

Instead, the second filling-in component cannot be explained by these models. In particular, non-oriented filters cannot explain the oriented flow. This problem can be overcome by adapting filling-in models to current models of texture segregation (Malik & Perona, 1990; Landy & Bergen, 1991). Texture processing has been hypothesized to involve a first stage of filtering that, in the case of textures made of oriented lines, consists of convolving the image with orientation-selective filters. Orientation-selective spreading can be modeled with different neural networks, each one receiving input from an oriented channel. The selectivity for line length annotated above indicates that these networks are also selective for spatial frequency. Lateral connections within each neural network allow spreading and smoothing of activity between filters. Within these neural networks gating of spreading can be produced by contours owing to texture segregation. A segregation contour between equiluminant textures is extracted from the filtered image, after an intermediate non-linearity, through second-order filters. Therefore, lateral spreading within an orientation-selective neural network can be gated by second-order contours. This mechanism can probably explain some classical results: for instance, it can explain the extension to textures of the Craik–Cornsweet pattern, as designed by Nothdurft (1985b).

Another explanation of the flow component of filling-in is that spreading within textures is allowed by suppression of the contour of each texture line element, so that brightness can flow outward from the line element. A possibility is that contours of texture line elements are processed, not at an early filtering stage, but at a later stage of surface representation. Contour processing of a line element might be actively suppressed when it belongs to a texture so that potential discontinuity points become embedded in a texture surface without discontinuities. On the other hand, emergent boundaries due to texture segregation become able to provide filling-in compartments at the surface representation level. A fundamental processing step in the analysis of the visual image consists of the segregation into figure and ground. The relevance of segregation contours in providing

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*Other experiments, not shown here, demonstrated a strong (direct) relationship between the length of texture line elements and the strength of the texture flow. In other words, a segregation border becomes increasingly able to start/stop texture filling-in as long as the length of texture line elements is increased. This finding agrees with psychophysical results on texture segregation (Nothdurft, 1985a).

boundaries to the flow component of filling-in constitutes an important mechanism commonly involved in texture perception (Caputo, 1997).

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