Rapid Communication

Context effects on texture border localization bias

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Abstract

Observers are able to locate precisely a border defined by changes in texture orientation. The prevailing theory is that such localization takes place using a hierarchical, filter-rectify-filter mechanism. An alternative theory is that contextual modulation causes the border elements to stand out. Here we show that perceived border location is inconsistent with contextual modulation from iso-oriented elements. The perceived location of a vertical border defined by vertical texture on one side, and horizontal texture on the other side, is biased towards the vertical texture. We found the same bias in a single row of texture. Therefore, the bias is not due to contextual influences from surrounding iso-oriented elements. Contextual influences between cross-oriented elements can explain the data.
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1. Introduction

The brain contains many different mechanisms that might subserve texture segmentation. In primary visual cortex (V1), neurons selective for orientation are more active near a texture border than within a region of uniform texture (for review see Nothdurft, Gallant, & Van Essen, 2000). This excess activity can be modeled computationally using a network of inhibitory and excitatory connections between nearby cells (Li, 2002). These contextual influences lead to excess activity in the vicinity of the boundary. While the excess activity might in itself signal the presence of a boundary, there exist also complex cells in higher visual-areas such as V2 that respond directly to borders (Peterhans & von der Heydt, 1993; Heider, Meskenaite, & Peterhans, 2000). These complex cells might respond to the excess activity in V1. Alternatively, they might form the final stage of a filter-rectify-filter (FRF) mechanism, responding to orientation modulation across V1 (for review see Landy & Graham, in press). Within the FRF scheme, there are two possible mechanisms for the second-stage filters. They may be driven by change in activity across V1

within a particular orientation channel. Alternatively, they may be driven by the presence of different orientations in different regions of V1, combining information from different orientation channels. Thus, there is potential redundancy in neural texture segmentation: the border is extracted by contextual influences in V1, but at the same time second-order filters respond to the border in V2, a preference which might itself arise from a number of different possible mechanisms. This is redundant to the extent that either V1 or V2 mechanisms alone might subserve border detection and localization. However, the V2 mechanisms may also be part of some more complex computation.

Human observers are able to locate a texture border with a high level of precision (Gray & Regan, 1997). In a texture composed of rasters or columns of elements, thresholds are typically less than the width of a single raster. However, the perceived location of the texture border is biased for certain stimuli (Popple & Li, 2001). When the texture on one side of a border consists of elements parallel to the border, and the texture on the other side of the border consists of elements at right angles to the border, the border appears aligned with the last raster of border-parallel elements, not halfway between the two textures (Fig. 1). As the texture elements are rotated, keeping the orientation contrast at the border constant at 90°, this bias reduces to zero in the

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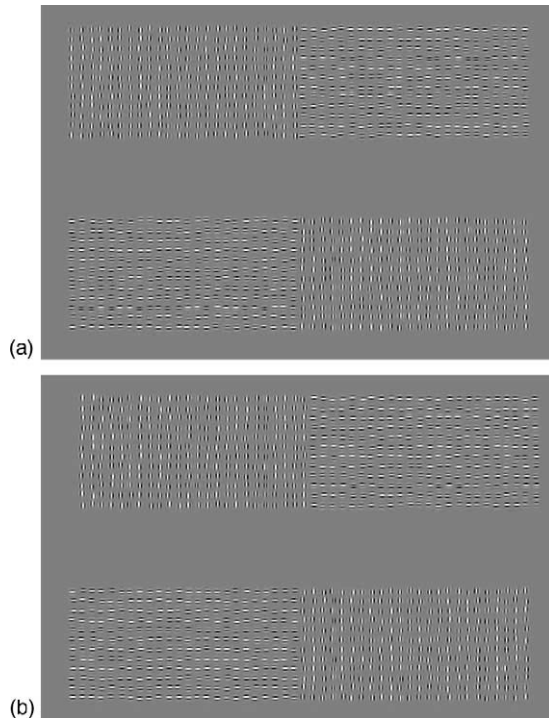*E-mail address:* apopple@spectacle.berkeley.edu (A.V. Popple).

Fig. 1. *Experimental stimuli.* (a) The upper and lower textures each contain a vertical border defined by orientation contrast. The upper border is perceived left of the lower border. (b) Shifting the upper texture to the right nulls this bias. The borders now appear aligned. Inspection of the outer edges confirms that the texture has been shifted by one column-width, or raster. This implies the border bias within each texture was 0.5 raster units. To visualize single rows, simply occlude everything except the bottom row of the upper texture and the top row of the lower texture. The bias is still the same.

symmetrical case where the texture on either side is at +45° and −45° to the border. Rotating the elements further gives a bias in the opposite direction.

Two very different models of texture segmentation are consistent with this bias. Wolfson and Landy (1995) found that a straight, vertical border between two textures could be discriminated accurately from a wavy, vertical border when the texture on one side was vertical (parallel with the border), and the texture on the other side at right angles to it. Discrimination was less acute when the texture on either side was oblique to the border, although the border was still defined by a 90° orientation contrast. They simulated this result with an FRF model, weighting the signal from the border-parallel (vertical) channel more than the other channels to fit the data. Graham and Wolfson (2001) later hypothesized that second-stage filters whose inputs are aligned with their preferred orientation are more prevalent, or efficient, than others. The weight given to the border-parallel channel also biases border location, assuming that border location is coded by the most active channel, or the activity-weighted mean across channels. Li (2000) successfully modeled the results of Wolfson and Landy (1995) using a network that simulated contextual influ-

ences in V1. Assuming that the texture border is signaled by the highlighted activities of the V1 cells, Li's model also predicted a bias in the perceived location of a border towards the elements parallel with the border. Thus, both models using second-order filters (like in V2) and models of contextual influences (based on V1 physiology) predicted the bias in perceived texture border location.

The geometry of the stimulus shown in Fig. 1 can be used to discriminate between the two models. According to Li's model, the context of iso-oriented elements present in the stimulus is crucial in determining the strength and location of V1 border highlights. This is because these iso-oriented elements give rise to the contextual influences causing the highlights. However, if the perceived bias in border location were due to the unequal weight given to the border-parallel, vertical channel in an FRF scheme, one row of texture should suffice.

To summarize the implications of iso-oriented influences in this stimulus: suppose we have one weight for influences from collinear neighbors (C), and another weight for influences from parallel neighbors (P). C and P may be positive (facilitatory) or negative (inhibitory). If C and P are both negative, elements on both sides of the border will be highlighted, since they will have fewer inhibitory inputs than elements far from the border. If C is positive and P negative, only the vertical border elements will be highlighted compared with the background elements.

Fig. 2 shows what happens if we concentrate only on inputs to the circled border elements from their immediate neighbors. In a texture (Fig. 2a), each vertical border element receives two C inputs and one P input, whereas each horizontal border element receives two P
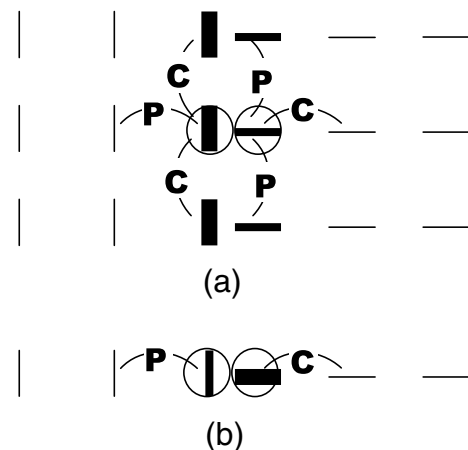

Fig. 2. *Influences from neighboring elements.* Line-width indicates saliency. C marks collinear influences, P parallel influences. (a) P must be more negative than C to obtain the excess saliency of the vertical border element and hence the observed bias. (b) In a single row, if P is more negative than C, the horizontal border element will be more salient than the vertical one. Bias is reversed.

but only one C input. Providing that P is more negative than C, the effect of contextual modulation will be to highlight the vertical border elements more than the horizontal border elements. Fig. 2b shows that in a single row, the vertical border element receives one P input, whereas the horizontal border element receives one C input. Thus, the effect of contextual modulation reverses in this case, selectively highlighting the horizontal border element.

As argued above, models composed of iso-oriented contextual influences predict a reversal in the perceived direction of border bias when going from texture to a single row. This is because the balance of unit activity shifts from the vertical border elements in texture, to the horizontal border element in the case of a row stimulus. To obtain this prediction, the model was simplified. In more general terms, at least we can expect to see a change in border bias when we eliminate the iso-oriented context that caused the bias, by removing texture rows.

The present study was designed to test this prediction.

2. Methods

Four observers with normal or corrected to normal visual acuity participated in this study. CW and GO were naïve as to its purpose.

Stimuli were generated by a Linux PC, and viewed from 1.0 m on a gamma-corrected VisionMasterPro-450 (70 Hz, 40 cd m^{-2}). The fixation was a 500 ms, 0.1° white outline circle. Experimental stimuli were 2.64° × 10.56° (150 ms) 12 × 48 textures or 1 × 48 rows of Gabor patches (50% contrast, $f = 12$ cpd, $\sigma = 0.04°$, where luminance from background, $l \propto \exp(-(x^2 + y^2)/2\sigma^2) \times \sin(2\pi xf)$, x being displacement from Gabor center along the axis of sinusoidal modulation, and y along the perpendicular axis; see Fig. 1 for sample stimuli). We used Gabors instead of bars so that they lined up when they had different orientations. Patches were arranged in a square grid texture of raster width 6σ, where σ is the spatial constant of the patches. The position of each patch was further jittered by up to $\pm1.2\sigma$, to prevent observers from aligning the columns of the grid to do the task. In the center of each texture was a vertical boundary defined by 90° orientation contrast. The upper and lower textures were mirror images of one another: if the upper texture contained vertical patches left of center and horizontal patches right of center, the lower texture contained horizontal patches left of center and vertical patches right of center. The textures were vertically separated by 0.86°. The horizontal offset of the upper texture was shifted between trials.

The task was to align the vertical border in the upper texture with that in the lower texture, and the dependent variable was the bias in this task. The observer indicated, on each trial, whether the upper border was left or right of the lower border. The orientation of the elements in each panel was varied (0°–90°), keeping the contrast at the border constant.

Trials were blocked by orientation. A nulling paradigm was used to measure the bias in perceived border location. We used a method of constant stimuli, and a single-interval forced choice procedure. In each block, 5–7 horizontal offsets of the upper texture were presented in a random order, with 20 trials at each offset. The frequency of responses 'left' was fitted with a cumulative normal to determine the point of subjective equality (PSE), where the observer responded left on exactly 50% of trials. The displacement of the PSE from alignment is twice the bias in perceived border location.

3. Results

There was a bias of about 0.5 rasters toward the vertical border elements, both for texture and row stimuli, indicating that observers saw the border at the edge of the vertical texture or row (Fig. 3). This bias varied monotonically with element orientation. Data from AP show that the bias at any given orientation was the same for texture and row stimuli.

4. Discussion

The data show that an iso-oriented context is not needed to produce a bias in perceived texture border location. This result is consistent with an FRF model of texture segmentation, such as the one proposed by Wolfson and Landy (1995), where bias is due to unequal weighting of the border-parallel channel. Graham and Wolfson (2001) suggested that second-order filters
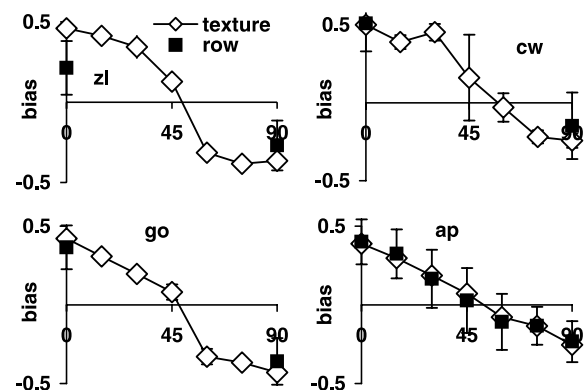

Fig. 3. *Results*. Bias (raster units left) is plotted against texture orientation left of the border (degrees, 0° = vertical). Bias was not reversed for single rows (filled squares) compared with texture (open diamonds). In texture, bias decreased monotonically from about 0.5 raster units toward vertical texture, to −0.5 raster units away from horizontal texture.

whose inputs are aligned with their preferred orientation are more prevalent or efficient than others. Alternatively, the horizontal alignment task might instigate top-down influences that favor vertical filters (Super, Spekreijse, & Lamme, 2001). Due to methodological limitations, our stimuli lasted 150 ms, and may therefore have been susceptible to attentional modulation that could have been avoided with a briefer stimulus duration. Different results might be obtained with shorter durations. Nevertheless, it seems unlikely that a pre-attentive process leading to unequal biases in segmenting texture and row stimuli should be totally overridden by a later process that gives exactly the same bias in both cases. However, until these results are replicated at a shorter duration this remains a possibility.

Our data appear to conform the FRF scheme, as implemented by Wolfson and Landy (1995). However, if Li's (2000) model is an accurate description of V1 activity, weighted filters cannot undo the difference between border locations in texture and row stimuli. To comply with our data, either (i) higher-order mechanisms that determine perceived border location receive their input before contextual influences are effected in V1, or (ii) the inputs to higher-order mechanisms are normalized. Alternatively, Li's model may be incorrect. Texture and row stimuli might in fact yield the same activity balance at the border in V1.

The geometrical argument presented in the introduction showed that iso-oriented contextual influences predict a reversal in bias between texture and a single row, which we did not find. Cross-oriented influences, however, predict that bias will remain the same in the two cases. Fig. 4 shows regions of contextual influence in a schematic stimulus containing a vertical border
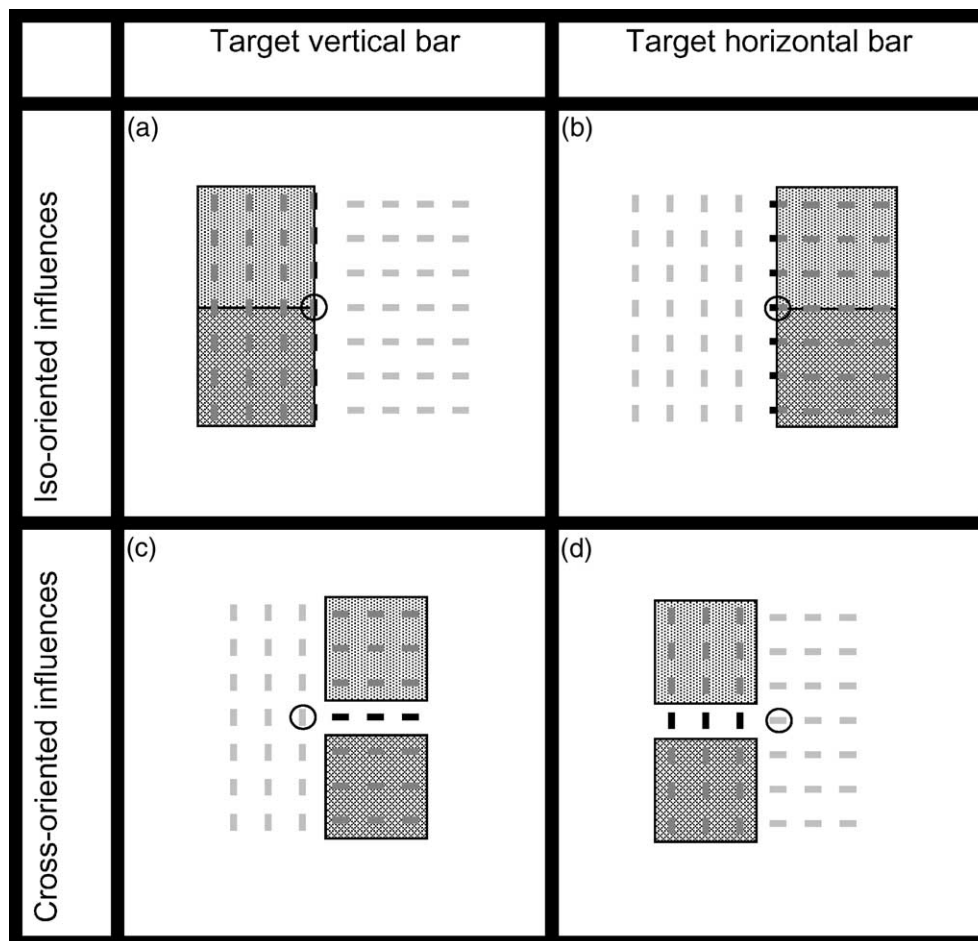

Fig. 4. *Contextual influences in a schematic vertical texture border.* (a) Iso-oriented influences on a vertical target are divided into the grey region above-left, and the darker region below-left of the target. The influences of split bars are split between regions. Residual influences come from the semi-highlighted bars along the border, collinear with the target. (b) Iso-oriented influences on a horizontal target are from the grey region above-right, and the darker region below-right of the target. Residual influences come from the semi-highlighted bars along the border, parallel to the target. *Identically shaded regions in (a) and (b) bear the same spatial relations to their targets after rotation. They are matched in their effects.* (c) Cross-oriented influences on a vertical target are from the grey region above-right, and the darker region below-right of the target. Residual influences come from the highlighted horizontal bars in the target row. (d) Cross-oriented influences on a horizontal target are from the grey region above-left, and the darker region below-left of the target. Residual influences come from highlighted vertical bars in the target row. *Identically shaded regions in (c) and (d) are matched.*

defined by vertical bars on the left, and horizontal bars on the right. Iso-oriented influences (a and b) come only from bars the same orientation as the circled target. Cross-oriented influences (c and d) come only from bars of the orthogonal orientation to the target. Shaded regions in a and b (showing iso-oriented influences) bear the same spatial relationship to their respective targets. Therefore, any difference between the inputs to the vertical and horizontal targets must come from the semi-highlighted bars above and below them. Shaded regions in c and d (showing cross-oriented influences) bear the same spatial relationship with their respective targets. Therefore, any difference between the inputs to the vertical and horizontal targets must come from the highlighted bars to their right and left. Inputs from bars above and below the targets are matched for vertical and horizontal targets, and therefore eliminating these bars does not affect the border asymmetry.

Cross-oriented excitation could result in the physiologically observed contextual influences (see Section 1), as well as cross-surround facilitation observed psychophysically (Wolfson & Landy, 1999; Yu, Klein, & Levi, 2002).

To distinguish between cross-oriented and iso-oriented contextual influences, the responses of V1 units must be recorded in the presence of single row borders falling within their receptive field. If responses in V1 follow Li's model and prove to be inconsistent with the psychophysically observed bias in perceived border location, this would provide strong support for the rectification of V1 output prior to texture segmentation. It would rule out at least some of the redundant texture segmentation mechanisms described in Section 1.

5. Conclusion

The visual cortex appears to contain redundant texture segmentation mechanisms. Our data show that current models of contextual influences in V1 are inconsistent with perceived border location. Perceived border location is consistent with the predictions of a biased FRF mechanism. However, an alternative model of contextual influences fits the data. This alternative model is based on cross-oriented rather than iso-oriented influences.

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