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Attention modulates psychophysical and electrophysiological response to visual texture segmentation in humans

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Abstract

To investigate whether processing underlying texture segmentation is limited when texture is not attended, we measured orientation discrimination accuracy and visual evoked potentials (VEPs) while a texture bar was cyclically alternated with a uniform texture, either attended or not. Orientation discrimination was maximum when the bar was explicitly attended, above threshold when implicitly attended, and fell to just chance when unattended, suggesting that orientation discrimination based on grouping of elements along texture boundary requires explicit attention. We analyzed tsVEPs (variations in VEP amplitude obtained by algebraic subtraction of uniform-texture from segmented-texture VEPs) elicited by the texture boundary orientation discrimination task. When texture was unattended, tsVEPs still reflected local texture segregation. We found larger amplitudes of early tsVEP components (N75, P100, N150, N200) when texture boundary was parallel to texture elements, indicating a saliency effect, perhaps at V1 level. This effect was modulated by attention, disappearing when the texture was not attended, a result indicating that attention facilitates grouping by collinearity in the direction of the texture boundary.

Keywords: Texture segmentation; Attention; VEPs; Psychophysics; Grouping

1. Introduction

It has been known for over 30 years that saliency of line-texture figures is higher when collinear elements in the figure group together (Field, Hayes, & Hess, 1993; Kapadia, Ito, Gilbert, & Westheimer, 1995; Nothdurft, 1992; Olson & Attneave, 1970) in a direction parallel to textural borders (Caputo & Casco, 1999). Grouping is not a property necessary to segment texture contours as such. Indeed, segmentation occurs by means of segregation based on orientation contrast, as well as grouping of texture elements (Field et al., 1993), and these two operations occur at a level of processing either concurrent or in close succession (Beck, 1982; Beck, Prazdny, & Rosenfeld, 1983; Julesz, 1981, 1986; Lamme, 1995; Nothdurft, 1992; Treisman, 1982; Treisman & Gormican, 1988). Grouping is a property that facilitates texture segmentation based on orientation contrast with consequent increase in saliency of segmented texture (Field et al., 1993; Nothdurft, 1992).

It is widely accepted that attention is allocated to the visual field after completion of grouping operations (Baylis & Driver, 1992; Beck, 1967, 1982; Moore & Egeth, 1997; Nothdurft, 1985, 2002; Sagi & Julesz, 1984; Treisman, 1982). This view is confirmed by studies that recorded cortical activity in human brain during texture segmentation (Bach & Meigen, 1992, 1997;

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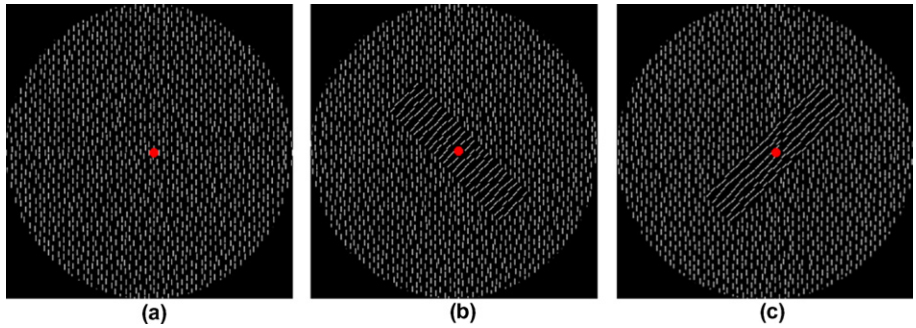

Fig. 1. Uniform texture stimuli (a) consisted of white vertical line elements 19′ long arranged on a diamond raster, with raster step of 30.5′ and jittered around their raster center by 0–2.7′. The segregation stimulus (b) consisted of a texture bar segregated from a uniform vertical texture displaying at the center the number 1 or 2. The texture bar comprised 6×24 line elements tilted either 45° or 135° at random. Note that at segregation edges, the local orientation contrast between the line elements of the bar and surrounding lines was kept constant (i.e., orientation difference always 45°). Two stimulus conditions were used. In the orthogonal condition (b), the bar short boundary had the same orientation as its line elements. In the parallel configuration (c) they were orthogonal with respect to bar orientation.

Fahle, Quenzer, Braun, & Spang, 2003). These showed a negative VEP component with latency around 200 ms, specifically elicited by textures pre-attentively segregated. However, Caputo and Casco (1999) showed that when attention is allocated on a texture bar during an orientation discrimination task, the VEPs associated with texture segmentation (tsVEPs, obtained by algebraic subtraction of uniform-texture from segmented-texture VEPs) present two peaks, with latency around 160 and 200 ms—20 ms faster with texture border parallel to texture elements vs. orthogonal. The new peak might be associated with attention involved in grouping, since the orientation discrimination task, used exclusively by Caputo and Casco (1999), involves attention and renders grouping necessary. The suggestion that grouping operations require attention also emerges from behavioral (Ben Av, Sagi, & Braun, 1992; Braun & Sagi, 1990, 1991; Yeshurun & Carrasco, 2000) and physiological data (Merigan, Nealey, & Maunsell, 1993; Motter, 1994).

To consider whether and how attention modulates texture segmentation, we evaluated both psychophysical and electrophysiological correlates of a texture-line figure segmentation, with attention: (i) not engaged on any task, (ii) engaged either (a) on spatial orientation of the texture boundary (texture figure attended), or (b) away from it on a central number that had to be identified (texture figure unattended).

The segmented texture figure was a bar oriented at 45° or 135°, presented on a uniform texture background (Fig. 1a). The boundary was either parallel (Fig. 1b) or orthogonal (Fig. 1c) to its elements.

In comparison with an orthogonal boundary, for a parallel boundary the texture elements are collinear and parallel to it. This geometrical arrangement can facilitate grouping of disconnected elements in the direction of the texture-figure boundary. In line with studies by other groups (Freeman, Sagi, & Driver, 2001; Gilbert, Ito, Kapadia, & Westheimer, 2000; Polat, Mizobe, Pettet, Kasamatsu, & Norcia, 1998), we asked whether this operation could be modulated by attention. We introduced this configural factor (boundary either parallel or orthogonal to texture elements) to assess whether attention modulates texture boundary segregation per se (based on orientation contrast), or else specific grouping operations that facilitate texture segmentation when the elements to be grouped are parallel to texture boundary. If attention generally modulates texture segregation, this would affect tsVEP amplitude (and/or latency) in the same way in the two configurations, since orientation contrast is constant. Alternatively, if attention modulates the facilitating of grouping by collinearity in the direction of the texture boundary, we would expect this specific effect, as reflected in tsVEPs, to be reduced when texture is unattended. Our results support this second hypothesis. When attention is engaged on the figure, we found that the higher saliency of parallel configurations was reflected in larger amplitude of tsVEPs, which occur early (N75, P100, N150, N200), perhaps at V1 level. With attention disengaged from the figure, the advantage in parallel-texture figure discrimination vanishes, as does the VEP correlate of this configural effect.

2. Experimental methods

2.1. Stimuli

In each trial, two kinds of stimuli were interleaved: uniform texture (Fig. 1a) and texture bar (Fig. 1b and c).

Stimuli were generated by a PC, displayed on a 15 in. color monitor (70 Hz vertical refresh) and viewed from a distance of 57 cm in a darkened room. Head movement was limited by a chin-rest. The monitor resolution was 640×350 with square pixel $2.7 \times 2.7'$. The monitor was viewed through a 16° diameter circular aperture.

A red dot or number was displayed in the center of uniform and texture bar stimuli, and observers were instructed to maintain fixation on it. Textures were defined by white line elements $19 \times 2.7'$, arranged on a diamond raster with raster step $30.5'$, presented on a dark background (0.6 cd/m^2). Line position was jittered around its raster center by $0–2.7'$. The look-up table was set such that the space average luminance of the texture was matched for vertical (11.45 cd/m^2), 45° and 135° (11.51 cd/m^2) orientations of the texture line elements. Pixel luminance values in the corresponding orientation conditions were 56 and 86 cd/m^2, respectively.

2.2. Subjects

One group of 10 observers and three groups of 60 volunteered as participants in Experiments 1a and 1b. Three groups of 10 observers participated in the VEP experiments (2a, 2b and 3). All subjects gave informed consent. They were aged 20–30 years, and selected to have absence of astigmatism and normal or corrected-to-normal vision.

2.3. Experimental design

Observers viewed a texture bar oriented at 45° or 135°, presented on a uniform texture background (Fig. 1a). The bar boundary (attended or not) had either the same orientation as local elements (Fig. 1b) or orthogonal (Fig. 1c).

2.3.1. Psychophysical design

Subjects viewed ten repetitions of four texture bars, presented at random within a block: boundary oriented right (parallel or orthogonal to its elements) or left (parallel or orthogonal to its elements). Experiment 1a consisted of two blocks and observers had to perform a two-alternative forced-choice (2AFC) task in each trial, to judge bar orientation. Frame duration was 13 ms. Pixel luminance of background lines was fixed in the first block (56 cd/m^2), whereas in the second the pixel luminance of background lines flanking the bar boundary was varied at random at five levels (29, 40, 56, 72, 88 cd/m^2) to give same average luminance but different local luminance.

Three groups of 60 subjects participated in Experiment 1b. Subjects in the first group had to perform a 2AFC task in each trial to judge bar orientation. Those in the second group had only to view passively the stimulus. The third group had to perform a 2AFC task in each trial to judge the number at the center of the display. Subjects of the second and third groups had a second task: after a random number (23–30) of trials, when presentation stopped, they were asked to report the orientation of the last presented bar, along with degree of certainty of their judgment. Frame duration was 840 ms.

2.3.2. VEP design

In the VEP experiments, onset–offset stimulation consisted of the cyclical alternation of segmented and uniform texture, each presented for 840 ms with no interval. Under these conditions, observers perceived the display as a static texture bar, cyclically appearing and disappearing from the uniform texture background (Fig. 2).

A 2AFC task was performed every three trials on average, between successive onset–offset stimulations, to avoid finger movement during recording. The task was to judge texture boundary spatial orientation of either short (Experiments 2a and 3) or long (Experiment 2b) boundary. Since subjects had to observe spatial orientation, the parallel (Fig. 1b) and orthogonal (Fig. 1c) stimuli were different, although in both cases the texture bars consisted of line elements tilted in the same direction. This texture orientation judgment requires grouping processes, since only integration across local orientations gives information on boundary orientation.

During stimulus presentation, observers had to maintain fixation on the central red dot or number, and eye movement was monitored. After presentation of three texture bar-uniform texture pairs on average, the onset–offset stimulation was suspended and the monitor remained dark, awaiting subject response. Observers used two keys to respond; an acoustic feedback was given for errors. The observer response re-started the onset–offset stimulation, which began with a 2000 ms display of a uniform texture to prepare fixation. No time-pressure was imposed on the observers, who were free to rest during the waiting period.

In one 800-trial session, four stimulus conditions were randomly intermixed: boundary oriented right or left, and parallel or orthogonal to its elements. Each uniform texture stimulus following the bar was classified according to whether it followed parallel or orthogonal figure conditions.

2.3.3. Recording and analysis

The electroencephalogram (EEG) was recorded from Ag/AgCl-coated cup electrodes placed at Oz and left (reference) and right (ground) earlobes. Electrode positioning followed the international 10/20 system. Electrode impedance was held below 5 kΩ. The EEG was amplified (BM 623, Biomedica Mangoni, Pisa, Italy) and digitally converted (CED 1401, Cambridge Electronic Design, Cambridge, UK) under control of a second PC. Stimulation and recording onset were synchronized with reference to the vertical retrace signal of the monitor displaying the stimulus. The EEG activity was digitized at 1 kHz with a resolution of 12 bits, with an amplifier bandpass of 1–50 Hz, had a gain of 50,000, and was stored on hard disk. Artifact rejection when signal amplitude exceeded 100 μV was carried out off-line.

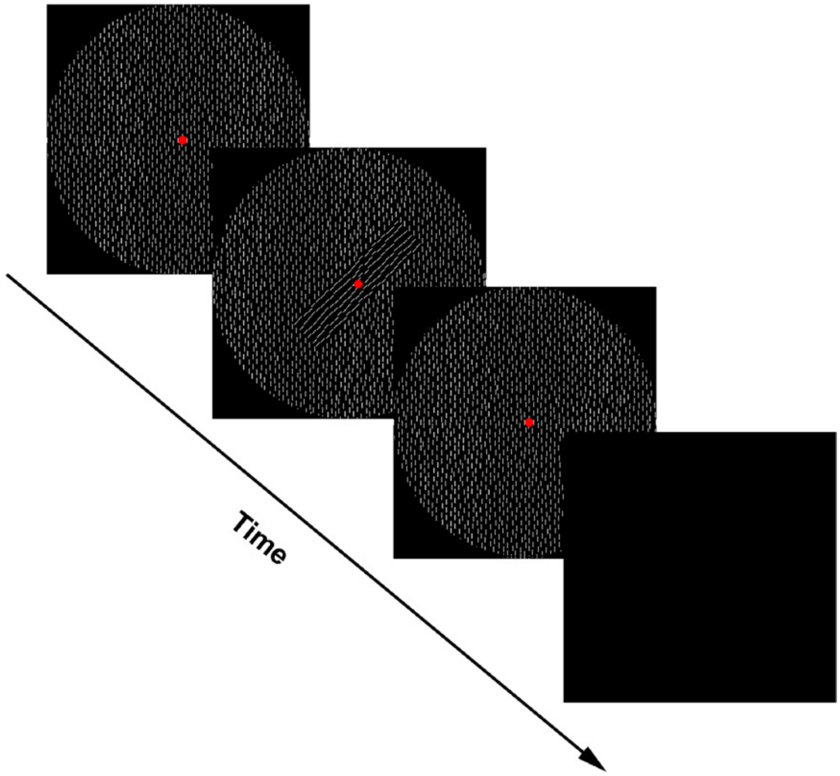

Fig. 2. The figure shows the sequence used in both psychophysical and VEP experiments.

The VEPs were obtained by averaging the signal separately for the three stimuli: background (separately for the two segmentation/background stimulus conditions), boundary parallel, and boundary orthogonal to its elements. These were then vertically aligned, taking their mean amplitude in the 0–50 range after stimulus onset as baseline. Since they overlapped, the VEPs of the two background-stimulus conditions were averaged into a single trace.

We looked for modulation of texture segmentation by attention by analyzing, in the 60–275 ms window, negative excursions larger for the segmentation-stimulus vs. the uniform texture VEPs. To do this, the response difference (tsVEP)[1] of VEPs was determined by algebraic subtraction of the uniform texture VEPs from either segmentation-texture VEPs after low pass-filtering (0–40 Hz) to aid peak localization. After this subtraction, we analyzed all tsVEP components (not just one as in previous studies). For each subject, tsVEP peaks with average latency at 85 (N1), 105 (P1), 148 (N2) and 210 (N3) ms were identified as the largest peak within the appropriate time window (60–90, 91–125, 126–174, 175–225, 226–275 ms). The advantage of using tsVEPs is that they reflect only processing involved in texture segmentation, since the effect of other variables (e.g., local processing of texture elements, internal noise) producing similar VEP correlates is cancelled by subtraction. Closer examination of the individual tsVEP traces in parallel and orthogonal conditions reveals that they appear to differ even for short latencies, as though some amount of residual noise were present at these latencies. To check this, we included an additional component, N0, as control in the 0–20 ms time interval when analyzing tsVEPs.

2.3.4. Eye movement monitoring

Eye movements were recorded through an independent channel, by placing two electrodes on the temporal sides of both eyes, at 1 cm from eye edge. Calibration was set so that, on average, any eye movement of 1.4° (along the horizontal axis) was discarded 50% of the times, and any eye movement of 2.8° (along the horizontal axis)[2] was discarded 100% of the times. Note, however, that any attempt to maintain fixation on part of the stimulus (e.g., the bar boundary) other than the cen-

[1] One tsVEP component at a given latency within a given time window arises only if its amplitudes in segmented and uniform textures are different, such that it specifically expresses texture segmentation.

[2] NB: 2.8° corresponds to the eccentricity of the bar's shorter border when projected onto the horizontal axis.

ter would require a change in fixation, since orientation changed, resulting in increased eye movement.

2.3.5. Summary of the experiments

In the psychophysical experiments (Experiment 1), one group of observers was asked to judge the orientation of the bar presented with very short exposure (Experiment 1a) in either presence or absence of local luminance noise. Three other groups of 60 observers were asked to judge orientation (45° or 135°) of each bar explicitly attended (group 1), or of only one of the bars (chosen at random in the 23–30 trials group). When executing this second task, either (i) attention was implicitly engaged on the bar during passive viewing (group 2), or (ii) the bar was unattended and attention engaged on a digit discrimination task (group 3).

In Experiment 2a, VEPs were recorded for a group of ten observers. There was only one session, where participants were asked to report, every three trials on average, the spatial orientation (45° or 135°) of the short boundary of the bar presented last. This is a difficult task requiring attention to be allocated away from the center of the display (*texture attended*).

In Experiment 2b, VEPs were recorded for a different group of ten observers. There was only one session, during which participants were asked to report, every three trials on average, orientation of the long boundary (45° or 135°) of the bar presented last. During the task the texture bar was attended (*texture attended*).

In Experiment 3, VEPs were recorded for a different group of observers while they performed two tasks in two independent sessions. In the first session, the task was number identification: observers had to report whether the last number presented at the center of the texture bar was 1 or 2.

This required engagement of focal attention on the number, so the texture figure was unattended during task execution (*texture unattended*). In the second session, the same group of subjects reported orientation (45° or 135°) of the short boundary of the bar presented last (*texture attended*).

3. Statistical analysis

The psychophysical results were analyzed using Chi-square and Man–Whitney tests (Experiment 1b) or repeated-measures ANOVA (Experiment 1a). Two-factors repeated measures ANOVAs, separate for each VEP component, were performed to analyze the effect of all tsVEP components. The data sphericity was tested using Mauchly's Test. Since in no case did this test reach significance, correction of the degrees of freedom was never applied (Keselman, Algina, & Kowalchuk, 2001).

4. Results

4.1. Psychophysical data

Because of the long exposure, accuracy was greatest in the psychophysical task executed during VEP recording. Fewer than 5% errors were made on average, this percentage remaining constant with both task (orientation discrimination of either bar or short boundary) and stimulus type (parallel or orthogonal bar).

Experiment 1a. Fig. 3 illustrates the results from Experiment 1a. Repeated-measures ANOVA revealed only a significant configural effect ($F_{(1,9)} = 32.6$, $p < 0.0001$), indicating higher saliency for the parallel bar, whether luminance noise was present or not. This demonstrates that the configural effect is genuine and based on different relative arrangement of elements and bar orientation, rather than luminance artifacts.

Experiment 1b. Fig. 4 illustrates the results from the three groups participating in the second psychophysical experiment. Subjects correctly discriminated bar orientation when the bar was explicitly attended. Regardless of configuration, when the bar was not explicitly attended because of passive viewing, performance was above threshold: 72% of observers (43 out of 60) correctly judged the bar orientation. The percentage of subjects responding correctly did not depend on bar configuration ($\chi^2(1) = 0.12$, $p > 0.05$). The results of the third group showed a detrimental effect of attention withdrawal from texture bar. Although the stimulus was viewed for 840 ms as in the other two conditions, response was chance: 55% of observers (33 out of 60) correctly judged the bar orientation. Again, the numbers of correct and wrong responses did not differ significantly, whether the bar was parallel or orthogonal ($\chi^2(1) = 1.03$, $p > 0.05$).

The mean confidence rating (Fig. 4b) given on a seven-point scale was large for correct responses but only when the bar was not explicitly attended (correct: 5.0;

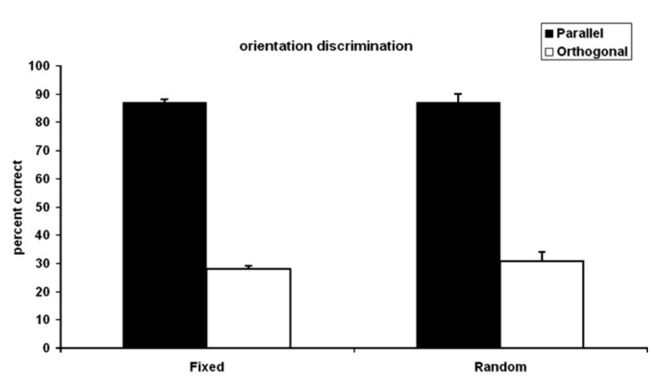

Fig. 3. The figure shows results obtained in Experiment 1a. Percentage correct is shown for parallel and orthogonal bar conditions in blocks 1 and 2.

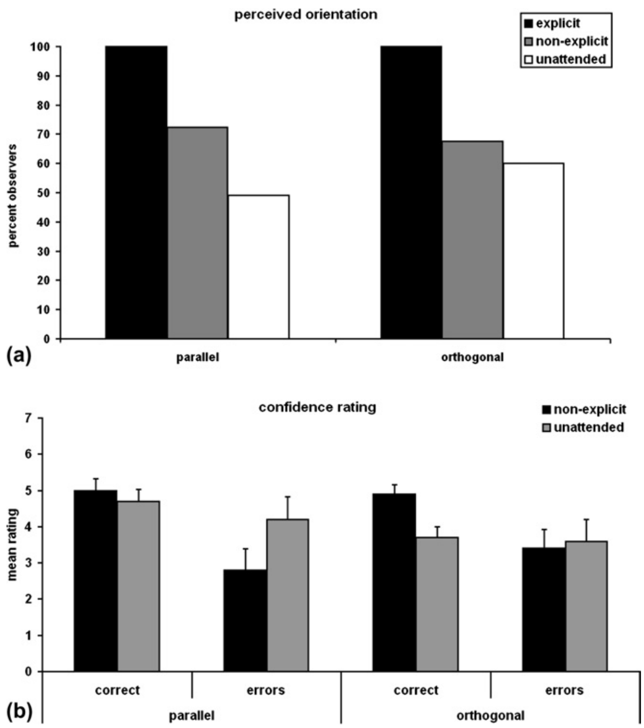

Fig. 4. Results obtained by the three groups participating in the second psychophysical experiment (Experiment 1b) are shown. Group 1 (explicit) judged bar spatial orientation every trial, with attention explicitly engaged on the bar. The figure reported the percentage of observers responding correctly to the bar orientation in one trial chosen at random in the 23–30 trials group. Group 2 (non-explicit) judged the spatial orientation of one of the bars (chosen at random in the 23–30 trials group) when viewing the texture bar passively (group 2). Group 3 made the same judgment as group 2 with attention engaged away from the bar in number discrimination (bar unattended, group 3). Figure (a) shows percentage of observers correctly discriminating bar orientation. Figure (b) shows the mean confidence rating value for correct and incorrect orientation judgment separately for parallel and orthogonal bar in the three conditions.

wrong: 3.1, Man–Whitney $U = 147$, $p < 0.0001$), not unattended (correct: 4.1; wrong: 3.9; Man–Whitney $U = 406$, $p > 0.5$). The mean confidence rating (Fig. 4b) was independent of stimulus for both non-explicit (parallel: 4.5, orthogonal: 4.4, Man–Whitney $U = 430$, $p > 0.05$) and unattended conditions (Man–Whitney $U = 342$, $p > 0.5$). This is an interesting result, and indicating that observers are less confident in their wrong orientation judgment (for both parallel and orthogonal bar), but only with attention not withdrawn from the bar by a second task.

Orientation discrimination and confidence rating results indicate that although the bar was not explicitly attended, orientation discrimination was possible, though not facilitated in the parallel configuration. On the other hand, the effect on the same two indices indicates that engaging attention on a second task not only eliminates the configural effect but also prevents orientation discrimination. Indeed, orientation discrimination fell from maximum to chance for both configurations when attention was disengaged from the bar. The results are in line with the very radical suggestion, the "perceptual blindness hypothesis", that in unattended-texture trials, neither texture segregation based on orientation contrast nor grouping occurs (Mack, Tang, Tuma, Kahn, & Rock, 1992; Rock, Linnett, Grant, & Mack, 1992). However, it is possible that some texture information is extracted when the texture is unattended. Indeed, our results show that attention withdrawal does not render observers globally less confident of their judgment with respect to passive viewing (mean confidence ratings was 4.5 and 4.1, respectively). This result does not preclude observer judgment being based on detection of misleading local textural information. Where local texture information is available in the absence of attention, we would expect to find electrophysiological correlates of texture segmentation in both attended and unattended texture figures.

4.2. VEP data

4.2.1. Eye movements

The percentage of trials discarded due to eye movement was less than 5% for each subject.

4.2.2. Electrophysiological correlates of texture saliency

In Experiment 2a, where the subjects had to judge short boundary orientation, the mean tsVEP component amplitudes in parallel and orthogonal conditions were: N0: −0.6, −0.4; N1: −1.86, −1.15; P1: −0.63, 0.80; N2: −3.45, −2.65; N3: −5.34, −4.58. A *t*-test was used to compare parallel/orthogonal difference in each component recorded in Experiment 2a. Individual tsVEP data and the grand mean of all 10 subjects are displayed in Fig. 5a. tsVEPs generally resulted in a larger negative excursion of all components in parallel vs. orthogonal configuration. The difference was significant in all components (N1: $t_{(9)} = -2.3$, $p < 0.05$; P1: $t_{(9)} = 4$, $p < 0.005$; N2: $t_{(9)} = -3.2$, $p < 0.01$; N3: $t_{(9)} = -2.5$, $p < 0.05$) except in N0 ($t_{(9)} = 0.76$, $p > 0.05$). By inspecting Fig. 5a, this configural effect can be seen in individual tsVEPs, around the appropriate mean latency (85, 105, 148 and 210 ms). None of the latency effects was found to be significant.

Our previous results (Caputo & Casco, 1999) showed significant shorter latency difference in N3 for parallel condition. We have not been able to confirm this result, possibly because we give N3 a different definition here, i.e., largest peak in the 175–225 ms time window.

In executing the task, the observers might have used a strategy of judging the whole bar orientation, reporting the short- boundary orientation as opposite to that of the bar. To check this, Experiment 2b asked a different group of observers to judge the orientation of the long boundary of the bar (the global bar orientation). If

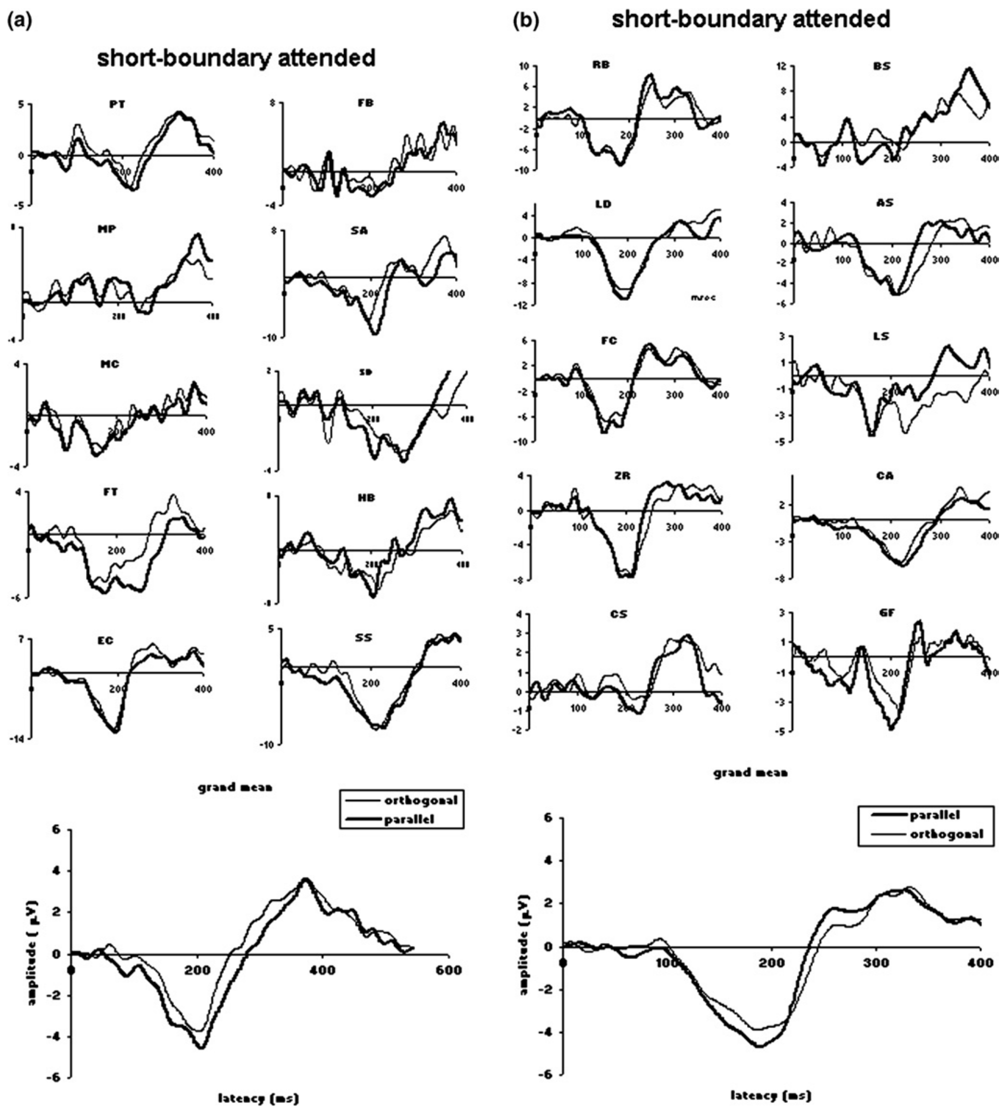

Fig. 5. (a) Results of Experiment 2a: individual tsVEP data and the grand mean of all 10 subjects. (b) Results of Experiment 2b: individual tsVEP data, together with the grand mean of all 10 observers. Each individual pair of traces displays the tsVEPs recorded for parallel (heavy line) vs. orthogonal (fine line) conditions.

observers in Experiment 2a also judged the global bar orientation, we found the configural effect inverted in Experiment 2b, since the elements are parallel to short boundary and orthogonal to long boundary, or vice versa. Individual tsVEP data are displayed in Fig. 5b, together with the grand mean of all 10 observers. The results showed a weaker (but still present) non-inverted parallel-orthogonal difference (parallel configuration having a larger amplitude vs. orthogonal configuration),[3] which was significant only for the N3 component ($t_{(9)} = 5.5$, $p < 0.01$). Mean amplitude of tsVEP components in parallel and orthogonal conditions (were: N0: −0.4, −0.5; N1: −0.9, −0.6; P1: −1, −0.6; N2: −3.4, −2.6; N3: −5.8, −5.1). This larger negative excursion of tsVEP components in the parallel boundary vs. the orthogonal boundary, regardless of whether short or long, indicates that the two tasks involved the same texture segmentation processing, differing only at decision level.

In Experiment 2a, we found a significant difference between parallel and orthogonal bar even for the first tsVEP components at 85 ms (N1) and 105 ms latency (P1). This is different from earlier findings from other groups. We wondered whether these early effects reflected texture segmentation. As tsVEPs are found from the difference between two VEP recordings, the

[3] NB: When the global bar configuration is parallel to texture elements, the short boundary is orthogonal, and vice versa. Nevertheless, the parallel, attended border (whether short or long) always has the larger amplitude.

configural effect reflected in these early components might be considered a result of luminance and contrast artefacts. This possibility is however unlikely, considering the results of Experiment 1a. These demonstrated that the configural effect was not reduced by introducing local luminance cues in parallel and orthogonal configurations while holding mean luminance constant. This suggests that even for this early component, the configural effect is genuine and does not depend on local luminance artifacts.

An effect of N3 was also found by Caputo and Casco (1999), but in contrast with their results, none of the latency effects was found to be significant. This is an interesting result, which concerns the underlying processes in texture segmentation, but goes beyond the scope of the present study.

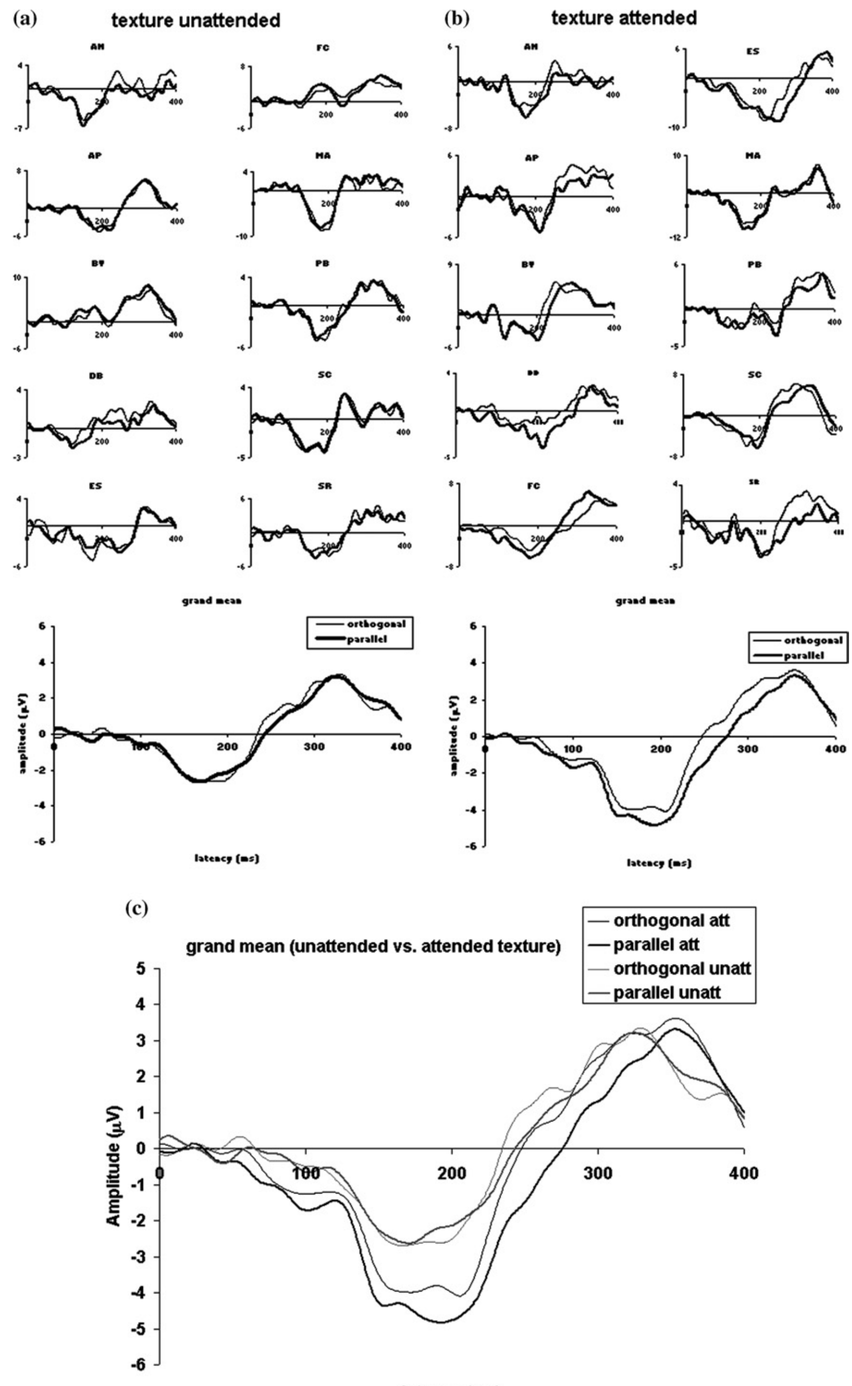

Fig. 6. The figure shows individual tsVEP (expressed in μV) elicited by parallel vs. orthogonal configuration, together with the grand mean of 10 subjects in (a) first block, unattended condition; (b) second block, attended condition; (c) four traces, representing mean tsVEP amplitude for attended vs. unattended condition, for parallel vs. orthogonal bar.

In order to investigate the role played by attention on configural effects of texture segmentation we decided to use the short boundary task for Experiment 3, since the configural effect was larger than in the long boundary orientation task, and the attention effect easier to demonstrate.

4.2.3. Effect of attention on tsVEPs

The effect of attention investigated in Experiment 3 is illustrated in Fig. 6. Individual parallel and orthogonal tsVEPs are shown in Fig. 6a (unattended condition group) and in Fig. 6b (attended condition group), together with the overall mean of each group. Mean amplitudes of tsVEP components in parallel-attended, orthogonal-attended, parallel-unattended and orthogonal-unattended were (Fig. 6c): N0: −0.4, −0.3, −0.3, −0.2; N1: −1.11, −1.29, −0.7, −0.7; P1: −0.3, 0.02, 0.38, 0.08; N2: −3.7, −3.2, −2.1, −2.4; N3: −4.7, −3.3, −2.6, −2.8. The repeated-measures ANOVAs with task and stimulus as factors showed no significant effect when performed on the amplitude data of N1 and P1 components. In contrast, the ANOVA results showed a significant (task × stimulus) interaction in N2 ($F_{1,9} = 5.26$, $p < 0.05$) and N3 ($F_{1,9} = 7.8$, $p < 0.02$). These results indicate that for these components, the configural effect was present when the texture was attended: N2 ($t_{(9)} = -2.3$, $p < 0.05$): −3.67 (parallel), −3.18 (orthogonal); N3 ($t_{(9)} = -2.3$, $p < 0.05$): −4.72 (parallel), −3.3 (orthogonal) in the orientation discrimination task, but not when it was unattended in the digit identification task: N2: −2.07 (parallel), −2.46 (orthogonal); N3: −2.65 (parallel), −2.85 (orthogonal). None of the latency effects was found to be significant.

To summarize, comparison between attended and unattended conditions shows that: (a) tsVEP components were still present in the unattended condition; (b) disengaging attention reduces (not significantly) tsVEP amplitude for both parallel and orthogonal configurations (Fig. 6c); (c) the configural effect vanishes when attention is disengaged from the texture.

These results provide an answer to our main question about the role of attention in texture segmentation. The finding that tsVEPs are not eliminated in the unattended condition clearly suggests that at least local texture segregation occurred when the bar was unattended. The finding that reducing attention reduces the negative excursion of tsVEPs also with bar orthogonal may indicate that the specific grouping required for orientation discrimination involves attention. Moreover, the cancellation of configural effect with figure unattended indicates that attention facilitates texture segmentation on the basis of grouping of collinear elements parallel to texture borders. As Fig. 6c shows, the electrophysiological correlate of this facilitation due to attention is a larger negative excursion in parallel vs. orthogonal bar condition. Indeed, t-test comparison of the difference

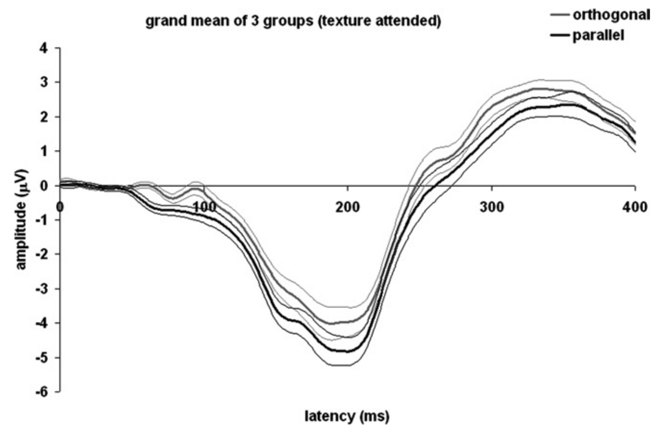

Fig. 7. The figure shows tsVEPs obtained by averaging individual traces of subjects in the three experiments (2a, 2b, 3) with attention explicitly engaged in the orientation discrimination task, together with the corresponding confidence band, for parallel vs. orthogonal conditions.

in unattended vs. attended condition amplitudes shows it to be larger in the parallel condition for both N2 ($t_{(9)} = -2.3$, $p < 0.05$) and N3 ($t_{(9)} = -2.8$, $p < 0.02$).

4.2.4. Comparison between conditions

The three experiments with the bar attended were performed with three different groups of subjects. The issue of whether the results differed in any way as a result of differences in conditions, or simply because of individual differences, was addressed by comparing the results of Experiments 2a, 2b and 3 (second block). The tsVEPs obtained by averaging individual traces of subjects in the three experiments, where attention was explicitly engaged in the orientation discrimination task, together with the corresponding confidence band, are shown in Fig. 7 for parallel vs. orthogonal conditions. Only for N1 component did the ANOVA reveal a significant group effect ($F = 4.08$, $p < 0.05$). *Post-hoc* comparison revealed a significant difference in N1 amplitude between each of the two groups performing short-boundary orientation discrimination vs. the group performing global-bar orientation discrimination (2a vs. 2b: $p < 0.01$) (3 vs. 2b: $p < 0.05$). This indicates that this latter group presents reduced N1 amplitude vs. the two groups performing the short-boundary task, but that these two groups do non differ from each other in N1 amplitude.

For the other tsVEP components, the configural effect (P1: $F = 5.7$, $p < 0.02$; N2: $F = 14.8$, $p < 0.001$; N3: $F = 14.56$, $p < 0.001$) was found to be significant, but not the group effect.

5. Discussion

Current theories tend to view segregation and grouping as closely related processes, operating either concurrently or in close succession (Beck, 1982; Beck et al., 1983; Julesz, 1981, 1986; Lamme, 1995; Lee, Mumford, Romero, & Lainroe, 1998; Nothdurft, 1992; Treisman, 1982; Treisman & Gormican, 1988). These two processes are thought to involve encoding by local feature detectors and subsequent extraction of the feature gradient following grouping of local features (Beck et al., 1983) or low-resolution filtering (Malik & Perona, 1990; Rubenstein & Sagi, 1990).

There are different views of the role of attention on segregation and grouping. The classic view is that attention is allocated to the visual field after accomplishment of segregative and grouping operations (Beck, 1967, 1982; Julesz, 1986; Nothdurft, 1985; Sagi & Julesz, 1984; Treisman, 1982). This view is confirmed by more recent psychophysical (Baylis & Driver, 1992; Moore & Egeth, 1997) and electrophysiological studies on humans (Bach & Meigen, 1992, 1997; Bach, Schmitt, Quenzer, Meigen, & Fahle, 2000; Fahle et al., 2003). However, several authors are in disagreement. Results from Ben Av et al. (1992) and Braun and Sagi (1990, 1991) indicate that segregation but not grouping can be performed when attention is engaged on a concurrent visual task. An even more radical finding is that in unattended-texture trials, neither texture segregation nor grouping occurs (Mack et al., 1992; Rock et al., 1992) and that both these operations require distributed attention (Beck & Ambler, 1973; Treisman & Gormican, 1988).

The main goal of our study was to assess whether attention modulated a process of texture segregation based on orientation contrast per se, or whether it modulated grouping operations. Our results suggest that grouping, but not segregation on the basis of local orientation gradient, involves attention.

5.1. Effect of attention on local texture segregation

The finding that tsVEP components, which specifically reflect texture segregation, are not eliminated in unattended conditions clearly suggests that at least local texture segregation does not require attention. Indeed, the procedure of calculating tsVEP ensures that if texture segregation had not occurred, all tsVEP components would have amplitude identical to zero. Our results show this not to be the case, and strongly suggest that in the unattended condition *local* texture segregation did occur. This is in agreement with the finding of Meigen and Bach (1993), that tsVEPs can be obtained even under steady-state conditions with fast stimulation frequency, where attentional processes are too slow, suggesting that tsVEPs reflect pre-attentive mechanisms. Also Schubo, Meinecke, and Schroger (2001) observed an N3 component, when texture segmentation was task-irrelevant, which was not affected by primary task complexity. fMRI findings (Kastner, De Weerd, & Ungerleider, 2000; Schira, Fahle, Donner, Kraft, & Brandt, 2004) show texture segmentation activations in the absence of perceptual awareness, a result compatible with the existence of a pre-attentive texture segmentation mechanism. Our results thus confirm the largely accepted view that perception of segregated-edge textures depends on pre-attentive detection of local orientation differences (Ben Av et al., 1992; Braun & Sagi, 1990, 1991; Nothdurft, 1992).

5.2. Effect of attention on grouping

Our results show that reducing attention lowers the negative excursion of tsVEPs in both configurations (Fig. 6c). Since the effect of attention is not significant, conclusion that grouping involves attention is invalid. However, supporting this interpretation are the psychophysical results. These show that observers are perceptually blind to bar orientation when their attention is engaged by another task. Since texture bar orientation cannot occur without grouping, these results strongly suggest that the specific grouping operation needed to execute the orientation discrimination task requires attention.

The psychophysical findings are of great interest since they demonstrate that orientation discrimination and the configural effect are both prevented in the unattended condition, whereas in the passive view condition only the configural effect is prevented. Therefore, grouping involved in the orientation task is only prevented with unattended bar. This latter result conflicts with the view that when observers are shown the critical stimulus without any previous information, neither texture segregation nor grouping occurs (Mack et al., 1992; Rock et al., 1992). Non-explicit attention may render observers simply unaware of the perceptually segmented texture: the suggestion is that they are attentionally, but not perceptually, blind.

The suggestion that the texture grouping process cannot function without attention is not new. Using a dual-task paradigm, Ben Av et al. (1992) and Braun and Sagi (1990, 1991) found that segregation but not grouping can be performed when attention is engaged in a concurrent visual task. Physiological findings (De Simone & Ungerleider, 1989; Merigan et al., 1993; Motter, 1994) also suggest that at least grouping operations require attention. Our novel finding concerns distinction of the effect of attention on grouping and on grouping by collinearity.

5.3. Effect of attention on grouping by collinearity

In reference to the above point, our third finding is indeed that the configural effect on tsVEPs disappears when attention is engaged by another task. This indicates that attention facilitates texture segmentation modulating grouping of collinear elements parallel to texture borders. Our results confirm that the effect of attention on grouping (reflected in tsVEP differences between attended vs. unattended conditions in both configurations) differs from that on grouping of collinear elements parallel to texture boundary (reflected in reduced configural effect in unattended condition). However, since tsVEPs represent the difference between two VEP recordings, one must consider whether the configural effect reflected in these early components could result from luminance and contrast artefacts (a larger portion of line elements could be closer to the background elements in one of the two stimuli). In numerous studies, Nothdurft has pointed out the high sensitivity of texture segregation mechanisms to such subtle stimulus details. However, we can exclude this possibility because, were it the case, Experiment 1a would have revealed a reduced configural effect in the local luminance perturbation.

To summarize, our study not only confirms that attention can modulate grouping, but in particular offers the novel finding from electrophysiological evidence that attention affects the facilitation provided by grouping of collinear elements parallel to the boundary. This is reflected in a larger negative excursion of tsVEPs when the texture boundary is parallel. When judging small boundary orientation, this configural effect was reflected in tsVEP components earlier than those previously reported as a correlate of texture segmentation (Bach & Meigen, 1992; Caputo & Casco, 1999; Han, Ding, & Song, 2002; Lamme, Van Dijk, & Spekreijse, 1992). This parallel/orthogonal difference was present only with texture boundary attended, and vanished when not attended.

These results support the suggestion that attention produces a modulation of grouping by collinearity. In a recent paper (Casco, Campana, Greco, & Fuggetta, 2004), we showed that this grouping of collinear elements also underlies perception of orientation flux inside the texture figure, and that this operation is modulated also by experience.

The neural basis of grouping by collinearity has been thought to reflect contextual influences in psychophysical and neural response (Gilbert et al., 2000; Ito, Westheimer, & Gilbert, 1998; Kapadia et al., 1995). Indeed, when texture elements are collinear or parallel, contextual influences facilitate target detection (Freeman et al., 2001), contour integration (Field et al., 1993) and surface segmentation (Olson & Attneave, 1970). Following psychophysical and neurophysiological results (Kapadia et al., 1995; Freeman et al., 2001; Gilbert et al., 2000) suggesting this facilitation to be largely modulated by attention, we speculated that modulation of contextual influences by attention may account for the attention-dependent variation of orthogonal/parallel difference in N2 and N3 components of tsVEPs.

At what level of processing is the modulation of grouping by collinearity affected by attention? Although our results shown a configural effect in the earliest tsVEP components and attention modulation of this effect at N2 and N3 level, they preclude establishment of the level at which the effect of attention on texture segmentation occurs. It is possible that our tsVEP effects reflect at least in part, top-down influences produced by post-segmentation. However, this interpretation does not fit well with our behavioral data, which show observers to be perceptually blind to segmented texture when attentional resources are reduced.

Instead, our results agree with neurophysiological results from both humans and monkeys, suggesting that this attentional modulation occurs very early in the central visual processing, probably at V1 level (Lamme et al., 1992) and could be based (Freeman et al., 2001; Gilbert et al., 2000) on horizontal intra-cortical connections linking cells with non-overlapping classical receptive fields (CRFs) and similar orientation preferences. Khoe, Freeman, Woldorff, and Mangun (2004) obtained the first evidence of facilitation due to collinearity for target flanked by collinear stimuli, reflected in an increase in polarity voltage deflection in the occipital scalp-recorded ERPs between 80 and 140 ms after stimulus onset. We also found an early electrophysiological collinearity effect with a different, texture segmentation task. Furthermore, our present study is the first to show modulation of this VEP correlate of a collinearity effect by attention. Although it cannot be denied that local texture segregation occurs without attention, our finding suggests that attention increases saliency of texture boundary resulting from lateral interactions between collinear elements in the direction of texture boundary.

A final interesting point is the extent to which our finding that attention affects grouping by collinearity is in line with energy models of texture segmentation (Malik & Perona, 1990). A very suitable means for accounting for texture figure segregation based on local orientation contrast involves a first-stage filtering of local orientation, followed by low spatial frequency filtering applied after rectification (Malik & Perona, 1990). Since in this model, local orientation information is eliminated by second-order large-scale filtering, our results may indicate that second—but not first-stage filtering is prevented when attention is disengaged. Recent data also suggest that attention intervenes at the level of second-order filters (Yeshurun & Carrasco, 2000).

A plausible alternative explanation of the configural effect, in line with energy models, is that, as parallel bar contains long collinear structures, the scale of the filter involved with parallel stimulus should be larger than for the orthogonal case. The source of the configural effect could lie in the different low spatial-frequency filtering scale used in parallel vs. orthogonal configurations. Indeed, the finding that the configural effect is reflected in earlier components in the short boundary orientation discrimination task supports this suggestion:

when judging the long boundary, the parallel configurations contain long collinear structures parallel to the boundary and short collinear structures orthogonal. The opposite occurs when judging the short boundary. However, the results of Experiment 2b suggest this not to be the case. If the use of different scale filters accounted for parallel/orthogonal differences, we would expect the configural effect to be inverted by changing the boundary to be judged (either short or long), but this was not found. Similar results in the two tasks indicate that attention affects grouping of local elements by collinearity.

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