



Configuration saliency revealed in short duration binocular rivalry

Yoram Bonneh, Dov Sagi *

Department of Neurobiology, Brain Research, The Weizmann Institute of Science, Rehovot 76100, Israel

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Abstract

Supra-threshold spatial integration was studied by testing the saliency of multi-Gabor element configurations in short duration binocular rivalry (dichoptic masking) conditions. Dichoptic presentations allow for a competition between spatially overlapping supra-threshold stimuli that involve non-overlapping monocular receptive fields in the first stage of visual filtering. Different spatial configurations of Gabor patches ($\sigma = \lambda = 0.12^\circ$) were presented to one eye (target) together with a bandpass noise presented to the other eye (mask). After a short rivalry period (120 ms) in which a dominance of one eye was established, a probe (a randomly positioned small rectangle of reduced contrast in the target) was presented for additional detection period (80 ms). Probe detection performance was measured (two-alternative-forced choice paradigm (2AFC)) by finding the mask contrast leading to 79% correct response. Results show that configuration saliency is consistently expressed as dominance in short-duration binocular rivalry, with similar results obtained for longer durations (200 ms and continuous presentations). We find that textures of high-contrast randomly oriented patches are more dominant than uniform textures where the effect decreases and eventually reverses with decreasing of contrast. For supra-threshold contours, however, we find that smooth collinear contours are more dominant than 'jagged' ones, regardless of phase and contrast. These findings suggest principles underlying early lateral integration mechanisms based on contrast dependent inhibitory and excitatory connections. This mechanism could be based on iso-orientation surround (2D) inhibition and collinear (1D) facilitation, with inhibition being more effective at high contrasts. © 1998 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Psychophysical and physiological evidence suggest that the visual input is first decomposed by local mechanisms or channels tuned to specific properties such as orientation, spatial frequency and direction of motion (Graham, 1989; DeValois & DeValois, 1990). The integration process that follows the initial decomposition stage, was examined in psychophysical contrast detection and discrimination tasks, which focus on the effect of spatial configuration and suggest spatial interaction between channels. Inhibitory and facilitatory spatial interactions were found between neighboring channels in contrast detection tasks (Sagi & Hochstein, 1985; Polat & Sagi, 1993; Zenger & Sagi, 1996), suggesting collinear long range facilitation possibly involved in contour integration and short range surround inhibi-

tion possibly involved in orientation pop-out and contrast gain control. Similar interactions were observed in apparent contrast studies in which the effect of a surround pattern on the perceived contrast of a central pattern was measured (Chubb, Sperling & Solomon, 1989; Cannon & Fullenkamp, 1991, 1993; Solomon, Sperling & Chubb, 1993; Cannon & Fullenkamp, 1996). Most of these studies show orientation and spatial frequency specific surround inhibition, but non specific inhibition (Cannon & Fullenkamp, 1991) and facilitation at low contrasts (Cannon & Fullenkamp, 1993) were also found.

Parallel physiological and anatomical studies of striate cortex in cat and monkey, revealed similar lateral interactions mediated by short and long range horizontal connections (Gilbert, 1992; Malach, Amir, Bartfeld & Grinvald, 1993) showing iso orientation surround inhibition (Blakemore & Tobin, 1972; Gilbert, 1992; Grinvald, Lieke, Frostig & Hildesheim, 1994) and collinear facilitation (Kapadia, Ito, Gilbert & West-

* Corresponding author. Tel.: +972 8 9343747; fax: +972 8 9344131; e-mail: dubi@nisan.weizmann.ac.il.

heimer, 1995; Polat & Norcia, 1996), with inhibition being more effective in high contrasts while excitation in low contrasts (Grinvald et al., 1994; Polat & Norcia, 1996). This dual effect was recently modeled computationally (Stemmler, Usher & Niebur, 1995; Somers, Toth, Todorov et al., 1996) explaining how fixed-strength long-range lateral connections can produce different effects as a function of contrast and pointing out the functional difference between high and low contrast contexts.

The integration process was also studied with high contrast bandpass stimuli in contour detection tasks. Gestalt effects of smoothness and proximity (Field, Hayes & Hess, 1993) as well as closure (Kovács & Julesz, 1993) were experimentally found for the detection of contour fragments embedded in textures of randomly oriented elements. Identification tasks, were also used recently to study global effects of spatial integration (Saarinen, Levi & Shen, 1997) where local orientation uniformity improved identification of a global E-shaped pattern of Gabor patches. Both results were accounted for by lateral interactions between orientation tuned filters possibly mediated by long-range connections in the primary visual cortex.

We have recently studied the detectability of multi-Gabor configurations at low contrasts (Bonneh & Sagi, 1998). We found that even at contrast threshold level, channel independence (Robson & Graham, 1981) does not hold and some local integration takes place, constrained by spatial proximity, continuity and orientation smoothness. The configuration effects were observed for both textures and contours and could be accounted for by co-operative interaction between collinear detectors assuming negligible inhibition.

Here, we investigate the effect of spatial configuration at high contrasts. Short presentations of binocular rivalry (that could be termed dichoptic masking) are used in which mask and target are presented to different eyes. This allows for a competition between spatially overlapping supra-threshold stimuli that involve non-overlapping receptive fields in the first stage of visual filtering. In the classical rivalry paradigm, discrepant stimuli are presented dichoptically to the two eyes, which results in alternating periods of monocular dominance. The observer reports the alternations, and stimulus predominance is determined by the relative dominance time. It has been found that stimulus predominance is mainly determined by relative 'stimulus strength' which is a combined effect of luminance, contrast, motion speed and contour density (Levelt, 1965; Blake, 1989) and affected by the pattern coherency and spatial configuration. A surrounding grating annulus was found to reduce predominance of a central target having similar orientation and spatial frequency (Mapperson & Lovegrove, 1991; Fukuda & Blake, 1992). Pattern coherence was found to group

parts of a pattern presented to different eyes (inter-ocular grouping) making the pattern rival in synchrony more frequently than chance level (Whittle, Bloor & Pocock, 1968; Wade, 1973; Kovács, Papathomas, Yang & Feher, 1996).

In the experiments, short duration rivalry is used to study the effect of spatial configuration. Using short exposures has the advantage of minimizing the effect of eye movements and avoiding the subjective report of observers used in classical rivalry paradigms. To achieve this, we developed a paradigm in which 'stimulus strength' can consistently be measured in short duration rivalry, while fused stimuli in too short presentations (Wolfe, 1983) or too low contrasts (Liu, Tyler, Schor & Clifton, 1992) previously observed, as well as local dominance (Blake, O'Shea & Mueller, 1992) cannot be reliably used to perform the task. We use a 2 AFC detection procedure in which different configurations of multi-bandpass stimuli are presented to one eye (target) while a bandpass noise is presented to the other eye (mask). Following a short rivalry period of 120 ms, a probe (a randomly positioned small rectangular zone of reduced contrast in the target) is presented for detection (80 ms). A staircase procedure is used to find the mask contrast leading to 79% correct response in detection of the probe. In this way, target and probe contrasts are kept constant and their effect can be tested. Using this procedure, we show that the effect of spatial configuration is consistently expressed in short duration binocular rivalry. We find that for high contrasts there is a distinction between 2D textures for which dominance is determined by the orientation gradients and 1D contours for which dominance is determined by uniformity and smoothness. However, at low contrast level uniform textures as well as uniform contours are more dominant. These findings suggest the principles underlying early lateral integration mechanism based on contrast dependent inhibitory and excitatory connections.

2. Methods

2.1. Apparatus

Stimuli were displayed as gray-level modulation on a Sony GDM2000TC color monitor, using a Silicon Graphics Reality Engine system. The video format was 120 Hz interlaced with 1280×450 pixels for each eye occupying a $13 \times 10.4^\circ$ area. Stimuli were viewed with CrystalEyes E-1 stereo glasses with optic shutters that alternate in 120 Hz synchronized with the monitor. The full open time of the shutters was 2.5 ms which made the upper part of the screen appear slightly darker (although this is usually unnoticed by observers). The mean display luminance was 40 cd/m^2 and the effective

display luminance when viewed with the stereo glasses was 7 cd/m^2 (we measured this directly and the result is consistent with 32% transmittance rate specified by the producer). The cross-talk between eyes was measured by testing the detection performance of one eye with stimulus presented to the other eye covered by an opaque eye patch. This cross-talk is due to the screen's phosphor afterglow and the dynamic range of the shutters and is typically 1:80 (according to the producer) though it can be larger as one measures downward across the screen. We found that the detection threshold in the crosstalk condition is about 15 times larger in amplitude, i.e. there is a crosstalk of about 7%. An 8-bit RGB mode was used and Gamma correction applied to produce a linear behavior of the displayed luminance. Stimulus generation and display was controlled by a SGI Crimson/Reality Engine workstation.

2.2. Stimuli

Stimuli consisted of a target and a probe displayed to one eye and a bandpass noise mask displayed to the other eye. All targets and masks consisted of multi-element Gabor displays. The luminance profile of one vertical Gabor patch is given by the product of a sinusoidal carrier of wavelength λ and amplitude A and a Gaussian envelope of standard deviation σ in the (x, y) space of the image, where I_0 is the background luminance

$$I(x, y) = I_0 + A \cos\left(\frac{2\pi}{\lambda} x + \phi\right) \exp\left(-\frac{x^2 + y^2}{\sigma^2}\right)$$

In all experiments we used the same Gabor parameters $\lambda = \sigma = 0.12^\circ$ of visual angle. We define Contrast of a given multi-element display as the amplitude of the generating Gabor signal (GS) relative to the background luminance $C_{GS} = A/I_0$. For example, the contrast of a GS with amplitude $A = 40 \text{ cd/m}^2$ and a background luminance $I_0 = 40 \text{ cd/m}^2$ (a peak luminance of 80 cd/m^2) is 1. The RMS contrast C_{RMS} of a given configuration depends on the density and amplitude of the Gabor patches and can be derived from the contrast of a single GS defined above C_{GS} by a multiplication factor $C_{RMS} = k C_{GS}$. A factor of $k = 0.77$ holds for the standard noise mask, $k = 0.71$ for the mask used to test contrast effect on texture saliency and $k = 0.26$ for any of the other texture configurations (which consist of non-overlapping patches) The noise mask consisted of 1764 randomly oriented Gabor patches arranged on a square matrix, with spacing of $1\lambda \pm 0.2\lambda$ uniform jitter. For testing the contrast effect on texture saliency, a different noise mask was used which consisted of 1568 patches arranged on a 14×14 3λ spaced matrix of clusters consisting of eight patches uniformly scattered in the range $\pm 0.9\lambda$.

Targets for testing texture saliency consisted of an array of 14×14 Gabor patches with 3λ inter-element spacing occupying $5^\circ \times 5^\circ$ of visual angle. The probe was a 4×4 elements square patch of reduced contrast in one of the configuration sides (see Fig. 2). Local Gabor orientation was varied between blocks from 0 (collinear) to fully random (uniformly distributed in the range $\pm 90^\circ$). Global orientation of the whole configuration was randomized between trials. Target and probe contrasts were fixed but selected individually for each observer. The individual configuration contrasts (defined by the amplitude of the generating GS, see above) used were (target/probe): GH-0.5/0.11, RP-0.45/0.06, OY-0.4/0.11, YB-0.8/0.06. Individual settings were needed due to individual differences between the eyes and overall sensitivity. Examples of uniform and random targets appear in Fig. 1, right column, together with a mask in the central column. The effect of binocular rivalry for these configurations can be appreciated by free fusion. In the actual experiment, stimuli were randomly rotated (both targets and masks).

Targets for testing contour saliency consisted of a circular arrangement of 25 Gabor patches with radius of 12λ (diameter of 2.9°) and inter-element spacing of 3λ . A randomly positioned arc of 14 patches (almost half of the circle) was erased from the target as a probe for detection. The local orientation of the circle elements was manipulated from a smooth circle via star-shaped circle ($45/135^\circ$ tangential) till a sun-shaped circle (90° tangential). An example of stimuli appears in Fig. 1, left column, for two typical circles: smooth (top) and star-shaped (bottom) The target contrast was 0.33, high enough to yield easy detection when dominant and low enough to be consistently suppressed by a high-contrast mask.

2.3. Experimental procedures

A two-alternative-forced choice paradigm (2AFC) was used in all experiments. Each trial consisted of two stimuli presented sequentially, both had a mask and a target presented dichoptically to different eyes, but only one had a probe. Before each trial, a small fixation circle was presented at the center of the screen. When ready, the observer pressed a key activating a trial sequence (see Fig. 2): a fixation (0.1 s), a no-stimulus interval (0.2 s), a first stimulus presentation, a no-stimulus interval (1.2 s total, 0.3 empty screen, 0.6 with fixation, 0.3 empty again), and a second stimulus presentation. Each stimulus presentation was divided into two parts: a rivalry interval (117 ms) of mask and target and a probe interval (83 ms) of mask and target with/without a probe. The observer was asked to perform a detection task, that is, to determine which of the stimulus presentations contained the probe. The first part (the rivalry interval), which contained no informa-

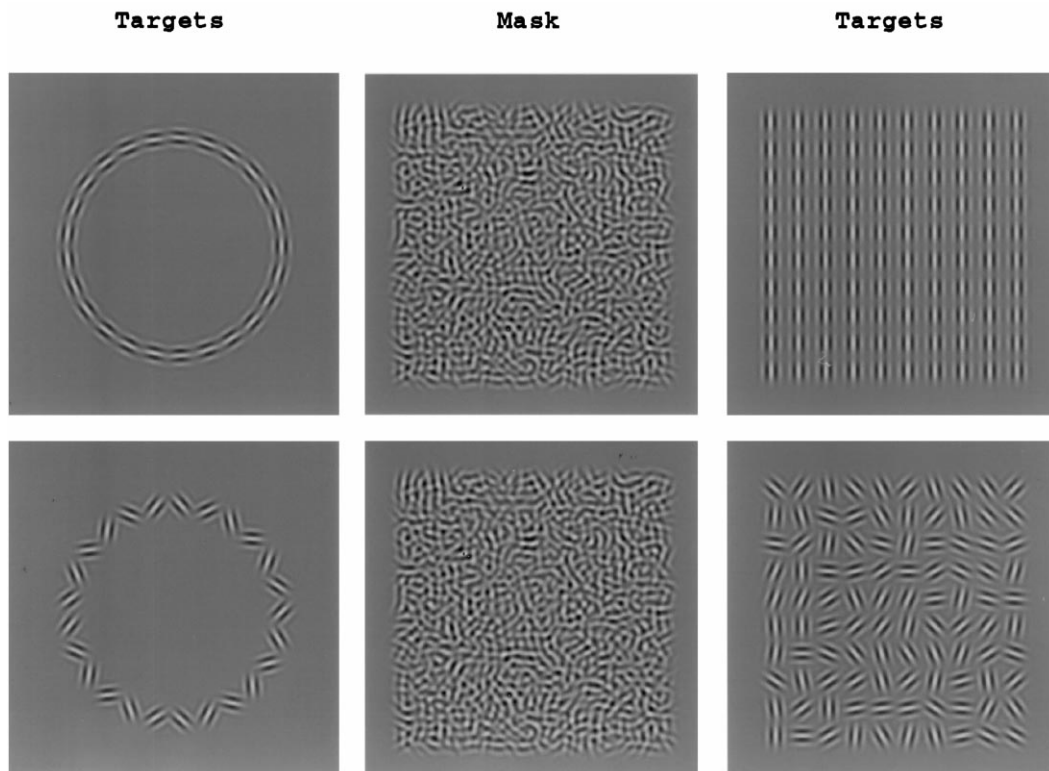


Fig. 1. Examples of stimuli used for testing the effect of orientation uniformity on texture and contour saliency. Right—Uniform (top) and random (bottom) textures. Left—smooth (top) and jagged (bottom) contours. A noise mask appears in the central column. The reader can test the saliency of the different configurations in binocular rivalry conditions by free fusing the central column with the right or the left columns. In the actual experiment, stimuli were randomly rotated relative to the screen.

tion for detection, was used to establish the dominance of the target and enable the detection of the probe. We avoid presenting the probe immediately (i.e. use one interval) since we try to measure configuration and not probe saliency and since during short periods, some abnormal fusion of the inputs from the two eyes may occur (Wolfe, 1983). However, we do not extend the total duration over 200 ms (except from one control experiment) to avoid or minimize the effect of eye movements.

Each block consisted of 50 trials on average (see Section 3), across which the Gabor signal configuration, target and probe contrasts and screen luminance were kept constant. The stimuli were viewed dichoptically (using stereo glasses) from a distance of 150 cm in a dark environment. Auditory feedback, by means of a keyboard bell, was given immediately after an erroneous response. Detection threshold was measured by changing the mask contrast, while keeping the target and probe contrasts constant. In this way, the difficulty of detection depends on the dominance in rivalry and not on target's monocular saliency which is kept constant. Mask contrast threshold was determined by a staircase method, which was shown to converge to 79% correct (Levitt, 1971). In this method, the mask con-

trast is decreased by 0.1 log units ($\sim 26\%$) after an erroneous response and increased by the same amount after three consecutive correct responses. The number of contrast reversals (change from increase to decrease or vice versa) within each block was counted, and the block was terminated after eight such reversals. Threshold contrast of a block was the averaged value of the last six reversals (the first two were ignored). Note that the measured threshold corresponds to the mask contrast for which the target is still dominant enough to give 79% correct detection. Thus, higher (rather than lower) thresholds correspond to more salient configuration.

3. Results

3.1. Orientation uniformity effect on texture saliency

The effect of orientation uniformity on supra-threshold saliency of Gabor textures in dichoptic masking conditions was measured by varying local orientation randomization level, with randomized global orientation. Previous results of threshold detection with similar but low contrast stimuli show lower thresholds for uniform textures (Bonne & Sagi, 1998).

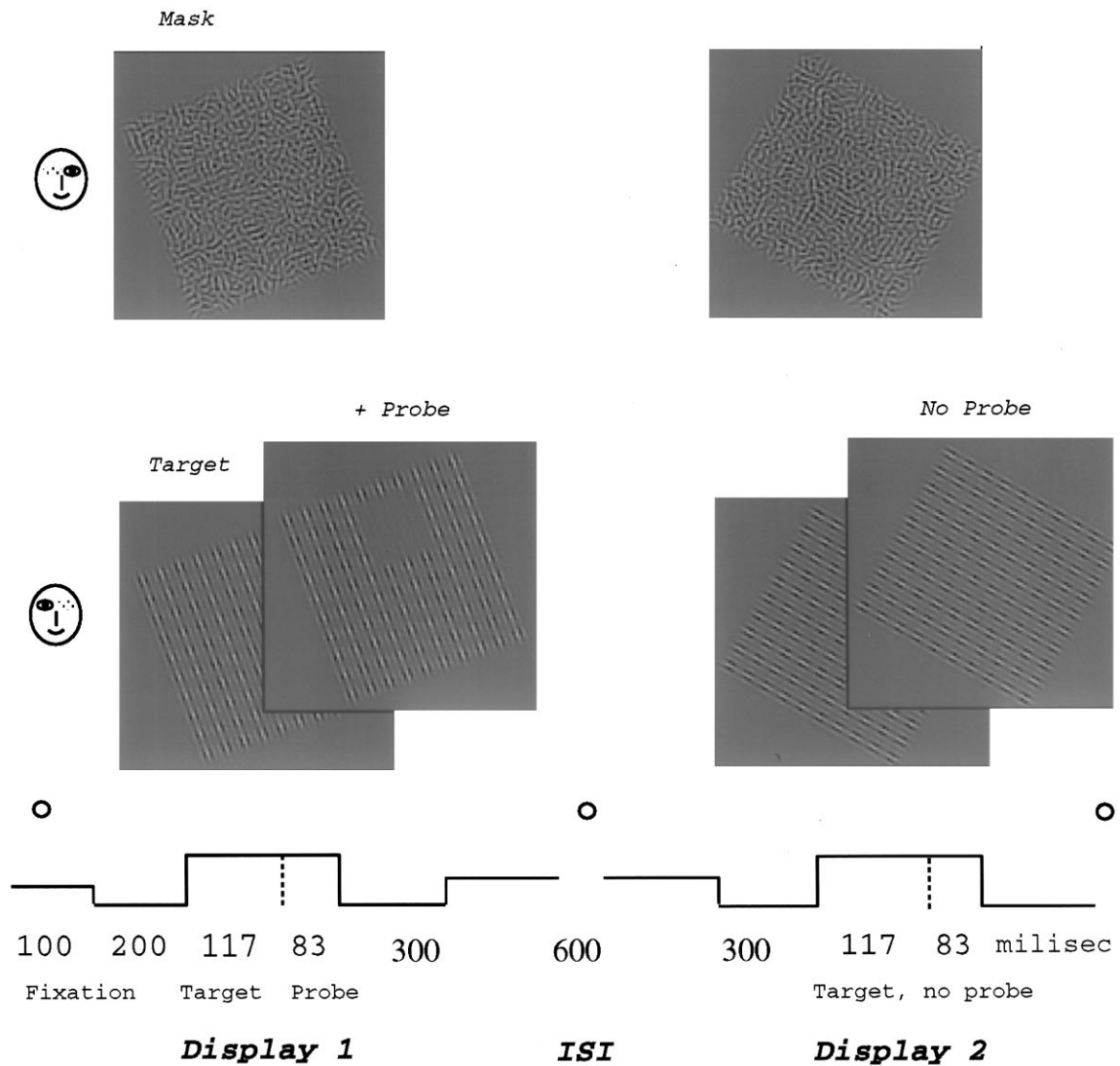


Fig. 2. The time course and stimuli of a trial sequence. Mask (top) is presented to the left eye and the target (bottom) to the right. A probe (a patch of reduced contrast in the target) is presented in one of the displays (first display in the figure). The sequence is: fixation (100 ms), no stimulus (200 ms), mask and target with/without probe (200 ms) inter-stimulus interval (1200 ms, 600 ms with fixation), and again mask and target. The global orientation of each display is randomized.

Results are shown in Fig. 3 for observers GH, RP, OY and YB. Mask contrast threshold (log units) is plotted as a function of orientation randomization range (0 for iso-orientation, 90 for full ± 90 randomization). Each datum point is the average of four to eight measurements. As the target contrast is kept constant, a higher mask threshold implies a more dominant target. An additional plot 'YB 200 ms' shows the results for observer YB with rivalry duration of 200 ms (instead of 117 ms) with all other parameters unchanged.

The results show that random configurations are more dominant in rivalry. Mask thresholds increase by more than 0.3 log units with increasing randomization (i.e. the random configuration can resist a higher contrast mask without being suppressed by it). The curve

for rivalry duration of 200 ms is very similar to the shorter-duration curves and indicates that the possible abnormal-fusion due to short durations (Wolfe, 1983) is not the source of the effect. Other parameters that effect the results are target contrast, inter-element spacing and probe-parameters (contrast, size, duration). The effect of contrast is directly addressed in the following experiments. The effect of spacing was not tested systematically, although preliminary measures indicate that increasing the spacing reduces the configuration effect as could be expected from short-range interactions. In addition, increasing the spacing of a uniform configuration in one directions (e.g. Y-axis) increases its saliency (the uniform texture becomes a set of smooth contours). These measures, however, showed a large variability because spacing effects the detectabil-

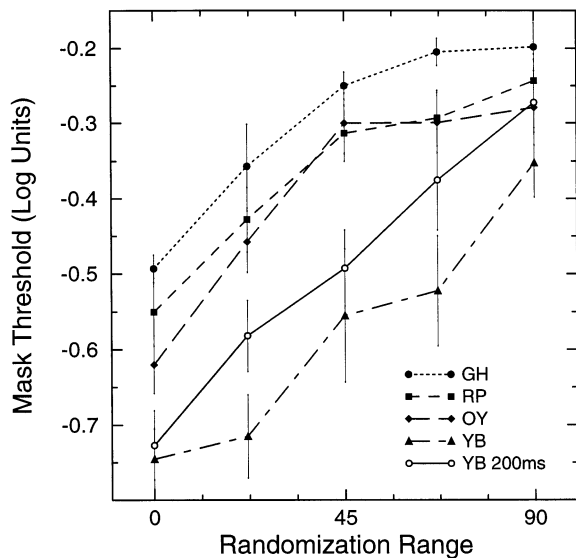


Fig. 3. Orientation uniformity effect on texture saliency. Mask contrast thresholds (log units) are plotted as a function of orientation randomization range (0 for iso-orientation, 90 for full randomization) for observers GH, RP, OY and YB. Error bars indicate 1 SE of the mean. For all observers, mask threshold increases (i.e. target saliency increases) with increased randomization.

ity of the probe. Spatial frequency was not varied, except from few pilot experiments with a lower frequency ($\lambda = 0.16$) that gave qualitatively similar results. The probe parameters were carefully chosen as to make the probe easily detected when the target is dominant and impossible to detect when it is suppressed. For that purpose individual probe contrasts had to be selected in order to get consistent measures. In general, the results show more variability than threshold detection results (Bonneh & Sagi, 1998). The main source of this variability is the contrast dependency (see Section 3.2) while another source of variability is the locality of rivalry (Blake et al., 1992) which can make one eye dominant in the probe's local region and the other eye dominant in other regions.

3.2. Binocular rivalry or pattern masking?

It is possible that the results of the previous experiment (texture saliency) do not reflect dominance in binocular rivalry, but rather saliency in a noisy background due to inter-ocular summation (stimuli appear abnormally fused in short presentations, see Wolfe (1983)). Thus, the inferiority of the uniform configuration could be explained, for example, by the effect of illusory completion of the probe which prevents its detection. To test this hypothesis, we carried out two different experiments. The first experiment was identical to the previous one, except that fused stimuli were presented to both eyes (monocular masking). Fused stimuli were produced by merging the half-resolution

images of the two eyes (interleaved rows, see Methods on stereo system) and re-dividing into two images of odd and even pixels. In this way, the same apparatus, procedure and parameters could be used (including stereo mode and glasses). Results for two observers on completely uniform and random configurations show that the uniform configuration is slightly more easily detected (0.1 log units difference). The results are very different from those obtained in dichoptic conditions (Fig. 3) where the random configuration had over 0.3 log units advantage over the uniform one.

In a second experiment, we tested one condition of uniform and random configurations in a 'classical' rivalry paradigm (similar to previous works, e.g. Fukuda & Blake, 1992). Two observers (GH and YB) tracked the rivalry of these configurations during 60 s periods, and reported fluctuations of dominance by depressing one of two keys, one for exclusive visibility (i.e. complete dominance) of the random configuration and the other for exclusive visibility of the uniform configuration. To counterbalance any eye-dominance effects, the observation periods were repeated five times with the random configuration displayed to the left-eye and the uniform to the right-eye and five times for the reverse combination; hence a total of ten periods of 60 s. Stimuli had a fixed contrast of 0.67 with other parameters identical to those used in the texture-saliency experiment. Results were computed as cumulative duration of dominance, averaged across eyes and observers. The random configuration was found to be dominant for 36.6 ± 5.6 s and the uniform for 12.8 ± 8.6 s (data averaged across observers and eyes, $N = 20$) which shows a clear superiority of the random configuration.

The results of both experiments, together with the 200 ms rivalry duration tested previously indicate that the effect measured in the short-duration rivalry experiments is not due to inter-ocular summation and is likely to reflect real binocular rivalry, though a combined effect of rivalry and summation cannot be ruled out.

3.3. Contrast effect on texture saliency

The difference between the sub-threshold results (Bonneh & Sagi, 1998) and supra-threshold results described in the previous experiment, suggests that contrast is a crucial parameter in the process of spatial integration. This observation is consistent with physiological, psychophysical and computational studies of visual context effects (Stemmler et al., 1995; Polat & Norcia, 1996; Polat, Mizobe, Pettet, Kasamatsu & Norcia, 1998). We studied the effect of contrast on Gabor texture dominance in rivalry by testing completely random (± 90) and uniform textures with varied contrasts.

Results are shown in Fig. 4 for observers YB, GH, and OY. Mask contrast threshold (without normalization) is plotted as a function of target contrast on a

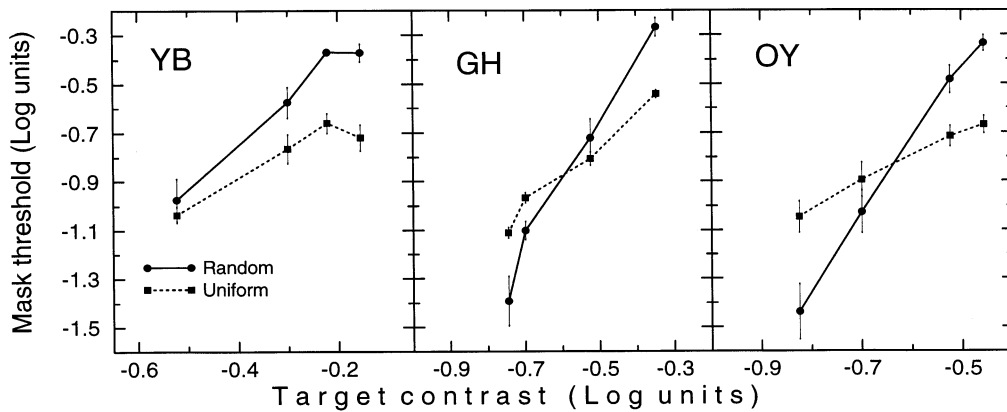


Fig. 4. The effect of contrast on texture configuration saliency. Mask contrast thresholds are plotted as a function of target contrast on a log–log scale for three observers and 2 configurations: completely uniform and completely random. A higher value of mask threshold corresponds to a more salient target. For all three observers, the advantage of the random configuration disappears for lower contrasts and for observers GH and OY the uniform texture becomes more salient.

log–log scale, where a higher value implies a more salient target. For all three observers, the advantage of the random configuration disappears for lower contrast levels and for observers GH and OY the uniform configuration is even more salient (observer YB was not tested with lower target contrasts for which he could not perform the task even without the mask). The turning point, where uniform and random configurations are equally salient, seems to occur around 0.3 contrast for all observers (extrapolating for observer YB), which may reflect a contrast level for which excitation and inhibition are balanced. However, more experiments are required to find the parameters which determine this contrast level (e.g. is it determined only by the configurations involved and not by the individual sensitivities).

3.4. Orientation smoothness effect on contour saliency

The advantage of random texture configurations over uniform configurations found in the previous experiments suggests that orientation gradients have a major effect on dominance in rivalry. We tested whether this applies to contours as well by varying the local Gabor orientation on a circular arrangement of patches. Here, the important factor is the local patch orientation relative to the circle tangent line at its position which we increased systematically for neighboring patches in opposite directions (see Fig. 1, left column). We preferred this method over the randomization method used for textures since it reduces stimulus variability.

Effects due to contour orientation smoothness are shown in Fig. 5. Mask contrast thresholds are plotted as a function of deviations from the tangential angle (0 for collinear, 45 for star-shaped, 90 for sun-shaped) with uniform phase ($\text{GH}^{++}, \text{YB}^{++}$) and with alternating phase (YB^{+-} , see below). A higher mask threshold

stands for a more salient target. Highest thresholds (best detectability) are obtained for smooth circles (0), Lowest for sun-shaped circles or similar (observer YB performs similarly on a star-shaped circle). The magnitude of the effect, i.e. the difference between smooth and sun-shaped conditions is more than 0.5 log units for both observers. In comparison, experiments with low contrast stimuli (Bonnef & Sagi, 1998), show a similar superiority of the smooth circle over a jagged one ($45/135^\circ$) but almost identical detectability of the smooth and sun-shaped circles (see Section 4). The term ‘jagged’ does not depend on the specific stimulus used.

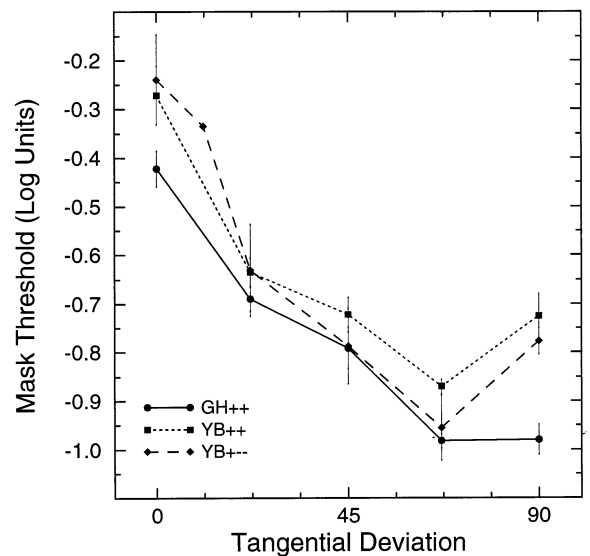


Fig. 5. Local orientation and phase effects on circular contour saliency. Mask contrast threshold is plotted as a function of orientation deviation from the contour tangent (0 for collinear, 45 for star-shaped, 90 for sun-shaped, see examples) for two observers with uniform phase ($\text{GH}^{++}, \text{YB}^{++}$) and for one observer with alternating phase $0/180$ (YB^{+-}). error bars indicate 1 SE. For both observers, performance decrease with reduced contour smoothness.

We tested a circle with random local orientation (one observer GH), which parallels the texture data, and found that it is more salient than the star-shaped but clearly less salient than the smooth one (0.25 log units difference).

3.5. Phase effect on contour saliency

If the advantage of a smooth circle over a jagged one is due to integration within the receptive fields of the first stage detectors, its saliency should decrease when the phase of neighboring elements differs. Previous studies found no effect of alternating phase on contrast threshold (Bonnef & Sagi, 1998), no effect of randomized phase on detection of a high contrast Gabor contour embedded in distractor patches (Field et al., 1993) and contrast polarity invariant facilitation with high-contrast masks (using lines or Gabor signals) at large separations ($> 3\lambda$) (Zenger & Sagi, 1996; Ishai & Sagi, 1997; Yu & Levi, 1997; Wehrhahn & Dresch, 1998). Phase independence was also obtained for surround inhibitory effects (DeAngelis, Freeman & Ohzawa, 1994). However, distance dependent phase effects were shown on detection enhancement of high contrast lateral masks (Zenger & Sagi, 1996) and it has been recently reported to have some effect on high contrast contour detection (Field, Hayes & Hess, 1997).

We tested the saliency of circular configurations with alternating phase of neighboring patches. In one experiment, we measured the orientation smoothness effect with alternating phase of 0 and 180 phase degrees (one observer) and found a curve which is very similar to that measured for the uniform phase (compare conditions YB⁺⁺ and YB^{+−} in Fig. 5). In addition, we tested different phase conditions for the smooth circle. One group of patches (e.g. the even ordered patches relative to a starting point) was either odd or even symmetric, the other group differed by 0, 90 or 180 phase degrees. Target contrast was fixed at 0.33. The results for two observers show no significant difference between the six different phase conditions. (0.01 ± 0.03 (90) and 0.04 ± 0.03 (180) log units difference from the uniform phase threshold, $N = 2$, odd and even symmetric conditions averaged). The lack of a phase effect on contour saliency suggests that phase insensitive second stage filters or lateral interactions are the basis for contour saliency.

3.6. Contrast effect on contour saliency

In the previous experiments, we found that smooth high-contrast contours are more salient than 'jagged' ones in short duration rivalry. In a previous study, we found that similar smooth contours have a lower contrast detection threshold (Bonnef & Sagi, 1998). This suggests that, unlike texture mechanisms, the mecha-

nisms of contour integration are effective at all contrast levels. We verified this more directly by manipulating the target contrast of smooth, star-shaped and sun-shaped circles and testing their saliency as was done in the previous experiment. Target contrast ranged between 0.3 and 0.6 (0.3 log units).

Results for two observers show that the smooth circle is the most salient at all contrasts (above 0.2 log units difference from the 'star'). The advantage of the smooth circle over the 'star' decreased with contrast for one observer, GH (0.36 ± 0.06 log units for target at 0.33 contrast, 0.2 ± 0.06 for target at 0.55 contrast), but was almost constant for the other (0.6 ± 0.05 log units at all measured contrasts). The 'sun' was slightly more salient than the 'star' at low target contrast of 0.33 (by 0.17 ± 0.07 log units for GH, 0.1 ± 0.04 for YB) and slightly less salient (though not by a statistically significant amount) at a higher target contrast of 0.05 (by 0.1 ± 0.08 for GH, 0.12 ± 0.06 for YB). The advantage of the 'sun' over the 'star' at low contrasts is qualitatively consistent with previous measures of contrast sensitivity (Bonnef & Sagi, 1998), but the magnitude of the current effect is much smaller.

4. Discussion

In this work, we studied supra-threshold spatial integration using short duration binocular rivalry, where different spatial configurations of multi-bandpass stimuli (Gabor signals) were presented to one eye (target) while a bandpass noise was presented to the other eye (mask).

Results show that configuration saliency can be consistently evaluated using measures of dominance in short duration binocular rivalry. We find that texture saliency is inversely related to local orientation uniformity, i.e. textures of randomly oriented Gabor patches are more dominant than uniform textures. However, the effect decreases and even reverses with decreasing of contrast, so that uniform textures become more dominant at low contrasts. For supra-threshold contours, on the other hand, we find that smooth collinear contours are more dominant than jagged ones, regardless of elements phase and contrast.

4.1. Interpretation of dominance in short duration binocular rivalry

Short durations and low contrast stimuli in binocular rivalry are known to produce some abnormal fusion (Wolfe, 1983; Liu et al., 1992). Thus, detection of targets in short duration rivalry may reflect the detection of signal in noise as measured in a previous study (Bonnef & Sagi, 1998). To avoid this situation, we used a rivalry period followed by a randomly positioned

probe, so that fusion during the first period or casual local dominance could not be used reliably for detection. We have also verified that monocular masking do not produce the same effects as in binocular rivalry, that longer rivalry durations (200 ms) produce similar results and that the main effect for textures can also be found using a ‘classical’ rivalry paradigm. Thus, the results appear to reflect conditions for a global target dominance in competition between low-level mechanisms, with minimal effects of memory or eye movements.

The relation between dominance in short and long-duration rivalry is not entirely clear. For the few cases we tested, we found similar effects for long duration rivalry. However, we observed that dominance in short durations is somewhat different from the classical ‘patchy’ appearance of local dominance in rivalry (Blake et al., 1992). When the mask contrast level is near dominance threshold, it often happens that a split display is perceived, i.e. a different eye dominates in each hemifield with a clear vertical border in the middle. More careful tests show that the right eye tends to dominate in the right hemifield and the left eye in the left hemifield, and that there are conditions in which the display is split horizontally with the target (a uniform Gabor texture) always dominating the upper field while the noise mask dominating the lower field. We verified that this is not an artifact of screen or stereo device used. Further investigation of this phenomenon is left for future work.

The present results can be interpreted as a measure for the strength of an independent monocular process, i.e. independent processing of independent signals originating from different eyes. The neural site of such a process is likely to be early (e.g. primary visual cortex) since its properties are consistent with a large body of physiological and psychophysical data discussed below. The neural site of the rivalry itself is a different issue that is still unresolved (Blake, Westendorf & Fox, 1990; Lehky & Blake, 1991; van der Zwan, Wenderoth & Alais, 1993; van der Zwan & Wenderoth, 1994; Sengpiel, Blakemore & Harrad, 1995; Leopold & Logothetis, 1996; Logothetis, Leopold & Sheinberg, 1996). The recent physiological evidence for binocular neurons that follow perceptual rivalry alternations at different levels of the visual pathway (V1, V2, V4, MT, IT) (Logothetis & Schall, 1989; Sengpiel et al., 1995; Leopold & Logothetis, 1996; Sheinberg & Logothetis, 1997) indicates that the independent ‘monocular signals’ reach higher processing levels which might affect our results. However, note that our results do not involve any perceptual alternations and might reflect different mechanisms than those involved in classical rivalry for which the accumulating psychophysical and physiological evidence apply.

4.2. *The effect of contrast*

Our results show that texture saliency depends on contrast, where textures of random orientation are more dominant at high contrast and uniform textures at low contrast. For contours, on the other hand, a smooth contour was found more salient than a jagged one, regardless of contrast. Similar stimuli were tested for their contrast detection threshold in a previous study (Bonneh & Sagi, 1998) that showed the superiority of both uniform textures and smooth contours. The current findings are consistent with a large body of evidence for contrast specificity of surround effects (Cannon & Fullenkamp, 1993, 1996; Polat & Norcia, 1996; Somers et al., 1996; Levitt & Lund, 1997; Sengpiel et al., 1997). Since we do not measure surround effects but relative saliency of different configurations, our results for high contrast can be interpreted as iso-orientation surround inhibition, orientation gradient facilitation or both, while collinear facilitation can account for the low contrast data. Although response to orientation gradients in V1 has been recently reported (Sillito, Grieve, Jones, Cuderio & Davis, 1995; Levitt & Lund, 1997; Nothdurft & Li, 1985), most current physiological and psychophysical findings are consistent with the high contrast inhibition and low contrast facilitation interpretation. Accordingly, our data show that lateral inhibition and facilitation depend significantly on the absolute contrasts of target and surround (we used uniform contrast) although dependency on relative contrast (Cannon & Fullenkamp, 1993) is also possible. Finally, our results do not show a contrast effect on contour saliency, although such effects were found in visual-evoked-potential (VEP) experiments for contour-type stimuli (Polat & Norcia, 1996; Polat et al., 1998).

4.3. *The difference between contour (1D) and region (2D) processing*

Our data show a clear difference between contours and regions processing. Contour saliency is determined by Gestalt properties such as smoothness and proximity which make the smooth circle more salient than a jagged one, regardless of contrast. Regions, on the other hand, are affected by contrast as discussed above. It has been suggested that contours and regions are processed differently (Zucker, 1986), as contours provide accurate localized orientation information whereas regions with surface markings provide a rough orientation impression. Thus, contours could be processed by integration of well-localized simple cells and regions by complex cells which do not code exact spatial relations.

4.4. Underlying mechanisms

Our data is consistent with a low level integration mechanism, presumably located in V1, based on lateral interactions between orientation selective neurons. The interactions are both inhibitory and excitatory, local configuration and contrast dependent. The data suggests iso-orientation surround (2D) inhibition and collinear (1D) excitation with excitation being more dominant in low contrasts and inhibition in high contrasts. The following points justify this interpretation:

1. The iso-orientation surround inhibition explains the superiority of the non-uniform Gabor texture in rivalry. It acts as a mechanism for suppressing the uniform to let the odd pop-out. It is consistent with a large body of evidence showing orientation (Blakemore & Tobin, 1972; Van Essen, DeYoe, Olavarria et al., 1989; Gilbert & Wiesel, 1990; Grinvald et al., 1994; Polat & Norcia, 1996; Solomon et al., 1993; Sengpiel, Sen & Blakemore, 1997) and spatial frequency (Chubb et al., 1989; Mapperson & Lovegrove, 1991) specificity (although measurable inhibition was found for different orientations as well, Cannon & Fullenkamp (1991)) and monocularly (Chubb et al., 1989). There are some indications for the non-isotropy of the inhibition, suggesting stronger inhibition along the direction orthogonal to the detectors main axis (i.e. between parallel orientation detectors in comparison to collinear) (Polat & Sagi, 1994; Adini, Sagi & Tsodyks, 1997). This might explain the very small saliency found for the sun-shaped circle (parallel patches, see Fig. 5 for the 90 value) in comparison with the high detectability (almost as good as the smooth circle) at contrast threshold level (Bonne & Sagi, 1998). Note however, that the superiority of orientation gradients in rivalry can also be explained by lateral facilitation between different orientations which has been recently reported (Sillito et al., 1995; Levitt & Lund, 1997).
2. The collinear excitation explains the superiority of a smooth contour over a 'jagged' one for both low (and even subthreshold Bonne & Sagi (1998)) and high contrast stimuli which is also insensitive to phase reversals. Alternatively, the high contrast phase insensitive effect can be attributed to non-optimal (lower frequency) filters or to second stage orientation filters that integrate across phases.
3. The contrast dependence of the interactions, which could be a result of network dynamics (Adini et al., 1997), explains the superiority of the uniform texture in threshold detection while a non-uniform texture is more salient in binocular rivalry. It is suggested that the surround inhibition suppresses the uniform in high contrast rivalry but is ineffective at threshold. The relationship between excitation

and inhibition appears to be a monotonic function of contrast as suggested by the gradual decrease and then reversal of the non-uniform configuration superiority in rivalry (see results for contrast effect on texture saliency).

4. The difference in connectivity architecture between excitation and inhibition accounts for the difference between regions and borders found in supra-threshold rivalry. Surround inhibition is two dimensional while excitation operates along borders (1D).

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