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Rapid Communication

The Role of “Contrast Enhancement” in the Detection and Appearance of Visual Contours

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We test the proposition that the appearance and detection of visual contours is based on an increase in the perceived contrast of contour elements. First we show that detection of contours is quite possible in the presence of very high levels of variability in contrast. Second we show that inclusion in a contour does not induce Gabor patches to appear to be of higher contrast than patches outside of a contour. These results suggest that, contrary to a number of current models, contrast or its assumed physiological correlate (the mean firing rate of early cortical neurons) is not the determining information for identifying the contour. © 1998 Published by Elsevier Science Ltd. All rights reserved.

INTRODUCTION

One of the current issues in vision research concerns how the information from different neurons is combined to allow the perception of a higher level feature. One such example is the problem of how the activity of neurons distributed along a contour are “linked” together to define the global contour. A number of previous studies have concentrated on our ability to detect collinear elements embedded in noise (e.g. Beck, Rosenfeld & Ivry, 1989; Moulden, 1994). However, it has not been clear in such studies whether the contour is detected by a single large receptive field or by an integration process among neurons. To isolate the integration process, a more recent approach has involved detecting curvilinear contours consisting of a path of spatial frequency narrowband, oriented micropatterns defined by an orientation linking rule. The path is embedded in a background field of identical but randomly positioned and oriented micropatterns (Field, Hayes & Hess, 1993). Such a stimulus is illustrated in Fig. 1(a). The path is defined by micropatterns whose orientations are correlated. This previous study produced evidence for an “association” or “linking” field which characterized the linking operation. This depended conjointly on distance and orientation such that elements that fitted along first order curves were more strongly linked.

Here we ask the question, “*what information does the visual system use to distinguish the path in Fig. 1 from its background*?” One obvious proposal, which is becoming commonplace in models of linking (Field *et al.*, 1993; Kovacs & Julesz, 1993; Yen & Finkel, 1996a; Pettet, McKee & Grzywacz, 1996), is that alignment, be it straight or along a curve, makes individual elements more active. A potential problem with such accounts is that mean firing rate and contrast are thought to be intimately related (Tolhurst, 1989). According to this view, if the path elements have higher activity because they are part of the path and activity is related to contrast, then the path elements should appear to be of a higher contrast than background elements when they are the same physical contrast (i.e. element a in Fig. 1(a) should be of a higher perceptual contrast than elements in b), although in some models (notably, Grossberg, Mingolla & Ross, 1997) the linking amplifies cell responses without eliminating their sensitivity to stimulus contrast.

The notion that contrast and perceptual linking are strongly associated is supported from the recent psychophysics of Kovacs & Julesz (1993) and Polat & Sagi (1993, 1994). In the former (a contrast discrimination task) contrast thresholds were elevated for elements comprising the contour. In the latter (a contrast detection task), lower detection thresholds were reported for an element flanked by two others when their local and global orientations were aligned. Kovacs & Julesz (1993) have argued that, on the basis of Weber’s law, their elevation in contrast discrimination thresholds is consistent with the facilitation of contrast detection thresholds (Polat & Sagi, 1993, 1994). Taken together these results might lead one to conclude that elements comprising visual contours should appear to be of higher contrast.

We investigate whether the visual system uses contrast (and its presumed neural correlate, mean firing rate) *per*

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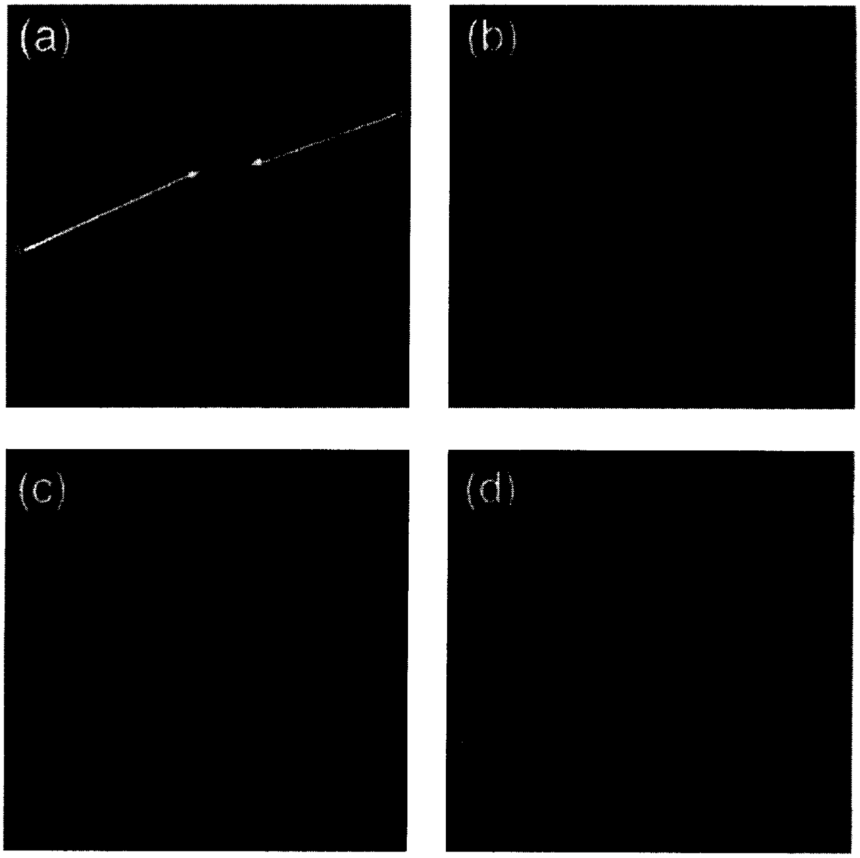

FIGURE 1. (a) Shows a 0 deg path where the contrast of all the elements (all 50%) are the same as those of the background elements. (b) Shows a 0 deg path whose elements have 40% higher contrast that those of the background. (c) Shows a random or misaligned path whose elements are 40% higher in contrast to those of the background. (d) Shows a straight path sloping 45 deg to the right in which all elements are uniformly random in contrast between the range 10–90%.

se in the linking process by first determining how vulnerable linking is to changes in local element contrast (see Fig. 1(d) for example). Secondly, we assess directly whether elements comprising paths appear to be of higher contrast than those comprising the background (the two elements indicated in Fig. 1(a)).

EXPERIMENT 1—METHODS

Subjects

Two of the authors, RFH and SCD, acted as subjects. Both are highly practiced at the path detection task.

Apparatus

An Apple Macintosh 7500 computer displayed stimuli (using routines derived from Dennis Pelli's VideoToolbox) and recorded subjects' responses. Stimuli were displayed, using a linearized look-up table, on a Nanao Flexscan 6500 monochrome monitor, with a frame refresh rate of 75 Hz. The screen was viewed binocularly at a distance of 95 cm and had a mean background luminance of 23.6 cd/m^2.

Stimuli

Stimuli were textures composed of a perturbed grid of "Gabor" micro-patterns. These patterns are sine-wave gratings windowed by an isotropic Gaussian:

$$G(x) = A\sin\left(\frac{x}{\lambda} + \phi\right)\exp\left[-\frac{x_t^2 + y_t^2}{2\sigma^2}\right] \qquad (1)$$

where A is the amplitude of the function, σ is the standard deviation of the Gaussian envelope, and λ and ϕ are the wavelength and phase, respectively, of the modulating sinusoid. All stimuli employed patches with ϕ set to 0 degrees, so that patches had zero d.c. terms. x_t and y_t are co-ordinates rotated by angle θ:

$$x_t = x\cos\theta + y\sin\theta$$

$$y_t = y\cos\theta - x\sin\theta$$

Patches were pre-generated in 1° steps and were spatially truncated at $\pm 2.5\sigma$. The wavelength of the modulating sinusoid, and the Gaussian space constant of the Gabor's envelope were equal and fixed at 0.38 deg. Thus, the central spatial frequency of the Gabor patches was 2.6 c/deg at a viewing distance of 95 cm. These values were selected in accord with previous studies (Field *et al.*, 1993). With these stimulus parameters the total viewing area was 12.3 deg. × 12.3 deg.

Each texture was made up of a set of 161 randomly oriented "background" elements and an embedded target

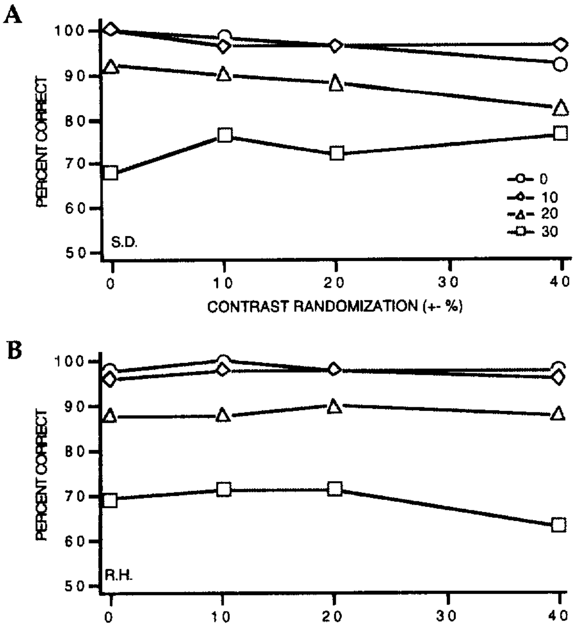

FIGURE 2. Path detection for two observers at 4 path angles (0, 10, 20, 30 deg) for elements of 50% base contrast whose contrast is varied between different ranges (0, 10, 20, 40%).

set of 8 elements. The target set of Gabor patches had their orientations aligned to the local orientation of a "path" joining them (Fig. 1(a)): a backbone of 8 invisible line segment of length 67 pixels and joined at an angle uniformly distributed from $\alpha - 4$ to $\alpha + 4$ degrees. α is called the *path angle*. For further details of the path-generation process see, Field *et al.*, 1993.

The contrast of elements was uniformly randomly varied around some mean value. However minimum contrast was fixed at 10% and the contrast of any elements falling below this was set to this value. This ensured that all elements in a display were visible.

Procedure

Each trial consisted of a 2 sec stimulus presentation, followed by a 1 sec ISI, followed by a second stimulus presentation. The subjects' task was to indicate, using the computer keyboard, which randomly selected interval contained the path. Each run consisted of 50 trials.

EXPERIMENT 2—METHODS

Subjects

Eight subjects served as observers, including the three authors. The other five were drawn from the staff of McGill Vision Research Unit who were all naïve to the purpose of the experiment. Visual correction was used as required. Subjects invariably found the task straightforward and required only minimal practice.

Apparatus

Identical to Experiment 1.

Stimuli

The stimuli were generated in a similar way to Experiment 1, except that the positions of the elements of the target set were constrained to fall along a vertically oriented, centrally positioned path. In the "path" condition, the orientation of all the elements were consistent with the presence of a contour, i.e. they were all vertical. Thus, the target appeared as a highly conspicuous vertical contour (Fig. 1(a)). In the "non-path" condition, the orientation of the target elements was random (Fig. 1(b)). In this condition if the contrast of target and background were similar, it would not be possible to disambiguate them. In order to ensure that subjects were fully aware which elements were having their contrasts adjusted, target contrast was initially set to 15–25% above or below the contrast of the background. Thus the target, in both "path" and "non-path" conditions, was initially clearly visible. In addition the subject had no uncertainty as to the position or orientation of the target.

Procedure

A method of adjustment was used. A stimulus was presented on the screen and the subject was required to adjust the contrast of the target until it matched that of the background. Subjects used four keys on the computer keyboard to alter contrast by either +10%, −10%, +1% or −1%. They depressed a fifth key to signal that they were satisfied with the contrast match, and this prompted the immediate display of a new texture.

TABLE 1. Mean contrast errors, expressed in fractional units (0.0–1.0), for matching between path and background elements in aligned and random paths (see fig 1(b) and (c)) of 25 and 50% contrast. Values in parentheses are the estimated standard deviation of errors

	Jitt. path 25%	Align path 25%	Jitt. path 50%	Align path 50%
DF	− 0.002 (0.022)	0.003 (0.026)	0.014 (0.038)	− 0.016 (0.015)
SCD	− 0.02 (0.03)	− 0.012 (0.017)	− 0.013 (0.05)	0.00 (0.029)
YW	− 0.003 (0.02)	− 0.017 (0.016)	− 0.012 (0.042)	− 0.04 (0.033)
IM	0.004 (0.014)	0.00 (0.085)	0.066 (0.033)	0.04 (0.018)
RFH	0.016 (0.027)	0.045 (0.022)	0.025 (0.032)	0.053 (0.02)
AH	0.000 (0.016)	− 0.003 (0.014)	0.016 (0.02)	0.014 (0.017)
RD	− 0.017 (0.019)	0.001 (0.015)	− 0.025 (0.029)	− 0.020 (0.04)
CW	0.015 (0.022)	0.001 (0.021)	0.009 (0.027)	0.007 (0.019)

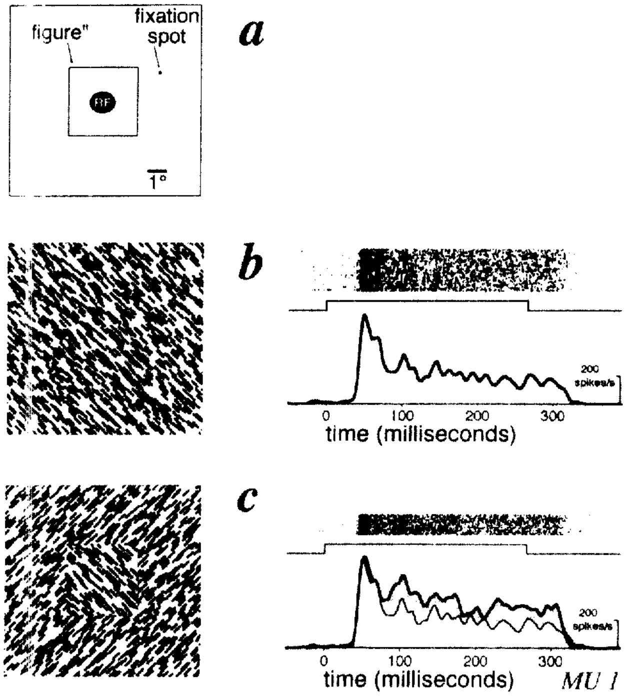

FIGURE 3. Illustration of the response of a multi-unit site to stimulation with a texture defined figure. In (a), the stimulus configuration relative to the conventional receptive field. In (b), the response to a homogeneous texture. In (c), the response to a texture defined figure. Note that the initial response is identical but the tonic phase (shaded region) is elevated in the figure condition. This figure is taken from Zipser *et al.*, 1996.

Sixteen stimuli were presented in each run. At the end of a run the mean and standard deviation of the subjects' contrast estimates were recorded. The "path" and "non-path" conditions were run both with background elements set to 25 and 50% contrast.

RESULTS

Figure 2 shows results for two observers for path detection where the contrast of all stimuli (path as well as background) was randomly varied between 0, 10, 20 and 40% about a base level of 50% (see Fig. 1(d) for example). Performance is seen to be largely independent of this contrast variation for the different path angles investigated (0, 10, 20, 30 deg). In the extreme case (i.e. 40%), the Gabors varied between 10 and 90% without any loss of performance.

The results for matching the contrast between elements making up the path and background are displayed in Table 1. This was done at two base contrasts, 25 and 50%, and for paths composed of aligned (Fig. 1(b)) and misaligned (Fig. 1(c)) elements. The mean contrast errors are low across all condition s (all around 1.5% with s.d. of 1%). There is no systematic bias in the estimated contrast of "path" compared to "non-path" stimuli. The null hypothesis, that the mean contrast error equals zero, cannot be rejected by a t-test ($P < 0.05$; 15 d.f.) for any of these results. t-values ranged from 0.0–0.37. A similar null hypothesis, that data from the jittered and aligned path conditions are significantly different, can also be rejected ($P < 0.05$; 15 d.f.).

DISCUSSION

We tested the hypothesis that contour linking is mediated by lateral interactions which enhance the apparent contrast of path elements, a view put forward by Kovacs & Julesz (1993) on the basis of their measurements of contrast discrimination as well as contrast detection data from Polat & Sagi (1993). Such a mechanism would be sensitive to disruption when the contrast of the individual elements was randomly varied. That hypothesis would also predict that the perceived contrast of path elements would be higher than that of neighbouring background elements. Neither of these predictions were confirmed.

The implication of many current models (Field *et al.*, 1993; Kovacs & Julesz, 1993; Yen & Finkel, 1996a,b; Pettet, McKee & Grzywacz, 1996; Polat & Sagi, 1993, 1994; Grossberg *et al.*, 1997) assume that linking depends upon, and in turn affects, the general activity levels of filters. Since contrast and the activity level of cells in visual cortex are presumed to be related (Tolhurst, 1989), the present results argue against the general activity of filters as being important for linking.

So what is the possible information that the visual system might use to identify "connectiveness"? We believe there are two possible accounts. First, it could be that different cells or different pathways are coding contrast and connectivity independently. In that case cells which code for contrast would fire differentially for contrast but not for connectivity and vice versa for the cells coding connectivity. Although this may be happening at some level of the visual system, and indeed the performance on Experiment 1 requires it, we do not currently favor this interpretation for early stages of cortical processing.

The second account which we favor and are currently exploring involves the relative activity of neurons at different times in their spike trains. Although some have proposed that oscillatory activity might be used to code higher level features (e.g., Singer & Gray, 1995; Yen & Finkel, 1996b), we prefer a different approach which does not require a mechanism for extracting high frequency oscillations. Recent work looking at the effects of surround context on the behavior of visual neurons has shown that individual neurons can independently vary in spike rate at different times following the response of the neuron (Zipser, Lamme & Schiller, 1996). Figure 3, for example, shows their results for a V1 neuron under conditions where the context (well outside of the classical receptive field) was altered. As one can see, the initial transient burst of activity in response to the two stimuli was essentially the same under the two conditions. However, the sustained response to the stimuli showed significant changes. Zipser *et al.* interpret their results as suggesting that feedback from higher levels of the visual system alter the response at this later point in the response of the cell.

The temporal coding strategy illustrated in Fig. 3 may also occur for contrast and connectivity. Whether the difference in sustained response is due to feedback from later stages or lateral connections, these data lead us to the possibility that the initial burst is due to feedforward activity and may provide information regarding contrast, while the variations in the later sustained components of the response provide information regarding the context (e.g. connectivity) of the stimulus. In our stimuli, this would suggest that the initial response of the cells would code for contrast and be the same whether or not the elements were part of the path or the background. However, for the cells responding to the elements along the path, there would be differential activity in the later sustained points of the response.

Although we are currently exploring this possibility psychophysically, an investigation looking directly at responses of V1 neurons would provide more conclusive evidence. At this stage, we can only propose this as one possible theory. However, such a theory is both biologically plausible and provides a solution to the dilemma that contrast and context appear to be coded independently.

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