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# Attentional effects on contrast detection in the presence of surround masks

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## Abstract

We studied how attention affects contrast detection performance when the target is surrounded by mask elements. In each display quadrant we presented a hexagon of six vertical Gabor patches (the 'surround'). Only one of the hexagons contained a central Gabor patch (the 'target') and the task was to report that quadrant (spatial four-alternative-forced choice). Attention was manipulated by means of a double-task paradigm: in one condition observers had to perform concurrently a central letter-discrimination task, and the contrast-detection task was then only poorly attended, while attention was fully available in the other condition. We find that under poorly attended conditions targets can be detected only when the target contrast exceeds the surround contrast (contrast popout) or when the target orientation differs from the surround orientation by more than 10–15° (orientation popout). When the target orientation is similar to the surround orientation, attention can reduce the contrast detection thresholds in some cases more than four-fold, demonstrating a very strong attentional effect. © 2000 Elsevier Science Ltd. All rights reserved.

*Keywords:* Attention; Contrast; Detection; Surround interactions; Segmentation

## 1. Introduction

Current psychophysical evidence suggests that attentional effects on contrast detection and contrast discrimination are very weak. Palmer (1994), for instance, has carried out an elegant search study where observers had to find a bright target among dimmer distractors. He could show that the performance deterioration with increasing number of distractors can be attributed entirely to the fact that additional distractors contribute noise at the decision stage. Sensory effects such as lateral masking between the different distractors or attentional effects that influence processing of target and distractors need not be assumed. Using Gabor patches, Foley and Schwarz (1998) have extended these findings to contrast detection and discrimination tasks, showing again that set size effects are accounted for well by the increased uncertainty (see also Laarni, Nasanen, Rovamo, & Saarinen, 1996).

Lee, Itti, Koch, and Braun (1999) used a dual-task paradigm to study attentional effects on contrast detection and discrimination. In this paradigm, thresholds for peripheral stimuli at 4° eccentricity were measured in two different conditions: the peripheral task was either fully attended, or it was poorly attended because observers had to perform a concurrent central letter-discrimination task that engaged their attention. Again, the results show that the effect of attention on contrast detection and discrimination are relatively small, i.e. 20% on contrast detection and 40–50% on contrast discrimination (see also Lee, Koch, & Braun, 1997).

However, in all these studies the target was always the element with the highest contrast in the display. One might suggest that attention may be required to detect elements (or to discriminate their contrast) if other high-contrast elements are presented in the display. This hypothesis is supported by the finding that set-size effects in visual search are much larger when observers search for the non-salient among salient ele-

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ments than vice versa (Treisman & Souther, 1985; Treisman & Gormican, 1988). Furthermore, search for the non-salient element among salient elements suffers considerably when observers have to perform a concurrent central task, while search for the salient element among non-salient elements is not affected much (Braun, 1994). In the current study we wanted to investigate in more detail (1) how surround masks affect contrast detection thresholds and (2) how these effects are modulated by attention.

Various studies have addressed the first part of the question, i.e. the effect of masks on target detection (Polat & Sagi, 1993; Polat & Sagi, 1994; Morgan & Dresp, 1995; Williams & Hess, 1998). Consequently, computational models have been developed that interpret surround effects in the context of neuronal networks with excitatory and inhibitory interactions (Foley, 1994; Zenger & Sagi, 1996; Itti, Koch, & Braun, 1999; Adini, Sagi, & Tsodyks, 1997). The basic belief is that masks suppress target detection by providing inhibitory input to the target unit, normalizing its response (Foley, 1994; Zenger & Sagi, 1996; Itti et al., 1999). An exception are collinear flankers, who are believed to provide additive excitatory input to the unit, accounting for the psychophysically observed flanker facilitation (Polat & Sagi, 1993; Polat & Sagi, 1994; Kapadia, Ito, Gilbert, & Westheimer, 1995; but see Williams & Hess, 1998 for an alternative view).

Relatively few studies, however, have addressed the second part of our question, namely, how surround interactions are modulated by attention. Notable exceptions are studies by Gilbert and colleagues: Ito, Westheimer, & Gilbert (1998) report attentional effects on flanker facilitation in a psychophysical study in both human and monkey. In these experiments, four lines (either isolated, or with a flanker) were presented in the periphery. One of the four lines, the target, differed in brightness from a reference line presented near fixation, and observers had to indicate whether the target's brightness was larger or smaller than the brightness of the reference line. In some conditions, the target location was precued and thus presumably attended, in the other condition the target could appear at any of the four locations, and observers thus had to distribute their attention across the display. The authors found that brightness-discrimination thresholds improved at the cued location; the magnitude of flanker facilitation (as indicated by the apparent brightness of the target), however, was larger when there was no cue and attention was distributed over the whole display. This suggests that focal attention weakens facilitatory surround interactions.

Remarkably, Ito and Gilbert (1999) found in a parallel monkey-physiology study that one monkey who showed increased facilitation in the distributed-attention situation also showed on average stronger response facilitation in V1 neurons when attention was distributed or focused away from the receptive field, rather than focused on the receptive field. However, the other monkey showed opposite effects: psychophysical facilitation as well as physiological facilitation were strongest when focal attention was directed towards the target. While the reason for the difference is still unclear, one can state in summary that psychophysical results and V1 recordings both suggest that attention modulated predominantly the excitatory interactions, and not the inhibitory interactions.

To address psychophysically the question of how attention modulates interactions between stimuli, we use a paradigm in which a Gabor patch (target) has to be detected in the presence of other Gabor patches (referred to as 'surround'). The surround patches were arranged in a hexagon around the target, i.e. we were not specifically probing excitatory flanker interactions, but tested also the more non-specific interactions from non-collinear flanks (Polat & Sagi, 1994; Kapadia et al., 1995), similar to many recent physiological studies (Van Essen et al., 1989; Sillito, Grieve, Jones, Cudeiro, & Davis, 1995; Kastner, Nothdurft, & Pigarev, 1997; Levitt & Lund, 1997). The contrast of the surround mask was varied across the whole range. We find very strong attentional effects on Gabor detection, with the magnitude of the effect depending on both the contrast and configuration of the surround.

## 2. General methods

### 2.1. Apparatus

Experiments were controlled by an O2 Silicon Graphics workstation, and stimuli were displayed on a 19″ raster monitor. Mean luminance $L_m$ was set to 40 cd/m$^2$. We used color-bit stealing to increase the number of gray levels that can be displayed (Tyler, 1997). A gamma correction ensured linearity of the gray levels.

### 2.2. Procedure

#### 2.2.1. Early-vision task

As stimuli we use Gabor patches. The luminance distribution $L(x, y)$ of a single patch as a function of spatial coordinates $x$ and $y$ is given by

$$L(x,y) = L_m + L_m C \cos(\omega[(x-x_0)\cos\theta + (y-y_0)\sin\theta] + \phi) \times \exp\left(-\frac{(x-x_0)^2+(y-y_0)^2}{2\sigma^2}\right) \quad (1)$$

The location of the Gabor patch is described by $(x_0, y_0)$, $\sigma = 0.18$ deg is the S.D. of the Gaussian envelope, $\omega = 4$ cpd is the spatial frequency of the grating, $\theta$ its orientation, $\phi$ its spatial phase, and $C$ is the contrast of the Gabor patch (ranging from 0 to 1).

The target Gabor patch was presented in one of the four quadrants at 4 deg eccentricity. Target orientation varied in different conditions between 0 and 30°. Each of the four possible target locations was surrounded by six vertical Gabor patches (the 'surround'), arranged in a hexagon around the target location (see Fig. 1). The distance between target and surround patches (and between neighboring surround patches) was always 1° of visual angle, corresponding to four times the carrier spatial frequency of the Gabor patches. The 24 surround patches all had equal contrast that varied between 0 and 80% in different conditions. The spatial phase of the target was always constant ($\phi = 0$) while the spatial phase of the surround patches was randomized. Viewing distance was 125 cm.

In the experiment, observers first fixated a fixation cross and then initiated the trial by pressing a space bar. Four circular cues appeared for 180 ms to indicate the four possible target locations. After a blank interval of $500 \pm 100$ ms, the stimulus was presented for 83 ms and then replaced by a blank stimulus (with fixation cross). We did not use any backward masking. Observers had to determine which of the four quadrants contained the target (spatial 4AFC). A 2:1 staircase was used, i.e. the contrast level of the target increased after each mistake, and decreased after two consecutive correct responses. This staircase converges at a level of 70.7% correct (Levitt, 1971). Because thresholds were often quite high the staircase procedure reached occasionally ceiling contrasts. We thus did not follow the common procedure to use the geometric mean of reversal contrasts as threshold estimate, but instead fitted a psychometric function to the data of each block, and used the 70.7% correct level of this fit as threshold estimate.

In the first experiment, target detection thresholds were measured as a function of surround contrast, which was varied between 0 and 80%. The target was either vertical like the surround (Experiment 1A) or it was tilted by 30° (Experiment 1B). In a second experiment, surround contrast was fixed at 40%, and target orientation was varied between 0 and 30°.

### 2.2.2. Attentional manipulation

To investigate the effects of attention, the observers were asked to perform each condition twice, with the early-vision task either 'fully attended' or "poorly attended'.

In the *poorly attended* condition observers had to perform concurrently to the early-vision task a letter discrimination task: five letters ('L' and 'T's) were presented in the center (see Fig. 1), and observers had to determine whether all letters were the same, or whether one was different from the others (binary yes/no task). The 'L's and 'T's were then masked with 'F's (SOA period varied between 164 and 236 ms for different observers). This task efficiently engages attention (Lee et al., 1997; Braun & Julesz, 1998). Observers were instructed to give priority to the central letter discrimination task, which also was the task they responded to first. In the *fully attended* condition observers were instructed to perform only the peripheral early-vision task. Note that visual stimulation was identical in the fully and poorly attended conditions and that the only difference between these two conditions lies in the instruction.

To ensure that observers perform optimally in the letter-discrimination task, *control* conditions with only the letter-discrimination task (and no early-vision task) were included as well. Blocks in the dual-task condition in which the central-task performance dropped clearly below the control condition performance were discarded from the analysis and the observer was required to repeat this condition immediately; the accuracy limit for acceptable blocks was set individually for each observer, but was typically around 80%. Only few blocks had to be discarded (less than 5% of all dual-task blocks). For the remaining blocks we find that

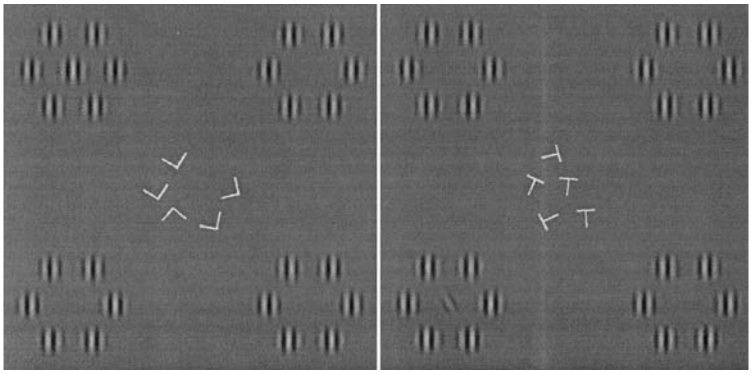

Fig. 1. Example stimuli. Each display quadrant contains a hexagon consisting of six vertical Gabor patches ('the surround'). Only one of the four hexagons contains a central Gabor target, which is either vertical (Experiment 1A) or tilted by 30° (Experiment 1B). The display also comprises five rotated letters ('L's and 'T's). To withdraw attention from the periphery, observers have to perform the central task, i.e. they have to decide whether all the letters are the same, or whether one is different from the others.

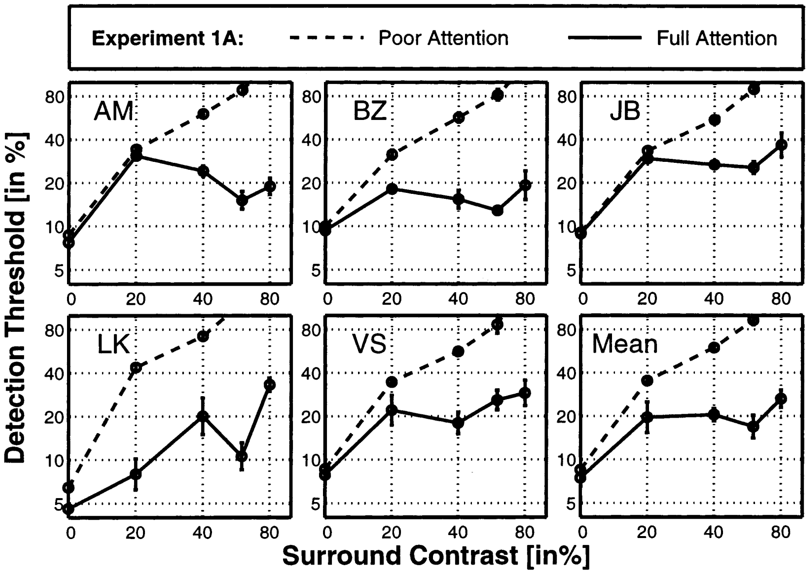

Fig. 2. Contrast detection thresholds of vertical targets (embedded in vertical surround). The error bars denote the S.E. of the mean across sessions, or mean across observers, respectively. In the poorly attended condition, detection is possible only when the target contrast is above the surround contrast, leading to a contrast popout. Availability of attention reduces thresholds considerably (in some cases more than four-fold).

central-task performance levels in the control condition (on average 88.7% correct) is comparable to central-task performance in the dual-task situation (on average 88.2% correct), suggesting that in the dual-task situation attention was well engaged in the center.

### *2.3. Observers*

Five observers with normal or corrected-to-normal vision participated in each experiment. Both experiments included at least three observers that were unaware of the purpose of the experiment. Because the dual-task paradigm is difficult for naive observers (Braun, 1998), observers were first trained for typically four to eight sessions, each lasting approximately 1 h, until performance converged. For each observer, only the last three sessions in the respective condition were used for the analysis.

## 3. Results

The results of Experiment 1A are presented in Fig. 2. Contrast detection thresholds are plotted as a function of surround contrast, i.e. the $x$-axis denotes the contrast of the patches that constitute the hexagons. Detection thresholds for poorly attended targets (dashed lines) are often larger than detection thresholds for the fully attended targets (solid lines). Thresholds are similar only in the absence of a surround (surround contrast 0%), confirming the results of previous studies. However, when there is a high-contrast surround, large attentional effects are observed.

In the poorly attended condition, targets are only detected when their contrast is considerably above the surround contrast, a finding that was very consistent across all five observers. Availability of attention leads to an enormous performance improvement, at least when surround contrasts are high. With a surround contrast of 60%, for instance, thresholds in the poorly attended condition are typically around 80%. When attention is available, these thresholds drop to around 20%, reflecting a fourfold decrease in thresholds with attention. Interestingly, performance in the fully attended condition reaches a plateau for surround contrasts above 20%, and does not follow a Weber Law-type behavior (as one would expect if the surround would act like a classical mask). A similar saturation of contrast thresholds with increasing mask contrasts has been observed by Palomares, LaPutt, and Pelli (1999). They suggest that the difference relates to a difference between masking (when peripheral letters are masked with grating or noise masks) and crowding (when peripheral letters are masked by other letters). In our case, masking patterns and target were very similar, thus, consistent with their findings, our surround might have interfered with the detection not in a classical masking process (Foley, 1994; Lee et al., 1999), but through crowding.

The results of Experiment 1B are shown in Fig. 3. This experiment was very similar to Experiment 1A, the only difference being that the target was now tilted by 30°, rather than being vertical like the surround. This small manipulation leads to a dramatically different pattern of results: first, performance is largely independent of surround contrast; second, attentional effects are much smaller (though still significant). The introspective reason for the difference between Experiments 1A and 1B is that in the latter case the target pops out, even at low contrast, due to its orientation difference and is thus always easy to see (whether attended or not).

Experiment 2 was carried out to document the transition between the pattern of results found in Experiments 1A and 1B. The surround contrast was kept constant at 40% and target angles were varied between 0 and 30° tilt. Results are shown in Fig. 4, with the detection thresholds plotted against the tilt angle. As we would have expected based on the previous experiments, attentional effects are large when target orientation is equal to the surround orientation, but are small for tilt angles of 30°. The transition occurs typically at a tilt angle of around 10–15°, varying slightly between observers. We would like to emphasize that very small changes in the stimulus (increasing the tilt angle from 10 to 15°) can cause surprisingly large threshold differences (in particular for observers LG, LK, and VS).

## 4. Discussion

This study reports strong attentional effects on Gabor patch detection. In contrast to previous studies, where the target usually constituted the element with the highest contrast in the display (Palmer, 1994; Lee et al., 1997; Foley & Schwarz, 1998), we investigated here also conditions in which the target had a lower contrast than surrounding mask elements. While the previous studies reported that attentional effects on contrast detection are either absent (Palmer, 1994; Foley & Schwarz, 1998) or weak (factor of 1.2; Lee et al., 1999), our data show that when Gabor targets are surrounded by mask elements attentional effects can be very strong (reaching up to a factor of four or more).

We found that the relative orientation of target and surround elements is very critical. If the surrounding Gabor patches have a very similar orientation to the target ( ± 10°), the surround mask is very efficient: in the unattended condition detection of the target is impossible as soon as its contrast is below the surround contrast. When attention is available, thresholds are much lower. Surround masks are much less efficient when the target patch is tilted by more than 15° with respect to the surround. In this case, contrast detection appears to be almost independent of the surround irrespective of whether the target is attended or not.

While the pattern of results is very clear and consistent across observers, it remains unclear what the mechanisms are that lead to this result pattern. While we do not attempt here to produce an exhaustive list of possible implementations, we do want to consider some possibilities in more detail. We distinguish in particular between very early implementations in which attention is presumed to affect processing in primary visual cortex, and later implementations where attention modifies processing in V2 or higher, up to the decision stage.

We first consider the possibility of modifications in primary visual cortex. Based on our data, one may suggest several different mechanisms: first, one might assume a strong *iso-orientation inhibition* in the poorly attended condition, which substantially deteriorates the detection of vertical targets, but has only little effect on tilted targets. Within this framework, attention would

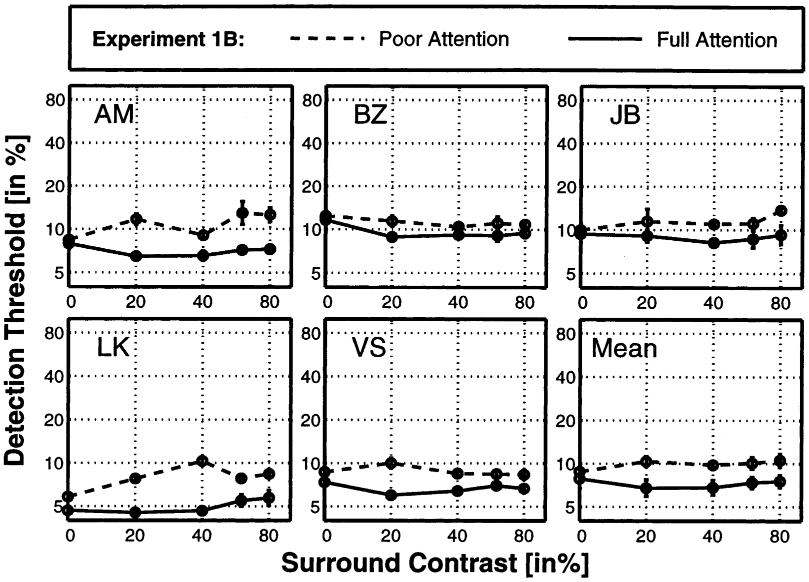

Fig. 3. Contrast detection thresholds of targets tilted by 30°. The error bars denote the S.E. of the mean across the sessions, or mean across observers, respectively. Detection thresholds are largely independent of surround contrast, and attentional effects are rather weak.

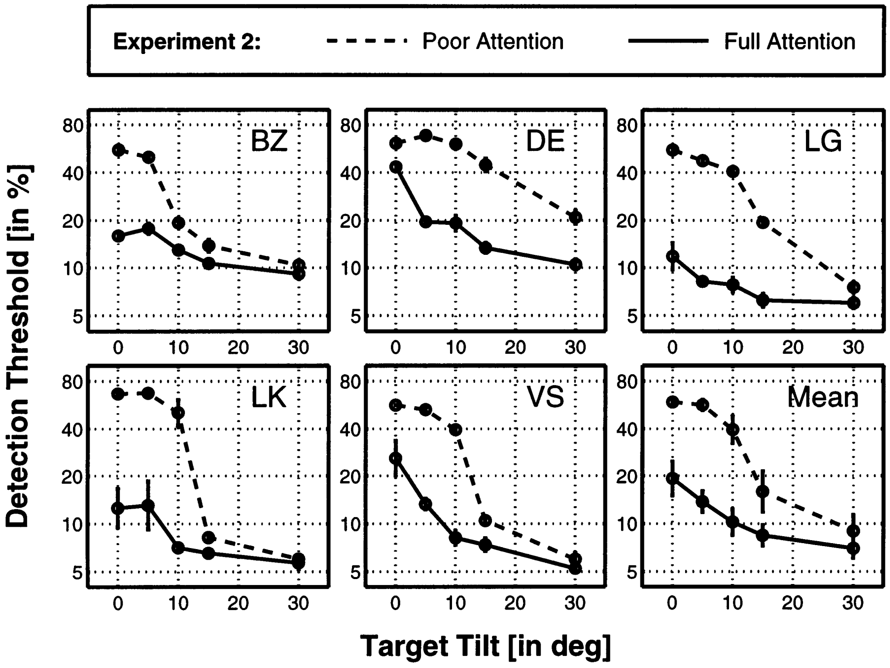

Fig. 4. Contrast detection thresholds as a function of tilt-angle (surround contrast is fixed at 40%). The error bars denote the S.E. of the mean across sessions, or mean across observers, respectively. The transition between the patterns of results observed in Experiments 1A and 1B is often rather sharp, and occurs at a tilt angle around 10–15°.

presumably reduce this *iso*-orientation inhibition, improving the detection of vertical targets while affecting tilted targets to a much lesser degree. The characteristics of this *iso*-orientation inhibition, however, would have to be different from the divisive inhibition suggested in several masking studies (Foley, 1994; Zenger & Sagi, 1996; Lee et al., 1999), as the masking functions saturate and do not follow a Power Law. This might arise from differences between masking and crowding (Palomares et al., 1999), although further research is required to understand the nature of the crowding mechanism.

Alternatively, there may be *iso-orientation facilitation* that is strong only in the unattended conditions, thus producing strong 'virtual targets' in the center, even when no target is presented. 'Real targets' then would need to have a higher contrast than the virtual targets in order to be detected. Within this framework, attention would reduce the efficacy of the facilitatory interactions that mediate the filling-in process, removing the virtual targets and thus making the detection of the real targets easier. When the target is attended, which is the condition that has typically been studied in psychophysical experiments (Foley, 1994; Solomon & Morgan, 2000), facilitation would be very small and might not be observable. When attention is removed (or very weak) strong faciliation that leads to filling-in might occur. This scenario is consistent with observations in awake behaving monkey that facilitatory effects can become weaker when the target is attended (Ito et al., 1998; Ito and Gilbert, 1999).

In addition to early processing stages, attention might have affected also later processing stages, meaning that information about the unattended target might still be present in primary visual cortex, but would get lost later on (in the absence of attention). Such a loss of information might be caused by competition, as suggested by Desimone and Duncan (1995). Within this framework, target and surround would compete for processing resources such as a receptive field in V4 (Reynolds, Chelazzi, & Desimone, 1999). If the target contrast is weaker than the mask contrast, the target loses competition, and the V4 cell codes exclusively information about the mask while the information about the target gets lost. Observers may be unable to directly base their decision on neuronal activities at earlier stages (He, Cavanagh, & Intriligator, 1996) and thus do not know anything about the target.

Indeed, when performing both the central task and the early-vision task in Experiment 1A (vertical target), observers have difficulties to estimate target properties. They do not perceive a hexagon of Gabor patches but rather 'a bunch of Gabor patches somewhere out there'. In other words, observers feel unable to tell whether a specific patch constituted the target, or whether it was part of the surround. They are able to identify (and detect) the target only when it pops out from the surround, either due to its higher contrast, or due to its unique orientation. Note that the concept of 'popout' might just be another way of stating that now the target and not the surround wins the neural competition.

When attention is available, competition is biased in favor of the attended target, by strengthening the connections from the target units onto the V4 neuron (Desimone & Duncan, 1995; Reynolds et al., 1999). The corresponding V4 cell would now become more sensitive to variations in target contrast, rather than surround contrast. Effectively, it would appear as if the V4 receptive field became smaller with attention (including the target but excluding the surround), a suggestion that is consistent with the hypothesis that attention increases spatial resolution (Yeshurun & Carrasco, 1998; Morgan, Ward, & Castet, 1998). As a result, the observer can now detect aligned targets at contrasts below the surround contrast.

Note that within the context of the biased-competition model our results would suggest that only neurons of similar orientation compete with each other, but that, when the target is tilted with respect to the surround, target information always reaches higher levels as soon as the target crosses threshold.

Attributing our attentional effects tentatively to a processing stage that corresponds approximately to V4 is attractive also in the light of the monkey lesion studies: in quadrants where the monkey has a lesion in area V4 or TEO, the monkey cannot detect a non-salient target (Schiller & Lee, 1991). The animals cannot make precise judgments about the orientation of a target in the presence of distractors located presumably within the same receptive field (De Weerd, Peralta, Desimone, & Ungerleider, 1999); however, the monkey can solve all these tasks in the normal quadrant.

Our results appear at first somewhat at odds with the finding of De Weerd and colleagues (1999) that detection of the target in the presence of distractors is not affected by the lesion. However, there are two important differences between the two experimental conditions (in addition to the species difference): first, in their experiments targets were always at high contrast, and monkeys achieved a performance level of above 97% correct in the normal as well as in the lesioned quadrants, thus an existing difference between the quadrants might have been masked by a ceiling effect. Second, they use luminance patches rather than grating patches as their distractors. Their distractors thus might share some properties of our non-aligned surround, creating perceptual popout. (Remember that for our tilted target attentional effects on target detection were also comparatively weak.)

Irrespective of the specific neuronal implementation of the attentional mechanism, our results are closely related to the literature on popout and visual search, which states that target detection is preattentive when the target differs from the distractors in a basic feature (such as orientation or color) but that target detection requires attention if there is no such feature difference (Treisman & Gelade, 1980; Bergen & Julesz, 1983; Sagi & Julesz, 1985; Braun & Sagi, 1990; Nothdurft, 1993; Palmer, Ames, & Lindsey, 1993). Our data is consistent with a similar hypothesis: when the target pops out from the surround its detection does not require focal attention. Attention is required, however, for detecting targets that do not pop out from their background. Or, put differently, targets with high saliency (i.e. targets that pop out) do not benefit much from additional attentional processing, while low saliency targets do (Itti & Koch, 2000).

The difference between our study and classical popout studies is subtle, but critical: in a classical popout experiment observers do not have any information about where the target is, therefore, they cannot make judgments about the target unless it pops out (simply because they don't know where the target is). In our study on the other hand, there is much less positional uncertainty. Observers knew where to look for the target: inside the hexagon! Surprisingly, this knowledge does not seem to help the observers; they apparently cannot render judgments about non-attended, non-salient elements. In other words, the detection of non-salient elements requires attention even when the possible target locations are known. This result could not have been predicted based on classical popout studies.

Our data further supports the hypothesis that the function of attention is to isolate an object from its background. Attentional effects are rather weak when the object is isolated already as a result of preattentive processes (such as orientation or contrast popout), but substantial attentional effects are observed when no segmentation occurs.

In summary, our results are consistent with current thoughts about attention, such as biased competition, or increased spatial resolution, but could not have been predicted based on these theories. Futher work is required to identify the neuronal mechanisms of the observed attentional effects.

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