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Effects of endogenous spatial attention on the detection and discrimination of spatial frequencies

Narayanan Srinivasan
Centre for Behavioural and Cognitive Sciences, University of Allahabad, Allahabad 211002, India; e-mail: ammuns@yahoo.com
James M Brown
Department of Psychology, University of Georgia, Athens, GA 30602, USA
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Abstract. Two experiments were designed to explore the relationship between visual attention and spatial-frequency processing using a cuing paradigm. In both experiments, the targets were a sharp-edged line segment with high spatial frequencies present and a blurred line segment with only low spatial frequencies present. In each trial an endogenous cue appeared at fixation indicating the probable location, left or right, in which a stimulus would appear. In experiment 1, a typical cuing effect was found with simple reaction times (RTs) for detecting the stimuli being faster when they appeared at a cued (ie attended) compared to an uncued (ie unattended) location. In experiment 2, choice RTs were measured, with participants indicating whether the sharp-edged line segment or the blurred line segment was presented in each trial. In this case, when it was necessary to process the spatial-frequency content of the stimuli, RTs were significantly faster at the attended location only for the sharp-edged line segment. For the blurred line segment without high spatial frequencies, RTs did not differ for attended and unattended locations. The results indicate that endogenous spatial attention interacts differently with high-spatial-frequency and low-spatial-frequency selective mechanisms depending on whether the task is to detect a stimulus or identify it on the basis of its spatial-frequency content.

1 Introduction

A number of studies by Weisstein and her colleagues have indicated a relationship between the perception and processing of figure regions and the response to high-spatial-frequency information, and between the perception and processing of ground regions and the response to low-spatial-frequency information (Weisstein and Wong 1986; Wong and Weisstein 1983). For example, Wong and Weisstein (1983) found that sharp-edged line segments were detected better in perceived figure regions than in perceived ground regions, while blurred line segments were detected better in perceived ground regions than in perceived figure regions. An attentional account might contend that their sharp-edged line segment results are also due to the fact that figure regions are attended to relatively more than ground regions. It is possible that attended regions of visual space are more sensitive to high-spatial-frequency and low-temporal-frequency information (Yeshurun and Carrasco 1998; Yeshurun and Levy 2003) while unattended regions are more sensitive to low-spatial-frequency and high-temporal-frequency information.

In general, irrespective of the type of model proposed to explain the effects of visual spatial attention, processing at attended locations is expected to be better than processing at unattended locations (although see Brown and Srinivasan 1996; Yeshurun and Carrasco 1998). For example, Yeshurun and Carrasco (1999) have shown that spatial attention improves performance in a spatial-resolution task even when their cue provided no information about the content of the target. While attention can facilitate performance when the location is known beforehand, can the preferential processing associated with attention be specific to certain information in the stimuli? There is evidence for selectively attending to different spatial-frequency-sensitive mechanisms. Information about different aspects (or levels) of an object is available via different spatial-frequency-sensitive mechanisms (Shulman and Wilson 1987). When various spatial scales are present, one spatial scale can be selectively attended to over others present in the stimulus (Julesz and Papathomas 1984; Shulman and Wilson 1987), with the visual system choosing a spatial-frequency channel appropriate for the spatial-frequency spectra of the stimuli and the task required. A subset of spatial-frequency channels can also be attended to in identification and detection tasks to reduce uncertainty and noise (Graham et al 1985).

Closely related to the present study, Brown and Srinivasan (1996) found an interaction between attention and global and local processing that was dependent on the spatial-frequency content of the stimuli. Valid cuing helped targets appearing at the local level, but did not help targets appearing at the global level. However, when low spatial frequencies were removed from the hierarchical stimuli, the facilitative effect of cuing was now found for targets at both local and global levels. In addition, covert spatial attention has also been shown to increase contrast sensitivity over a wide range of spatial frequencies under different task conditions (Carrasco et al 2000) suggesting that covert spatial attention affects spatial-frequency processing.

Given the evidence of an interaction between attention and the spatial-frequency response of the visual system, how might attending to a location change the response to spatial-frequency information at that location? If, in general, attending to a location facilitates processing, then there should be facilitation independent of the spatial-frequency content of the stimuli. However, if attention interacts with spatial-frequency processing as Brown and Srinivasan (1996) have suggested, then precuing the location should facilitate high-spatial-frequency processing, but may have little or no effect on low-spatial-frequency processing. While many of the studies examining this issue have used exogenous cuing (Cameron et al 2002; Carrasco et al 2000), here we used an endogenous location cuing task. We also used invalid cuing trials to explore processing in unattended locations in addition to valid and neutral trials (Cameron et al 2002; Carrasco et al 2000).

2 General method

2.1 *Participants*

Introductory Psychology students participated for course credit (experiment 1, $N = 26$; experiment 2, $N = 38$). All observers had normal or corrected-to-normal visual acuity and were naive to the purpose of the experiments.

2.2 *Stimuli and apparatus*

A sharp and a blurred target were used in both experiments. The sharp target was a line segment subtending 0.6 deg (height) $\times$ 0.06 deg (width) that contained both low and high spatial frequencies. The blurred target contained only low spatial frequencies and was produced by low-pass filtering the sharp target such that only frequencies $\leqslant 4$ cycles deg^{-1} remained. The blurred target subtended 0.84 deg (width) $\times$ 0.30 deg (height).

Stimuli were presented on a NEC PM-2000 RGB monitor controlled by a Data Translation Frame Grabber (DT2861) interfaced with an Everex computer. Observers sat 125 cm from the monitor with their chin in a chin-rest and entered their responses via the computer keyboard. Experiments were conducted in a dark room with the monitor as the only light source. The luminance of the dark background was 3.0 cd m^{-2}. The peak luminance of the sharp and blurred targets was 4.2 cd m^{-2}. Observers were told to maintain fixation at the beginning of each trial and fixation was not explicitly monitored.

2.3 *Analysis*

Trials with response times (RTs) greater than 1000 ms and less than 100 ms were excluded and the mean RTs were calculated for each condition. Error rates were also calculated. Observers with error rates greater than 10% were excluded from the analysis (experiment 2, $N = 9$). No differences in error rates were found across the different conditions in the two experiments.

3 Experiment 1

In the first experiment different groups of observers detected the presence or absence of either the sharp or blurred target. On the basis of the faster response of the visual system to low than to high spatial frequencies (Breitmeyer 1975), RTs were expected to be faster to the blurred than to the sharp target. Endogenous cuing was expected to facilitate responses for both targets, because the spatial-frequency content of the stimuli was irrelevant to the task. Considering stimuli were above threshold and clearly visible, any indication a stimulus was presented would be sufficient for observers to make a response.

3.1 *Method*

3.1.1 *Design and procedure.* Observers started a trial by fixating a small fixation spot at centre screen and pressing the spacebar key. A cue (a left arrow, a right arrow, or a plus sign) replaced the fixation spot 500 ms later. The cue appeared for 100 ms followed immediately by either a briefly presented (16 ms) target or nothing at all. When a target was presented, it appeared either 3 deg to the left or to the right of fixation. The left-arrow cue indicated a target would most likely ($p = 0.80$) appear at the left location in that trial, the right-arrow cue indicated it would most likely ($p = 0.80$) appear at the right location, and the plus-sign cue indicated it was equally likely ($p = 0.5$) to appear at either location in that trial. There were a total of 600 trials with 300 target-present and 300 target-absent trials. The trials were split evenly within each cue condition, resulting in 200 trials with the left-arrow cue, 200 trials with the right-arrow cue, and 200 trials with the neutral cue. For example, with the left-arrow cue, 100 were target-present trials in which the target appeared at the left location (valid condition) on 80 trials and the target appeared at the right location (invalid condition) on 20 trials while the remaining 100 were target-absent trials. With the neutral cue, targets appeared at the left location for 50 trials and the right location for 50 trials, and the target was absent for the remaining 100 trials.

Observers made a two-alternative forced-choice response to the presence or absence of a target in each trial. All observers used their right hand and pressed the left-arrow key with their index finger and the right-arrow key with their middle finger. Target type was a between-subjects variable with one group of observers detecting the sharp target and a second group detecting the blurred target. Within each group, half the observers pressed the left-arrow key when the target was present and the right-arrow key when it was absent while the other half used the opposite response pattern. A 120-trial practice block preceded the 600-trial experimental block.

3.2 *Results and discussion*

The mean RTs for various conditions are shown in figure 1. As expected, RTs to the blurred target (311 ms) were overall faster than to the sharp target (340 ms). However, a 2 between (response type) $\times$ 2 between (target type: sharp, blurred) $\times$ 2 within (location: left, right) $\times$ 3 within (cue: valid, neutral, invalid) analysis of variance (ANOVA) on the mean RTs found the effect of the cue ($F_{2,44} = 40.58$, $p < 0.001$) to be the only significant main effect. As figure 1 shows, cuing had a facilitative effect. Valid RTs were faster than invalid RTs for both sharp and blurred targets. Cuing helped in the detection of a target irrespective of its spatial-frequency content (sharp-edged or blurred line segment).

The significant response type $\times$ location interaction ($F_{1,22} = 49.74$, $p < 0.0001$) indicates that a standard Simon effect (Hedge and Marsh 1975; Simon et al 1981) was present. RTs when the response key to be pressed (L/R) and the location (L/R) were

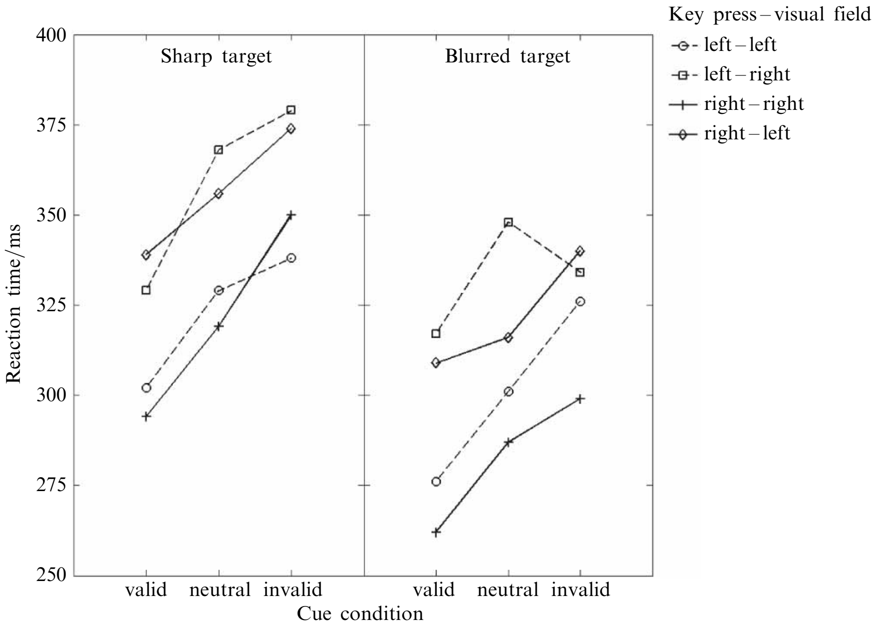

Figure 1. Reaction time to the detection of sharp and blurred targets as a function of cue validity.

compatible (306 ms) were faster than when the response key and the location were incompatible (341 ms). A left-hemisphere/right-visual-field (LH/RVF) advantage for low-spatial-frequency processing and a right-hemisphere/left-visual-field (RH/LVF) advantage for high-spatial-frequency processing has been shown in identification and discrimination tasks, but usually not for detection tasks (Christman 1989; Kitterle et al 1990). Our insignificant target-type × location interaction indicates no overall hemispheric differences in our detection task too. However, the significant target-type × location × cue interaction ($F_{2,44} = 4.98$, $p < 0.01$) indicates that there was a hemispheric difference in the effect of cuing depending on the target type and where it appeared. Why might this happen? It may be informative to consider what an observer is doing on invalid trials. This interaction may indicate an ability to shift attention away from the visual field/hemisphere specialised for the spatial-frequency content when an invalid cue has made the observer attend to that visual field initially. When an invalid cue leads observers to initially engage the hemisphere not specialised for the spatial-frequency content it may be more difficult to disengage attention from it. For example, the LH/RVF would be specialised for sharp-target processing, while the RH/LVF would be optimal for blurred-target processing (Christman 1989; Kitterle et al 1990). When the cue indicated the sharp target would appear to the right, but it invalidly appeared on the left, it was easier to disengage from the RVF where high-spatial-frequency processing is optimal and respond to the target in the LVF. The cost of invalid cuing in this case was 35 ms compared to the converse (disengaging from the non-preferred LVF to the RVF) where the cost was 53 ms. The same comparisons hold true for the blurred target. The cost of invalid cuing was 25 ms when the observers had to disengage from the preferred LVF to the RVF, compared to disengaging from the non-preferred RVF to the LVF where the cost was 42 ms. While this account is certainly speculative at this point, the results indicate that further exploration may be warranted of this complex interaction between endogenous spatial attention, the sensory characteristics of the stimuli (ie spatial frequency), and the hemisphere processing the stimuli.

In this experiment, observers had to respond only whether or not a target was present and only to the presence or absence of a single target type (sharp or blurred).

The cue not only provided information about the probable location of target, but also conveyed information regarding the probability of the correct response. Thus, observers did not have to pay attention to the spatial-frequency content of the target in making a correct response. In addition, the observers could base their judgment on the presence of temporal transients for simple detection in experiment 1. What would happen if observers had to identify the target when it appeared at the two locations? To address this question, in experiment 2 a sharp or a blurred target was presented in each trial and RT was measured to discriminate the two targets. It can be noted that, while the cue provides information regarding the probable location of the target, it does not provide any information regarding the content of the target.

4 Experiment 2

This experiment forced observers to attend to the spatial-frequency aspects of the stimuli by having them decide whether the sharp-edged or blurred line segment was presented in each trial. In essence, observers may now have to monitor both low-spatial-frequency and high-spatial-frequency mechanisms. In some ways then, this procedure is similar to Brown and Srinivasan's (1996) in the sense that in their experiments subjects had to monitor the global (ie low-spatial-frequency) and local (ie high-spatial-frequency) levels in each trial for the presence or absence of a target letter in their hierarchical letter stimuli.

In the detection task of experiment 1, endogenous cuing of the location facilitated responses to both sharp and blurred targets. Would a similar facilitation be found in a discrimination task where subjects would have to attend to the spatial-frequency content of the stimuli? If cuing a location produces a general facilitation of processing that occurs irrespective of spatial-frequency content, then cuing should facilitate responses to both sharp and blurred targets. However, if Brown and Srinivasan's (1996) results generalise to our paradigm, then cuing should always facilitate responses to the sharp target (ie containing high spatial frequencies), but not responses to the blurred target (ie containing only low spatial frequencies).

4.1 *Method*

4.1.1 *Procedure.* All procedural details were the same as in experiment 1 except that now a target (either sharp or blurred) was presented in each trial and observers had to identify it. A 120-trial practice block preceded a 900-trial experimental block that consisted of 120 valid, 75 neutral, and 30 invalid trials for each target at each location. One group used a response pattern (RP1) where they pressed the left-arrow key when a sharp target was presented and the right-arrow key when a blurred target was presented. The other group pressed the right-arrow key when a sharp target was presented and the left-arrow key when a blurred target was presented (RP2).

4.2 *Results and discussion*

A 2 between (response pattern: RP1, RP2) $\times$ 2 within (target: sharp, blurred) $\times$ 3 within (cue: valid, neutral, invalid) $\times$ 2 within (location: left, right) ANOVA on mean RTs showed significant main effects of target ($F_{1,27} = 46.04$, $p < 0.001$), cue ($F_{2,54} = 18.31$, $p < 0.001$), and location ($F_{1,27} = 18.43$, $p < 0.001$). Tukey's pairwise comparisons were used to probe the significant main effects and interactions and all differences noted below were significant at $p \leqslant 0.05$. The RTs for the various conditions are shown in figure 2. As might be expected, blurred-target RTs were faster overall (21 ms) than sharp-target RTs. The significant cuing effect indicates that cuing did facilitate processing, with RTs for valid 7 ms faster than neutral and 15 ms faster than invalid. Neutral RTs were also 8 ms faster than invalid. The significant location effect was due to RTs being 10 ms faster to targets presented at the right location than those presented at the left location.

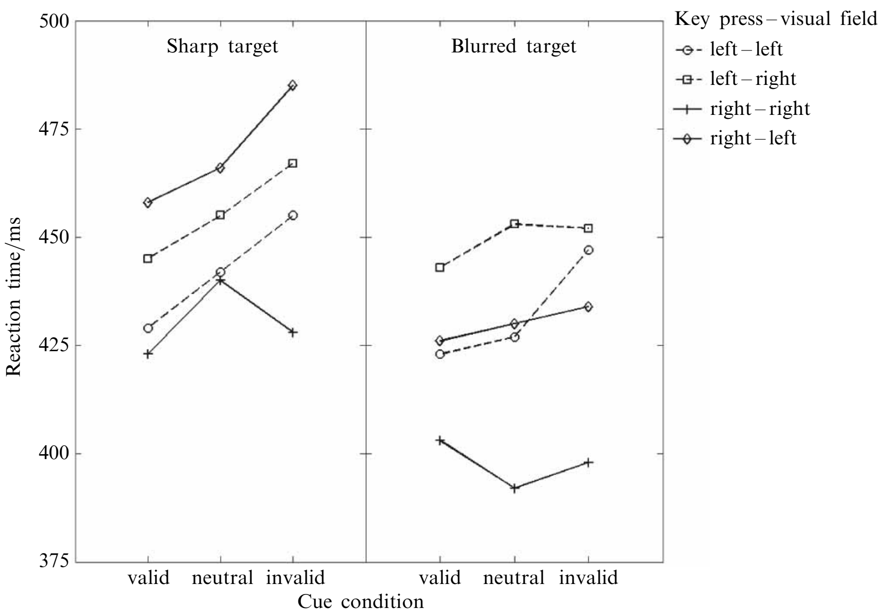

Figure 2. Reaction time to the discrimination of sharp and blurred targets as a function of cue validity.

Of particular interest was the significant interaction between target and cuing ($F_{2,54} = 4.28$, $p < 0.02$). Overall, cuing (ie attention) did facilitate responses to the sharp and blurred targets. For sharp targets valid RTs were 12 ms faster than neutral, and 20 ms faster than invalid. For blurred targets, however, valid RTs were different only from invalid RTs (10 ms). The cost of an invalid cue was half as much for blurred target as compared to sharp targets. However, a posteriori comparisons that included the response pattern and location variables along with target and cue showed that, for the most part, cuing facilitated sharp-target but not blurred-target responses. Significant facilitation was found for the sharp target (ie valid RTs were significantly faster than invalid) under both incompatible response conditions and the compatible response condition when the target appeared at the left location. Only the incompatible-response condition, when the sharp target appeared at the right location, produced no difference between valid and invalid cue conditions (see figure 2, sharp target, right – right). Of most importance, all blurred-target conditions produced insignificant RT differences between the valid and invalid cue conditions. Thus, when broken down by response pattern and location, cuing did facilitate processing in three out of four sharp-target conditions, but had no benefit for blurred-target processing. This is in sharp contrast to models of attention where attention benefits information processing within the attentional field.

The significant interaction between cuing and location of the target ($F_{2,54} = 5.73$, $p < 0.006$) was due to the different trends of RTs going from valid to neutral to invalid for the two locations. In the left location, RTs increased from valid to neutral to invalid. In the right location, RTs increased from valid to neutral, but were no different between neutral and invalid.

A significant interaction between response pattern and target ($F_{1,27} = 16.27$, $p < 0.0001$) was due to RTs to the blurred target being 27 ms faster for RP1 (left = sharp, right = blurred) compared to RP2 (left = blurred, right = sharp), while sharp-target RTs were not different for RP1 (449 ms) and RP2 (450 ms).

There were significant three-way interactions between response pattern, target, and cue ($F_{2,54} = 3.68$, $p < 0.03$), between response pattern, target, and location ($F_{1,27} = 79.47$, $p < 0.009$), and between response pattern, cue, and location ($F_{2,54} = 4.80$, $p < 0.01$).

All three interactions involved response type indicating an underlying influence of the Simon effect intermixed with stimulus and cue variables. While these are interesting effects in their own right, they were not the focus of the present experiments, and will need further experiments to delineate clearly. The main finding of this experiment was the interaction between the endogenous cue and target indicating that the effectiveness of the cue was essentially absent for responses to blurred targets compared to sharp targets.

5 Discussion

We typically have the phenomenal impression that our performance is better or things are clearly seen when we are attending to a location. The experimental literature supports these impressions. For example, cuing the upcoming location of a stimulus has been found to facilitate performance in detection and discrimination tasks (Bashinski and Bacharach 1980; Carrasco et al 2000; Downing 1988; Posner et al 1978, 1980). However, the present experiments demonstrate that endogenous spatial attention may not always facilitate processing (also see Yeshurun and Carrasco 1998). In our study, when the task was to detect the presence or absence of sharp-edged and blurred targets, precuing the location always facilitated responses. This was not the case, however, when the two stimuli had to be discriminated. Cuing the location produced little or no facilitation for the identification of blurred targets.

The results are similar to the findings that attention may enhance spatial resolution in a cuing task and may actually impair performance in a task that may not need higher spatial resolution (Yeshurun and Carrasco 1998, 1999). Attentional benefits were also found to be larger for higher spatial frequencies in at least some of the discrimination task conditions compared to low spatial frequencies (Carrasco et al 2000). While attention was shown to decrease thresholds for all spatial frequencies (Cameron et al 2002), it is possible that attention may interact differently with different spatial frequencies with suprathreshold stimuli in discrimination tasks. It is to be noted that only spatial frequencies up to 8 – 10 cycles $\deg^{-1}$ were investigated. There are also other differences worth noting between the current study and other studies exploring the relationship between spatial attention and spatial frequencies (Cameron et al 2002; Carrasco et al 2000). The current experiments used endogenous cuing, whereas other experiments have used exogenous cuing. Another significant difference is the use of invalid cuing trials in the current study. The use of invalid cuing trials might provide a better way to investigate the effects of processing at unattended locations than neutral cuing trials. While attention may be partially spread or split across locations in neutral cuing trials, it is more likely that the location of interest is unattended in invalid cuing trials. Despite these methodological differences, these experiments and the current study suggest interesting interactions between covert spatial attention (endogenous or exogenous) and the response to spatial-frequency information, especially in discrimination tasks.

Physiological evidence also suggests possible linkages between attention and spatial resolution (Desimone and Duncan 1995; Moran and Desimone 1985). It has been hypothesised that enhanced spatial resolution could result from increased sensitivity of the neurons with the smallest receptive fields that are more sensitive to high spatial frequencies at the attended area which in turn may inhibit neurons with larger receptive fields that may be more sensitive to low spatial frequencies (De Valois and De Valois 1988; Yeshurun and Carrasco 1998, 1999). Thus, enhanced spatial resolution will benefit the processing of higher spatial frequencies but may not benefit low spatial frequencies present in the stimulus.

Why would there be differences in the way attention interacts with spatial-frequency processing? When we 'direct' our attention somewhere in our visual field, it is usually for the purposes of obtaining detailed information about objects at that location which involves the processing of higher spatial frequencies. Gross visual changes indicating unusual events at unattended locations would likely involve movement and low-spatial-frequency information. The present results and those of Brown and Srinivasan (1996) indicate a relationship between attended processing and high-spatial-frequency information and between unattended processing and low-spatial-frequency information. Further experiments will be needed to map out the specific differences in spatial-frequency processing in attended and unattended regions due to covert and overt attention.

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