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Spatial attention in early vision

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Abstract

The present study addressed whether the allocation of attention to a particular region in space can prevent processing of distractor information from non-attended regions. A cue indicated the area in visual space where the target singleton would be presented. Observers were required to detect this target singleton and ignore a distractor singleton presented within a non-attended region. The results indicate that the allocation of attention to a region in space cannot prevent the processing of unwanted information from elsewhere in the visual field. It is concluded that the function of the allocation of attention is not to enhance the processing capacity within the attended region but rather to attenuate interference from distractors in unattended regions. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

At any given moment in visual processing, particular regions of the visual field may receive more elaborated processing than others. Typically over the past few decades the most dominant explanation for why it is useful to limit processing to

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relevant areas is the notion that there are limits on the amount for processing resources available for perception, cognition and action (e.g., Broadbent, 1958; Kahneman, 1973). If resources are allocated to the relevant stimuli only, these stimuli are processed faster and more accurately at the expense of unattended, nonrelevant stimuli. The role of resource allocation in visual perception typically has been studied by means of spatial cueing tasks in which an initial cue indicates the location where the impending target is most likely to appear (Eriksen & Hoffman, 1972, 1973; Posner, Snyder & Davidson, 1980). In line with the resource allocation models, it is assumed that processing resources are allocated to the location where the target is likely to appear. Because processing resources are limited, allocating attention to the cued location will result in a withdrawal of attention from uncued locations. Relative to a neutral condition, in which no prior information about the location of the target is given, a resource allocation model would predict better performance at the cued location and worse performance at the uncued location. Numerous cueing experiments have indeed shown these cue validity effects for both response times (Eriksen & Hoffman, 1973; Posner, 1980) and discrimination accuracy (Hawkins et al., 1990; Van der Heijden, Wolters, Groep & Hagenaar, 1987).

This notion that attention can be conceived of as a resource has led to a metaphor describing the allocation of attention of attention in visual space as a spotlight (Broadbent, 1982; Posner et al., 1980) or as a zoom-lens (Eriksen & James, 1986; Eriksen & Yeh, 1985), suggesting that attention can be narrowly or widely focused depending on the task demands.

In addition to cueing tasks, evidence for limited processing resources is also found in visual search tasks in which observers are required to find a particular target among nontarget elements. If many nontarget elements compete for a limited pool of processing resources, then only a limited amount of resources can be allocated to each element. Typically, time to find the target increases with the number of nontarget elements present in the visual field suggesting that fewer and fewer resources become available for each element (e.g., Duncan & Humphreys, 1989; Treisman & Gelade, 1980). However, when searching for an element defined by a single distinctive feature (i.e., a feature singleton), there are no capacity limitations: Time to find the target is independent of the number of elements present in the visual field (e.g., Treisman & Gelade, 1980). The finding that performance is not affected by the number of elements in the visual field indicates that there are basically no capacity limitations in performing the task.

It is important to note that it is generally assumed that a feature target is detected through early, spatially parallel and automatic coding (Treisman, 1988) and should be independent of the allocation of spatial attention. It is further assumed that early in vision specialized modules code feature singletons independently across the image. Early representations of a visual image consist of local descriptions that represent properties such as orientation, color and movement. These basic representations proceed in a bottom-up, parallel fashion across the visual image independent of the focus of attention (e.g., Ullman, 1984).

Recently, Theeuwes, Kramer, and Atchley (1999a) showed that even in a feature search task in which there was parallel search without capacity limitations, spatial cueing had a large effect on performance. When attention was directed to a region in space opposite to that in which the target was located, response times were about 30 ms slower than when it was allocated to the region which contained the target. It is important to note that the neutral condition in which both regions were cued produced results that were similar to the valid cueing condition suggesting that there were small, if any, costs for processing both regions at the same time, a finding which is in line with the notion that there were no capacity limitations.

Theeuwes et al.'s findings (1999a) shed new light on typical resource allocation models that suggest that spatial precues can only have an effect when there are processing resource limitations. The results showed that even when there are no capacity limitations (i.e., search is performed in parallel) there can still be a large effect of the allocation of attention. Based on these findings Theeuwes et al. suggested that the function of allocating attention in space may not so much be the enhancement of processing in one region by directing the limited capacity attentional system but rather may operate as a filter to block information from distractor elements. In line with the spotlight or zoom lens models it is assumed that within the beam, events are admitted to further processing and outside the beam events are not processed. The underlying notion is that the visual system limits its work by using a simple visual property such as location to eliminate a large part of the input early in the stream of processing. Only the input from the selected area is passed on to higher level mechanisms to be analyzed and identified.

An example of spatial location as the basis for selection to prevent interference from distractors comes from the classic study of Eriksen and Eriksen (1974). Participants were required to make a choice reaction to a letter appearing at a known location. If other letters, appropriate to a different reaction, were separated from the target by more than 1 degree of visual angle, their identity had no effect on responding (see also Eriksen & Schultz, 1979; Miller, 1991). Because subjects knew the location of the impending target they are able to filter out irrelevant information from other locations. Only elements falling within the hypothetical spotlight (i.e., within 1° of the target) affected responding to the target. These results fit well with a notion of a spotlight as a filtering mechanism: Within the beam, events are admitted to further processing and outside the beam they are not.

In a search paradigm, Yantis and Jonides (1990) and Theeuwes (1991) also showed the ability of spatial attention to filter out irrelevant information. When the location of the impending target letter is usually cued with absolute certainty, onset and offset singletons elsewhere in the visual did not capture attention. It was argued that focusing attention to a location in space enables the filtering out of information from other locations. Theeuwes (1994) suggested a top-down controllable variable-size attentional window that may act as an early spatial filter. The function of such a window is to limit processing to only those elements within the attentional window and prevent processing of elements outside the attentional window.

Along similar lines, Treisman and Gormican (1988) suggested the group scanning hypothesis indicating that attention may be pooled within a small subarea of space in order to exclude surrounding areas. The underlying notion is that attention can be restricted to a small subarea of space enabling the exclusion of the surrounding regions of the visual field. In other words, selection can be thought of as a spatial window that can be narrowly or widely focused (Treisman & Gormican, 1988). For example, Treisman (1982) suggested that a red X surrounded by green Xs is centrally masked by the presence of a red T elsewhere in the display unless attention is focused on its local group. Focusing attention on a local group makes it possible to exclude the irrelevant red T. Along similar lines, Theeuwes (1996a) showed that a conjunction of color and shape can pop-out because grouping, on the basis of color, enabled subjects to direct their attentional window to a smaller subset of elements allowing parallel search within the smaller subset of elements. Nakayama and Silverman (1986) also showed that when subjects can direct their attention to a particular plane in depth, a target defined by a conjunction of features becomes, within that particular depth plane, a target defined by a single primitive feature (see also Theeuwes, Atchley & Kramer, 1998).

The present study examines the nature of attentional filtering (e.g., facilitation of target processing versus inhibition of distractors) during parallel, preattentive processing. It tests the notion that the function of allocating spatial attention is to limit interference by favoring some locations over others. The underlying idea is that the spotlight of attention is necessary for filtering information and not for resource allocation. Directing attention to a location in space enables blocking information from distractor elements that may interfere with the processing of relevant elements. The task employed was a feature search task similar to that of Theeuwes et al. (1999a) in which it was demonstrated that cueing effects exist even when there are no capacity limitations in performing the task. Participants had to search for a primitive feature (a red line segment among gray line segments). Identical to Theeuwes et al. (1999a), rather than cueing the exact location of the target, a particular area was cued (the left or right side of the stimulus field) within which the target was likely to appear. In other words, unlike typical cueing experiments where the exact location was cued, in our study, participants still had to *search* for the target among a large set of non-target elements within the attended area. As in Theeuwes et al. (1999a), the number of elements in the display was manipulated to verify whether this task could be performed without any capacity limitations. This is important because it refutes the possibility that cueing effects are due to resource allocation strategies.

To determine whether the allocation of attention operates like a spatial filter, an element with a unique feature (i.e., a distractor singleton) was presented at the uncued location within the visual field. If participants are able to block information from the unattended area in the visual field one would expect that the presence of the distractor will fail to have an effect on search for the target feature. If, however, directing the attentional window to the cued location cannot prevent processing information from an uncued location one would expect that search time will be slowed by the presence of the distractor singleton.

2. Experiment 1

Participants viewed displays consisting of two stimulus arrays, which were presented to the left and right sides of fixation. Display size was manipulated by varying the number of line elements in each of the arrays (15 or 25 line elements in each array). Participants had to determine the orientation of a red line segment (tilted to the right or left). The tilted target line segment always appeared in the cued side either in the left or the right stimulus array. A gray outline box served as a cue indicating with a 100% validity that the target line segment would be presented in the stimulus field that was encompassed by the gray outline box. We choose to use a 100% valid cue because previous experiments have shown that only a cue that is 100% valid allows the filtering of information from other areas in the visual field (Yantis & Jonides, 1990). In the distractor condition, simultaneously with the target line segment a red vertical distractor line segment appeared in the uncued stimulus array, i.e., in the stimulus array opposite of where the target line segment appeared. Participants were instructed to ignore the red vertical distractor line segment. If directing attention to a location in space enables blocking information from distractor elements, one would expect that the time to find the target line segment will not be affected by the presence of a distractor element at the non-attended non-cued location. If, however, directing attention to a location in space cannot prevent processing of information at unattended locations one would expect that the presence of a distractor will have a detrimental effect on responding. Search times were compared to a neutral condition in which the target line segment could appear with equal probability in either stimulus array. The neutral condition provides a baseline indicating the effect of the distractor when attention is not directed in advance to a location in space.

2.1. Method

2.1.1. Participants

Eight participants ranging in age between 18 and 30 years participated as paid volunteers. All had self-reported normal or corrected-to-normal vision and reported having no color vision defects.

2.1.2. Apparatus

A 486 Personal Computer with an SVGA color monitor controlled the timing of the events, generated stimuli and recorded reaction times. The '/'-key and the 'z'-key of the computer keyboard were used as response buttons. Each participant was tested in a sound-attenuated, dimly-lit room, his or her head resting on a chinrest. The monitor was located at eye level, 95 cm from the chinrest.

2.1.3. Stimuli

The visual field consisted of two stimulus arrays (4.5° × 7.5°) presented to the left and right sides of fixation (see Fig. 1) at an eccentricity of 4.5° (fixation point to center of the stimulus array). Each stimulus array consisted of either 15 or 25 line elements, half of which were tilted, the other half were vertical (length 0.6°, tilt 23° randomly to either left or right) which were presented at random locations on a 4 × 8 grid. The first display contained either 30 (15 on the left side and 15 on the right side)

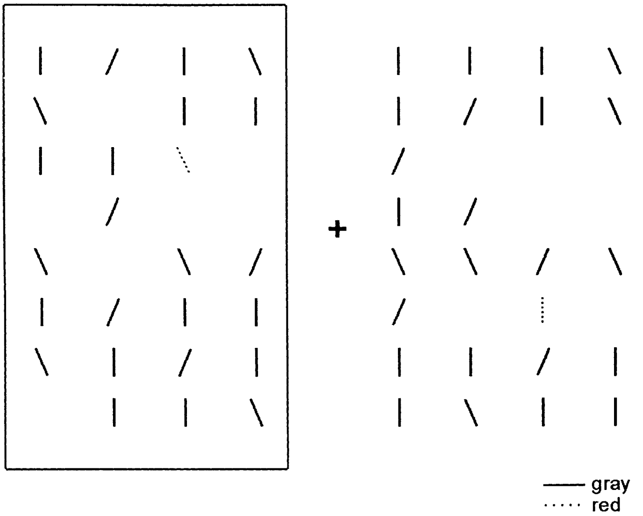

Fig. 1. Sample of a stimulus display (with display size 50). Participants had to determine the orientation of the tilted red line segment and ignore the vertical red line segment (both presented here dashed). The outline rectangle served as a cue and indicated with an 100% validity the stimulus array in which the tilted red line target segment would be presented.

or 50 (25 left side, 25 right side) gray line elements. After 1000 ms a gray outline box (5.9° × 9.9°), serving as a cue, was presented encompassing either the left or the right stimulus array. One hundred msec after the onset of the outline box, the color of one randomly chosen tilted gray element changed into an equiluminant red (5.8 cd/m^2), constituting the target line segment. The target line segment was either tilted to the left or to the right, the orientation determining the appropriate response key (tilted to the left the z key and tilted to the right the / key). In the distractor condition, simultaneously with the presentation of the red target line segment, the color of one randomly chosen vertical gray element changed into red, constituting the to-be-ignored distractor line segment. In the condition in which a cue was presented the target always appeared at the cued side (i.e., the attended side) and the distractor always at the opposite uncued side (i.e., the unattended side). Also in the neutral condition the target and distractor line segment appeared in opposite stimulus arrays. In the neutral condition two outline boxes encompassed both arrays indicating that the target was to appear with an equal probability in either the left or right stimulus array.

Both the target and distractor line segments were revealed by changing the color gray of one of the line segments into an equiluminant red. We choose equiluminant color changes because previous research has shown that equiluminant color changes do not capture attention even when observers are set to look for it (Theeuwes, 1995). This ensured that the feature detection consisted of the detection of a unique color (i.e., a red element among gray elements) instead of the detection of a luminance change.

The display was extinguished after another 100 ms. The total time of cue and stimulus field was 200 ms, a duration too short to make directed eye movements.

2.1.4. Design and procedure

Each participant performed 224 experimental trials. There were equal numbers of trials for each of the following factors: type of trial (cued or neutral), distractor (present or not), and display size (30 and 50 elements). All factors were randomly varied within blocks. Participants were told that the outline box indicated with certainty the side at which the red target line would be presented. The fixation cross remained on throughout a trial. Participants were told to keep their eyes fixated at the fixation dot. Participants received 224 practice trials prior to the experimental trials. Participants received feedback about their performance (in terms of RT and error rates) after each block of 56 trials.

2.2. Results

Response times (RTs) longer than 1000 ms were discarded, which led to a loss of 1.2% of the trials. Mean RTs were submitted to an ANOVA with display size (30 vs 50), cue type (cued vs neutral) and distractor (present or not) as factors. There were main effect of cue type ($F(1,7) = 39.0; P < 0.001$), and distractor ($F(1,7) = 67.9; P < 0.001$). Display size was not reliable ($F(1,7) < 1$). There were interactions between cue type and distractor ($F(1,7) = 11.1; P < 0.05$) and between distractor and display size ($F(1,7) = 7.2; P < 0.05$). The absence of a display size effect ($F < 1$) indicates that search was performed in parallel without any capacity limitations indicating that resource allocation strategies could not have played a role. Fig. 2 presents the results.

Planned comparisons showed that in the condition in which there was no distractor, cueing hardly had an effect (514 ms with cue, 523 ms without cue; $F = 3.7; P = 0.09$). This result replicates earlier findings of Theeuwes et al. (1999a,b) who showed a small and unreliable cueing effect of 8 ms between the neutral and valid cue condition. However when a distractor element was present, cueing did have a reliable effect ($F(1,7) = 28.8; P < 0.001$). In the condition in which a distractor was present, the cue enabled participants to better resist distraction than when no cue was provided suggesting that directing attention to a region in space does help to block information from distractor elements. However, as is clear from Fig. 2, the cue cannot completely block all information from unattended uncued areas. The condition in which participants are cued to direct their attention to the region opposite of where the distractor is going to be presented is about 35 ms slower than the condition in which no distractor is presented ($F(1,7) = 76.2; P < 0.001$; 514 ms vs 550 ms). These results clearly indicate that directing attention to a region in space cannot completely block unwanted information from other “non-attended” regions in space, the cue can only attenuate the distraction effect. In the case in which no cue is provided the distractor feature causes an interference of about 70 ms while in the case in which a cue is provided the interference is reduced to about 35 ms.

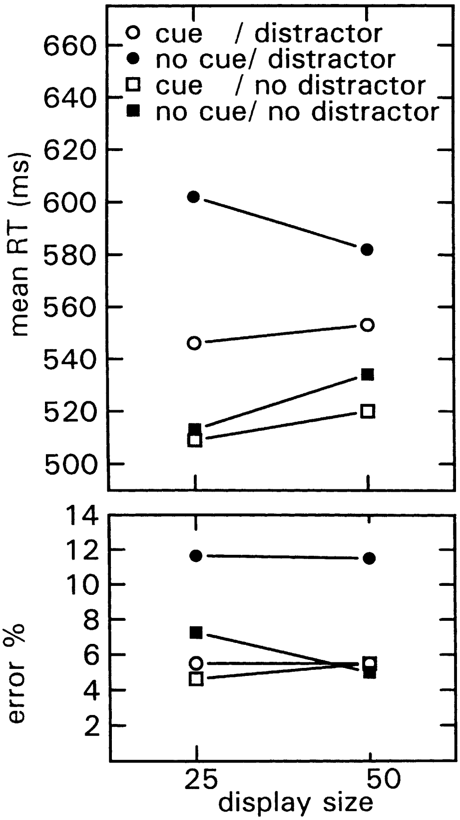

Fig. 2. Experiment 1: Mean RTs and error percentages for search with or without a distractor singleton under cueing or no cueing conditions.

ANOVAs performed on error rates showed effects of cue type ($F(1,7) = 15.2; P < 0.001$), and of distractor ($F(1,7) = 12.0; P < 0.05$). None of the interactions were reliable. Consistent with RT, error rates were lower when a cue was present (5.3% vs 8.9%) and were lower when there was no distractor (5.6% vs 8.6%).

2.3. Discussion

The neutral condition in the present experiment reveals the interference of a singleton that has the same color as the target singleton. Obviously in this condition subjects select the wrong element in about half of the trial. The interference effect caused by a singleton that has the same color as the target is about 70 ms. The question addressed in the current experiment was how much of this interference effect will be reduced when subjects are able to direct their attention in advance to the correct region in space. In other words, to what extent can the allocation of attention to a region in space act as a filter to prevent the processing of unwanted information?

The results indicate that the interference effect of about 70 ms is reduced to about 35 ms suggesting that the filter is not able to block out all unwanted information, but at best can only attenuate the processing of unwanted information? Even though there is agreement that directing attention to a location in space (e.g., Eriksen & Eriksen, 1974) or a local group (Treisman & Gormican, 1988) can prevent interference from distractors, the present study shows that this mechanism is not prefect. Even though the distractor was presented at the opposite side of the visual field (center to center distance between the stimulus arrays was 9°) and participants were cued with absolute certainty to direct attention to one particular stimulus area, distraction from the irrelevant singleton at the opposite stimulus array could not be prevented.

One could argue that the 100 ms SOA between the cue and the target was not enough to enable well-enough focusing of attention to the region in space where the target was going to appear. This could be the reason that there still was an interference effect of about 35 ms. Even though such a claim could be valid, it should be realized that the cue was an abrupt onset and there is strong evidence that 100 ms is enough to allow focusing of attention (see e.g., Theeuwes, 1991) such that there are benefits for stimuli presented near the location of the onset. As noted, we did not go beyond an SOA of 100 ms (complete cue and stimulus field duration of 200 ms) in order to prevent the execution of directed eye movement to the region in space where the target was going to appear.

The current results of the no distractor conditions show that cueing in tasks involving singleton search has basically no benefits (a non-significant 8 ms effect). Theeuwes et al. (1999a) also showed that cueing did not result in any benefits; they did, however, show that cueing can result in significant costs when the cue encompasses the incorrect stimulus field. Theeuwes et al. (1999a) suggested that this may suggest that the function of attention is not so much to process information in one region but rather to *inhibit* processing in other regions.

3. Experiment 2

An important question concerns the nature of the interference effect. On the one hand, it is possible that directing attention to a local subregion does indeed exclude processing of information from other areas as suggested by Treisman and Gormican (1988). In Experiment 1 response times may have increased because the local pop-out of the unique feature within the attended area was somewhat slower because a similar feature was present elsewhere in the visual field. For example, Theeuwes (1991, 1992) showed that reducing the saliency of a target may increase response times without affecting the slope of the search function. In other words, even though a target may become less salient it may still be detected by parallel processing, as was observed in Experiment 1. According to this line of reasoning the interference effect (i.e., the increase in RT) observed in the condition in which participants directed their attention to a subregion is that, due to the presence of a distractor, it takes longer for the target to pop-out from the stimulus array than in the condition in which there is no distractor.

Alternatively, it is possible that processing cannot be restricted to the attended area suggesting that the distractor singleton within the non-attended stimulus array is also processed. In this view, it is impossible to restrict processing to only those elements falling within the attended area. Since the absence of a display effect as observed in Experiment 1 indicates that processing is conducted pre-attentively, in parallel, it may very well be impossible to restrict processing to only the attended area. The irrelevant distractor within the unattended array may be detected preattentively and its presence may call attention to itself.

In order to determine whether the irrelevant singleton was processed, we used the response compatibility paradigm (Eriksen & Eriksen, 1974; Eriksen & Hoffman, 1972), in which subjects have to ignore a stimulus that is either compatible or incompatible with the response to the target. In previous studies (Theeuwes, 1996b; Theeuwes & Burger, 1998; Theeuwes et al., 1999b) investigating whether subjects could intentionally ignore salient singleton elements, the element to ignore was either identical or different from the target element. The results showed that the identity of the element to ignore had an effect on reaction time suggesting that spatial attention was captured by the distractor element. Subjects were faster when the distractor element was identical to the target (compatible with the response) than when the distractor element was different from the target (incompatible with the response).

To determine whether the distractor singleton in the unattended stimulus array was processed, we presented a slightly tilted red line segment within the uncued stimulus array. The line segment was either identical with the target line segment (and therefore compatible with the response) or different from the target line segment (and therefore incompatible with the response).

3.1. Method

3.1.1. Participants

Eight participants ranging in age between 18 and 28 years participated as paid volunteers. All had self-reported normal or corrected-to-normal vision and reported having no color vision defects.

3.1.2. Design and procedure

The task was similar to that of Experiment 1. Instead of having a neutral condition, in the current experiment the cue always indicated the stimulus array where the target would be presented. As in Experiment 1, participants determined the orientation of a red line segment among gray elements. In the no distractor condition only a target line segment was presented within the attended area. In the distractor condition, simultaneously with the target, a red distractor line segment similar to the target was presented at the uncued side. The distractor line segment was either compatible (i.e., identical) or incompatible (different) with the target. Participants received 224 practice trials and 224 experimental trials. In half of the trials, a distractor was present, which could either be compatible or incompatible with the response; in the other half no distractor line segment was present. Participants were instructed to respond to the line segment appearing within the cued stimulus array and ignore the line segment appearing in the uncued stimulus array.

3.2. Results

Response times (RTs) longer than 1000 ms were discarded, which led to a loss of 0.41% of the trials. Mean RTs were submitted to an ANOVA with display size (30 vs 50) and distractor (present or not) as factors. There was a main effect of distractor ($F(1,7) = 6.4; P < 0.05$). Again, display size was not reliable ($F(1,7) < 1$). For the distractor condition, planned comparisons showed a compatibility effect ($F(1,7) = 7.5; P < 0.05$). As is evident from Fig. 3, compatible responses were significantly faster (mean of 514 ms) than incompatible responses (mean of 530 ms).

ANOVAs performed on error rates showed a main effect of display size ($F(1,7) = 6.4; P < 0.05$). There is a trend towards fewer errors in the no distractor condition at the large display size.

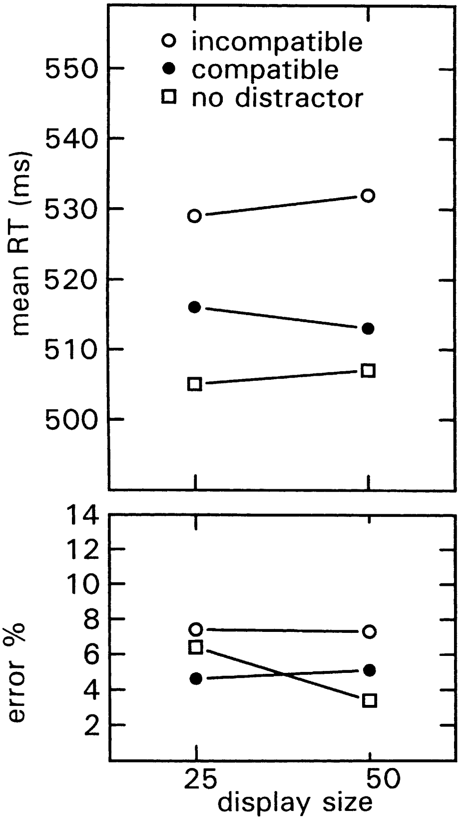

Fig. 3. Experiment 2: Mean RTs and error percentages for distractor conditions for search with no distractor and for search with a compatible or incompatible distractor.

3.3. Discussion

The compatibility effect indicates that the identity of the irrelevant distractor at the "unattended" side did have an effect on the response to the target line segment. When the distractor singleton was identical to the target singleton and therefore compatible with the response, response time was faster than when the distractor line segment within the unattended area was incompatible with the response to the target line segment, a result which is similar to that of Theeuwes (1996b) and Theeuwes & Burger (1998). These findings suggest that directing attention to the cued region could not prevent processing of information from the uncued side. This implies that processing of information is not limited to the region at which the attentional window is directed.

The finding that the identity of the to-be-ignored distractor singleton had an effect on responding to the target suggests that the orientation of the distractor was processed at some point before a response was given. In previous studies (e.g. Theeuwes, 1996b; Theeuwes & Burger, 1998) these compatibility effects were considered evidence that attention was captured by the irrelevant singleton. Because capturing of attention implies that focal attention was directed to the irrelevant singleton, the identity of the singleton became available thereby affecting the speed of responding to the target. In these previous experiments, in which participants searched for a particular letter among non-target letters (i.e., information that is considered not to be available at the early preattentive level), such an interpretation seemed fitting. Yet, in the current task, in which participants searched for the orientation of a line segment, it is conceivable that both the uniquely colored target and uniquely colored distractor singleton were processed in parallel, suggesting that the orientation of the line segments of both target and distractor singleton became available in parallel. Such an account was recognized by Folk and Remington (1998) to account for Theeuwe's (1996b) earlier findings. Again, since the current experiment involves orientations of line segments which can be processed by early parallel processing (as evidenced by the absence of a display size effect) it is conceivable that the compatibility effect represents parallel processing of the orientations of two unique singletons rather than the capture of spatial attention to the location of the distractor.

4. Experiment 3

The pattern of interference caused by the distractor singleton within the unattended area as found in Experiments 1 and 2 suggest that directing spatial attention to a region in space cannot prevent processing information from other regions. Obviously, processing is not limited to the area to which attention is directed. However, even though processing of unwanted information from unattended areas cannot be prevented completely, its processing can be attenuated as evidenced by a reduction of the interference effect.

The current findings suggest that spatial attention does not operate as a filtering mechanism to prevent processing information from unattended areas but rather affects the priority by which information is read out from the first parallel stage (e.g., Duncan & Humphreys, 1989). In this view, information at the cued location will have a higher probability of access to visual short-term memory (VTSM) than information at the uncued location. Similarly, on the basis of experiments involving multiple targets, Müller and Humphreys (1991) suggested that cueing affects the order with which targets are selected from a spatial map of multiple display locations. The cued located is assigned priority over elements at uncued locations which compete for selection.

In line with this reasoning, the current findings could be explained by assuming that processing occurs in parallel across the visual field both within the attended and unattended areas and that information from the attended area has priority over information within the unattended area. Given the finding that cueing had costs but few benefits (see the current Experiment 1 and Theeuwes et al., 1999a), it is plausible to assume that the function of attention is not so much to process information in one region but rather to *inhibit* processing in other regions (e.g., Cave, 1999; Cepeda, Cave, Bichot & Kim, 1998; Moran & Desimone, 1985). This would suggest that activation from the singleton within the unattended area will build up more slowly and therefore more time is needed for the activation to reach a threshold.

Experiment 3 tested the hypothesis that spatial attention modulates parallel processing by inhibiting unattended areas in visual space. If inhibition occurs within the unattended area, it would imply that the activation from the distractor singleton builds up more slowly than in a neutral condition in which attention is evenly divided among both regions in space. As shown in Experiment 1, inhibition of the distractor singleton will obviously cause less interference (in the cueing condition an interference effect of about 35 ms) than when the distractor singleton is not inhibited (in the neutral condition an interference effect of 70 ms).

In order to examine the time course of activation of the distractor singleton under cueing and no-cueing conditions, the onset of the distractor singleton was delayed with a variable SOA relative to the presentation of the target singleton. If cueing an area in visual space causes inhibition of the distractor within the uncued area one would expect that with enough time between the presentation of the distractor and the target singleton the interference effect will decrease or disappear.

4.1. Method

4.1.1. Participants

Ten participants ranging in age between 18 and 25 years participated as paid volunteers. All had self-reported normal or corrected-to-normal vision and reported having no color vision defects.

4.1.2. Design and procedure

The task was similar to that of Experiment 1. The time between the presentation of the target singleton and the distractor singleton was systematically varied

(0, 16, 33, 50, 66 ms SOA between the target and distractor). In addition, there was a condition in which no distractor was presented. These conditions (SOA 0, 16, 33, 50, 66 ms and no distractor) as well as display size (30 vs 50 elements) were presented equally likely within a block of trials. The cue and neutral condition which were identical to Experiment 1; yet unlike Experiment 1 they were presented in separate block of trials. Half of the participants started with the cue condition, the other half with the no cue condition. Participants received one block of 244 practice trials followed by 224 experimental trial in each cue condition.

4.2. Results

RTs longer than 1000 ms were discarded, which led to a loss of 0.5% of the trials. Mean RTs were submitted to an ANOVA with display size (30 vs 50), cue type (cued vs neutral) and SOA (0, 16, 33, 50, 66, no distractor) as factors. There was a main effect of display size $(F(1,9) = 11.63; P < 0.01)$, cue type $(F(1,9) = 14.88; P < 0.01)$ and SOA $(F(5,45) = 17.82; P < 0.001)$. There was also a reliable interaction between cue type and SOA $(F(5,45) = 3.78; P < 0.01)$.

Even though in this Experiment display size was reliable, search was performed in parallel because the larger display size gives slightly faster RTs (520 ms) than the smaller display sizes (529 ms). Again, there is no evidence for capacity limitations in performing this task.

To examine the time course of interference of the distractor under cueing and no cueing conditions planned comparisons were performed. In the no cue condition, relative to the no distractor condition, the distractor caused reliable interference at all levels of SOA (all *Ps* < 0.05). However, in the cue condition, only 0, 16 and 33 ms SOA caused reliable interference (all $P's < 0.05$). There was no reliable interference in the 50 and 66 ms SOA condition. Fig. 4 presents these results. As is clear from Fig. 4, with cueing the RT in the no distractor condition is the same as in the distractor condition when the target is presented at least 50 ms ahead of the distractor. In the no cue condition even a separation of 66 ms is not enough to prevent distraction.

An additional comparison between cue and no cue conditions when no distractor is present indicates a small RT benefit of about 18 ms which, in the current experiment, was reliable $(F(1,9) = 5.6; P = 0.041)$.

ANOVAs performed on error rates showed no reliable effects.

4.3. Discussion

When no distractor is present, cueing had only a relatively small effect suggesting that in the current type of singleton detection task, the allocation of attention can only marginally enhance processing (see also Theeuwes et al., 1999a). However, cueing does have a large effect when a distractor singleton is present. As in Experiment 1, cueing attenuates the effect of the distractor: When target and distractor

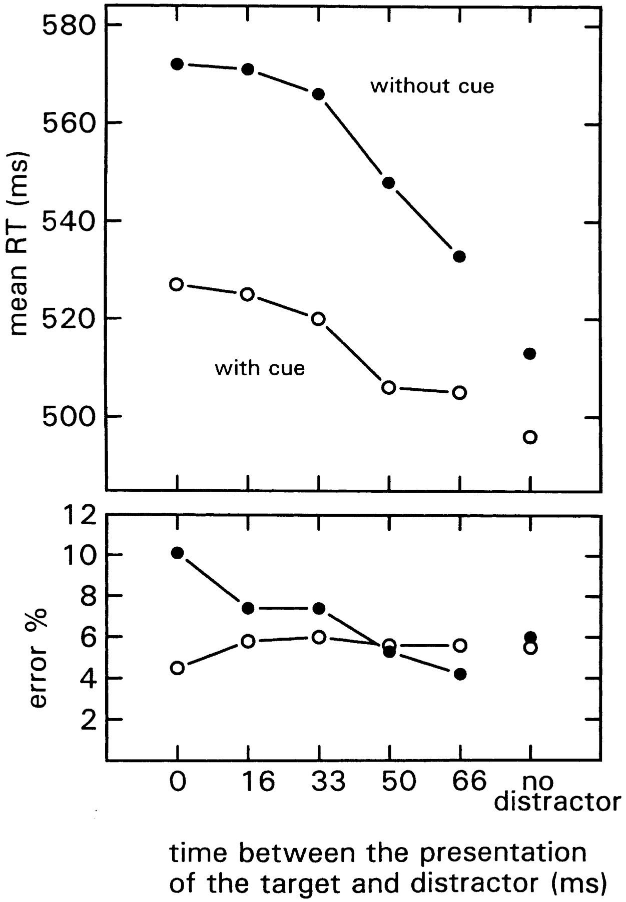

Fig. 4. Experiment 3: Mean RTs and error percentages for cueing and no cueing conditions as a function of SOA between target and distractor presentation ("no" indicates the no distractor condition).

were presented simultaneously, the distractor causes an interference of about 60 ms without the cue and about 31 ms with the cue. Again, it suggests that directing attention to an area (the attended area) enables the inhibition of processing of information in another area (the unattended area).

The time course of the interference effect suggests inhibition of the distractor singleton. It is assumed that both the target and the distractor singleton are processed in parallel. Because the distractor singleton is inhibited, its representation builds up more slowly and more time is needed to reach threshold. It is assumed that as soon as a distractor reaches threshold it competes for attention, thereby affecting the response. Fig. 4 suggests that without a cue a delay of about 66 ms has the same effect as a cue when there is no delay between distractor and target presentation. This would suggest that cueing attenuates the processing of the unattended area with a delay of somewhere between 50 and 66 ms.

5. General discussion

The current findings show that the function of the allocation of spatial attention is not the enhancement of processing capacity within the attended region but rather to attenuate interference from distractors in unattended regions. The results suggest that processing occurs in parallel both within the attended and unattended regions. When no distractor singleton is present, cueing has little effect because there is no distracting information to attenuate. In these conditions, processing occurs in parallel and the singleton target pops-out against the background of nontargets. When a distractor singleton is present at the unattended side, the results show that the cue cannot restrict processing to the attended area only. Instead, it appears that directing attention to one region in space causes a slower processing of information within the unattended area. It is assumed that both target and distractor singletons are processed in parallel (i.e., they both pop-out within the region); yet because attention is directed to one side, the processing of information at the other side is slowed (i.e., it takes somewhat longer for the distractor to pop-out). It suggests that the incoming image is analyzed by a spatially parallel processing irrespective of the where attention is allocated in the visual field. Yet, the rate of processing within the attended and unattended area is different: the rate of processing within the attended area is unaffected by the allocation of attention while the rate of processing within the unattended area is slowed.

The spatial filtering mechanism suggested here is different from the notion that attention is necessary because there are limits in the amount of processing capacity available. In line with models proposed by LaBerge and Brown (1989), Mozer (1991) and Luck and Hillyard (1994) the current findings suggest that attention is used to suppress the processing of unattended items rather than to facilitate the processing of attention items directly. For example, Luck and Hillyard (1994) suggested "a spatial filter that simply attenuates information from irrelevant locations, allowing information from unfiltered regions of space to processed with minimal crosstalk from competing objects" (p. 1001). These authors showed that an ERP component (labeled as N2pc) is involved in inhibiting or suppressing distractor items in order for the target to be selected. The N2pc component was elicited by targets in the presence of distractors but not by isolated targets. In the current experiments there was always the possible danger of crosstalk from the competing stimuli because a distractor singleton could be present within the unattended area. If the distractor was present, spatial filtering reduced the crosstalk significantly as evidenced by the reduction in interference. If the distractor was not present, cueing had little effect because there was no competing information to inhibit. In these circumstances, processing the target singleton could take place without interference.

The current notion fits well with the recently proposed Feature Gate model by (Cave, 1999; see also LaBerge, 1995 for a similar account). According to this model, the flow of information at each input location is governed by an attentional gate for that location. Each gate will limit the flow of information from its location when that information could potentially interfere with information from other locations. Cave suggests that "all the features from one particular location (e.g., color and orientation) will pass along connections through an open attentional gate to the output, while features at other locations will be inhibited by closed gates to prevent them from appearing in the output" (p. 8). The current findings indicate that the closed gates at the nonattended locations cannot *prevent* features from reaching output and affecting responding. Cave recognizes that the gates at different locations are modulated by top-down and bottom-up factors. The top-down system is engaged only when a target with known feature is being sought. In other words, the top-down system favors locations with known target features over locations with features that do belong to the target. In the current experiments, the location cue, which had a 100% validity, served as an unequivocal cue to open the gate at the attended area and close it at the unattended area. The fact that the closed gate could only slow the processing of the distractors rather than *prevent* the distractor information from being processed may be because the feature singleton participants were looking for (i.e., a red singleton) within the attended area was the same feature that had to be ignored within the unattended area. In line with Cave's notion, the top-down system that favors locations that contain a red singleton (target or distractor singleton) may have prevented complete inhibition within the unattended area.

The finding that allocating spatial attention to a particular region cannot prevent the unattended area from being processed may not be surprising because both target and distractors are *feature* singletons. Basic features are coded in parallel, in early visual processing and are assumed to be detected pre-attentively, that is *before attention operates* (Neisser, 1967). Typically search functions are flat (near zero slopes) and response times to detect the target average 400–600 ms (Treisman & Gormican, 1988). The current findings indicate flat search functions and response times near 500 ms suggesting that indeed target and distractor singletons are most likely detected pre-attentively in early vision. Yet, even though the current results indicate that processing does indeed occur in parallel across the image, the present results also indicate that spatial attention modulates this parallel coding possibly by inhibiting unattended areas in visual space (e.g., Motter, 1994).

The current findings represent evidence against early selection theories that assert that focusing attention on a single region in space enables the exclusion of processing of information from other locations. Instead the current findings are consistent with a late selection account that assumes that a first stage of parallel processing establishes attentional priorities and registers all items across the visual field to the point that identification from which they activate associated response codes (e.g., Duncan & Humphreys, 1989; Müller & Humphreys, 1991; Van der Heijden, 1992). Given this account there are two possible (not mutually exclusive) ways to explain the current spatial cueing effects: spatial cueing may affect the priority by which the information is read out from the first parallel stage. In line with Duncan and Humphreys (1989) notion, since the storage capacity of visual short-term memory (VSTM) is limited, access to VSTM is limited as well. The outcome of the parallel process (in our case the target and distractor singleton) compete with one another for access to VSTM. Information from the cued location is assigned priority over the uncued location. In this view the speed of parallel processing within the attended and unattended region is not affected; the cueing effect is due to the probability of access to the VTSM.

Another way to explain the current findings is to assume that cueing affects the speed of parallel processing within the attended and unattended regions differently: Within the attended region parallel processing proceeds at its normal speed (i.e., in terms of the Feature Gate model, the gate within this region is open) while within the unattended area parallel processing is slowed causing a slower build up of activation of the distractor. Note that the slowing of the parallel process is not due to capacity limitations but is a way to accomplish visual selection. Even though in theory these explanations are different in the sense of where in the system selection is accomplished one could also claim that the explanations are basically identical if it is assumed that the modulation of the speed of parallel processing within the attended and unattended areas is the mechanism that determines the priority by which the information is read out from the first parallel stage.

The current study provides evidence for spatial attentional filtering in early vision indicating that attention acts as a filter gating the flow of information from input to response within the attended area and attenuating the flow of information within unattended areas. Moran and Desimone (1985) suggested that attention is better conceived of as a mask than as a beam. Our results are consistent with this proposal.

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