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J. Theeuwes

PARALLEL SEARCH FOR A CONJUNCTION OF COLOR AND ORIENTATION: EVIDENCE FOR SEQUENTIAL PREATTENTIVE PARALLEL PROCESSING

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SUMMARY

The present study shows that search for a conjunction of color and orientation can be performed in parallel when the target is embedded in a homogeneous colored subgroup of nontarget elements. The results provide evidence for the notion of sequential global-to-local parallel processing in which the first global stage allows the rejection of one subgroup of elements followed by a second local stage which rejects the local subgroup of elements. Experiment 1 shows that parallel search for a conjunction target can only occur when the elements are spatially grouped. Experiment 2 shows that parallel processing of a conjunction target is not limited to small display sizes but also occur in displays consisting of 49 elements. Implications of the present findings for current theories of visual search are discussed.

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Parallel zoeken naar een conjunctie van kleur en oriëntatie: evidentie voor een sequentieel parallel proces

J. Theeuwes

SAMENVATTING

Deze studie laat zien dat het mogelijk is om parallel te zoeken naar een conjunctie van kleur en oriëntatie wanneer de target in een homogene subgroep van gekleurde elementen geplaatst is. Deze resultaten suggereren een sequentieel globaal-naar-lokaal parallel proces waarbij het eerste globale parallelle stadium één subgroep van elementen afwijst gevolgd door een tweede lokaal parallel proces dat de andere subgroep van elementen afwijst. Experiment 1 liet zien dat parallelle verwerking van een conjunctie target alleen kan optreden wanneer de elementen spatieel gegroepeerd zijn. Experiment 2 liet zien dat parallelle verwerking van een conjunctie target niet alleen optreedt bij displays met weinig elementen maar ook optreedt in displays met 49 elementen. Implicaties van de verkregen resultaten voor recente theorieën voor visueel zoeken worden besproken.

1 INTRODUCTION

Visual processing is thought to involve two sequential stages (e.g., Cave & Wolfe, 1990; Duncan & Humphreys, 1989; Hoffman, 1978, 1979; Sagi & Julesz, 1985; Treisman & Sato, 1990). The first stage operates at every location at the same time and performs a rapid, somewhat error-prone, analysis of the display, segmenting the visual field into functional units. Only features—properties such as brightness, color, orientation, and size—are computed, at every location in the visual field (e.g., Treisman & Gelade, 1980).

The second stage of visual analysis is spatially serial. Analyses are performed one item and one location at a time by driving an attentional focus through the visual field (see, e.g. Ullman, 1984). As a metaphor this process is compared to driving a "spotlight of attention" (e.g., Posner, 1980) through the visual field, sequentially illuminating different locations (e.g., Theeuwes, 1993). This stage performs detailed perceptual analysis, and is required to combine information from different feature maps into complex object representations and is necessary to locate elements in the visual field (Treisman & Gelade, 1980; Treisman, 1988; Treisman & Sato, 1990). Visual *selection* determining which element is processed first, second, third, etc., is thought to occur when an element enters this second stage of attentive processing (see Theeuwes, 1993 for a review). This stage is required to make a decision and to activate a response.

Parallel-to-serial sequential processing typically shows up in visual search tasks, in which an observer is asked to determine whether a target stimulus is present among a variable number of distractor stimuli. In tasks in which an observer has to detect a target defined by a primitive feature such as color, orientation, size and brightness, there is hardly an effect of the number of distractor stimuli (e.g., Egeth, Jonides & Wall, 1972). Typically, search functions with slopes which are less than 5 or 6 ms per item are considered to reflect preattentive parallel search (Treisman & Souther, 1985). Such a "pop-out effect" is used as a diagnostic that the information that defines the target is available at the preattentive parallel level (Treisman & Gormican, 1988). For example, a red object embedded in an array of green distractors will pop-out, that is, the time to detect the red object is independent of the number of green objects. Although the presence of the red item is uniquely coded at the preattentive parallel stage, it is assumed that the target item should enter the second attentive stage of processing before a response can be given (e.g., Johnston & Pashler, 1990; Theeuwes, 1993; Tsal & Lavie, 1993). In other words, following preattentive processing, spatial attention is shifted to the location of the red item, implying that the red item enters the second stage of attentive processing.

In contrast, when the target is defined by a conjunction of features, each of which is separately present among the nontarget elements (e.g., a red X among red Os and black Xs Treisman & Gelade, 1980), the time to find the target increases linearly with the number of nontarget elements in the display. This pattern of results has been taken as indicative of a spatially serial element-by-element search. The finding that the slope for target absent trials is twice as steep as the slope for target present trials is taken as evidence that serial search is self-terminating (e.g., Quinlan & Humphreys, 1987). Because display elements can only be classified as targets and nontargets by means of the second stage of attentive processing, serial scanning through the display is necessary giving a large effect of the number of nontargets on search times.

Although the original Feature Integration Theory (FIT, Treisman & Gelade, 1980) assumes that only attentive processing is involved in conjunction search, it is likely that some preattentive processing at a featural level will take place parsing the visual field into different groups of elements. Recent theories of visual search recognize the initial preattentive segmentation and assume that this segmentation might "guide" search for conjunction targets (e.g., Egeth, Virzi & Garbart, 1984; Kaptein, Theeuwes, & Van der Heijden, 1993; Treisman & Sato, 1990; Wolfe, Cave & Franzel, 1989; Zohary & Hochstein, 1989).

For example, in a study conducted by Kaptein et al. (1993), subjects searched in a circular display for a vertical red line segment between randomly mixed slightly tilted red line segments and vertical green line segments. In order to detect the target, a conjunction of features (e.g., red and vertical) was required. Kaptein et al. (1993) showed that subjects searched serially only through the red items without any interference from the green items (for a similar finding, see Egeth, Virzi & Garbart, 1984). The results indicate that also in case of conjunction search, preattentive processing may be involved parsing the visual field into red and green items.

Kaptein et al.'s (1993) findings can be explained by a parallel-to-serial sequential processing system involving a parallel rejection of the green elements followed by a serial scan of focussed attention on the red elements. If subjects are capable of rejecting in parallel the green elements altogether, then theoretically it should be possible to detect the conjunction target (the vertical red line segment) as a feature within the red subset of slightly tilted line segments (see also Treisman, 1982). In other words, if subjects are capable of directing attention to a perceptual group (e.g., the red items) whose components are spatially dispersed then it must be possible to conduct a feature search among the elements of one group without interference from the elements in the other group. For example, McLeod, Diver and Crisp (1988) showed that when searching for a conjunction target, subjects can segregate an array into moving and stationary elements and conduct a feature search among the moving elements. Kaptein et al. (1993) showed that in case of a conjunction search for color and orientation this was not possible: search through the red elements took about 25 ms per element. The reason that this could not be done can be attributed to the fact that red and green elements were mixed within the display. It is likely that attention can be directed to spatially grouped items only and not to a subset of elements (e.g., only the red elements) that are mixed with other distractor types (e.g., Duncan & Humphreys, 1989; Treisman, 1982).

Given these considerations, spatially grouping the red elements should allow the detection a conjunction target by means of parallel processing. Duncan and Humphreys (1989) hinted towards this idea and noted that "perceptual grouping and weight linkage might allow performance to be independent of array size even in conjunction search" (p. 455). In their theory, an image is hierarchically segmented into linked groups and subgroups producing structural units. Parts that are described within the same whole are linked together. Each structural unit may be described within a set of elementary properties such as relative location, motion, color, surface texture, etc. Along similar lines, Treisman (1982) suggested that perceptual grouping allows to set up candidate objects for further processing. Attention may be first allocated to a group as a whole, subsequently followed by focal attention to individual elements (e.g., Kahneman & Henik, 1977).

Treisman (1982, exp.2) tested a similar hypothesis using displays in which 1, 4 or 9 groups of items were positioned on a 3 × 3 array (9.7° × 9.7°). Perceptual grouping was obtained by placing the items within a group close together. Because there was spatial separation between the groups of items, the groups of items formed either 1, 4, or 9 separate "objects". Within these "objects" there were either 1, 4, or 9 items. Given the items present within the whole display, the target was a conjunction; Yet, within a particular group the target stood out against the local background as a feature. Search time serially increased with the number of groups, suggesting that subjects serially searched the separate groups of items. There was also an increase in search time with the number of items within the group; Yet, not so much as would have been expected when subjects would have searched serially through the display.

In all, the data of Treisman (1982) hinted that in displays in which there are different separate "objects", search may be serial between groups and, at least to some extent, parallel within groups. Although Treisman (1982) attributed these findings to attentional processing mechanisms, the results can simply be explained by assuming that subjects moved their eyes from one object to the next, and performed an attentional (feature) search within the group of items. Treisman (1982) obtained reaction times between 600 and 2400 ms which is undoubtedly within a range that allows directed eye movements. The finding that spatial density has little effect on conjunction search RTs in a "standard" conjunction search experiment (Treisman, 1982, exp. 3) cannot be used as evidence that eye movements did not occur in the experiment with the grouped items.

In displays in which items are not grouped as separate objects, it is likely that serial search between and parallel search within groups of elements will also occur. For example, Pashler (1987) suggested that when searching for a conjunction target, for clumps up to eight elements at a time, search might be a limited capacity *parallel* self-terminating process giving small display size effects and equivalent slopes for target present and absent trials. Search is serial, self-terminating between these clumps of 8 items. Along similar lines, Treisman & Gormican (1988) suggested for feature search the "group scanning" hypothesis which claims that the size of the attended area can be varied. When fine discriminations between targets and nontargets have to be made, subjects may reduce the size of the attentional spotlight, resulting in search through sub-groups, checking items within groups in parallel. Within the focus of attention, activation is pooled for each feature map, giving an assessment of the likelihood that a particular feature coded by the map is present in the attended area.

The present study investigates whether subjects can search for a conjunction target in parallel when this target is embedded in a homogenous group of nontarget elements. Because presentation time of the display was too short to make directed eye movements, it is ensured that the observed results are due to attentional mechanisms. Testing this hypothesis is important because if it is possible to detect a conjunction target in parallel when located in a homogenous group of nontarget elements, theoretically it has to be inferred that at least *two sequentially parallel* operating processing stages are involved before serial attention is deployed. It is assumed that the first preattentive operation causes the group of red elements to pop-out from the green elements, followed by a second preattentive operation causing the vertical target line segment to pop-out from the slightly tilted line segments.

2 EXPERIMENT 1

Similar as in Kaptein et al. (1993) subjects had to search for a vertical red line segment among green vertical and red tilted line segments. Contrary to Kaptein et al. (1993) who used circular displays, in the present experiment displays were used in which elements were distributed in a grid of potential locations. The display was organized in such a way that the red elements always appeared in a group. If subjects are capable of two sequential parallel processing operations then it is expected that the conjunction of color and orientation will pop-out, that is, it is expected that search time is independent of both the number of red and green nontarget elements in the display.

2.1 **Method**

Subjects

Sixteen right-handed subjects, ranging in age from 18 to 26 years, participated as paid volunteers. Eight subjects were randomly assigned to the "grouped" condition, and 8 to the "random" condition. All had normal or correct-to-normal vision and reported having .10 color vision defects.

Apparatus

A SX-386 Personal Computer (G2) with a NEC Multisync 3D VGA color screen (resolution 640x350) using Micro Experimental Laboratory software package controlled the timing of the events, generated pictures and recorded reaction times. The '/'-key and the 'z'-key of the computer keyboard were used as response buttons. Each subject was tested in a sound-attenuated, dimly-lit room, his or her head resting on a chinrest. The CRT was located at eye level, 97 cm from the chinrest.

The display elements consisted of green (CIE x,y chromaticity coordinates of .303/.594) or red (coordinates of .620/.353) line segments which were matched for luminance (8.8 cd/m^2). The fixation cross was presented in white (33.0 cd/m^2) on a black background (0.5 cd/m^2).

Stimuli

The stimulus field consisted of 1, 2, 4, or 8 vertical green line segments (0.6°) and 1, 2, 4, or 8 tilted 20° clockwise red line segments (0.6°). The target was a red vertical line segment (0.6°). In order to detect the target, a *conjunction* of features (color and orientation) was required. In target-absent trials, the red vertical line was replaced by a red nontarget line segment. The centers of the line segments were positioned on an imaginary 4 × 4 matrix (4.2° × 4.2°). The target line segment could appear in any position within the 4 × 4 matrix. In the random condition, all trial elements were randomly distributed within the 4 × 4 matrix. In the grouped condition, the red elements always occupied adjacent positions so that they appeared as a group. Two red elements always occupied either horizontal or vertical adjacent positions. Four red elements were always presented in squares. Eight red elements were always presented in a 2 × 4 or 4 × 2 array within the 4 × 4 array. The green elements were allocated randomly to the remaining empty locations. Fig. 1 gives examples of stimulus displays with 4 red and 8 greens elements for both the grouped and random condition.

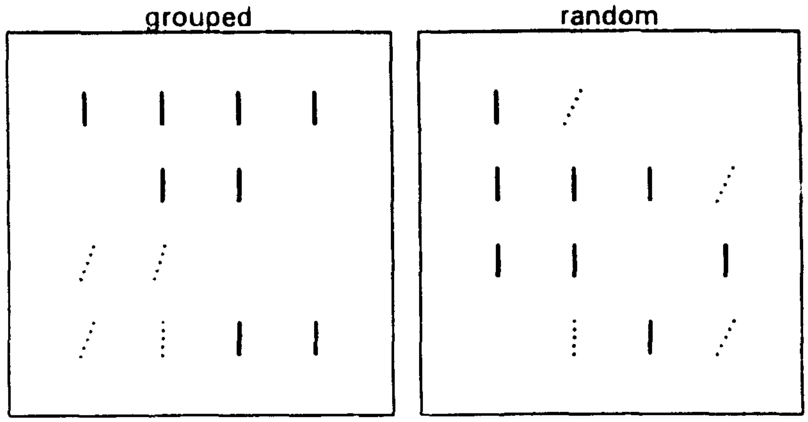

Fig. 1 Examples of stimulus displays used in Experiment 1 for the grouped (left panel) and the random (right panel) condition. Red line segments are dashed, green line segments are solid. In this example, there are 4 red and 8 green elements; the red vertical target line segment is located in the left lower corner, second from the left.

Procedure

The task was similar to that in Kaptein et al. (1993) consisting of a visual search task in which subjects searched for a red vertical line segment. Half of the subjects responded "yes" if a target was present by pressing the "/" key on the keyboard with their right hand and "no" if it was not by pressing the "z" key with their left hand. This assignment was reversed for the other half of the subjects.

At the beginning of a trial, a central fixation dot appeared for 700 ms. The fixation dot was replaced by the stimulus field which was presented for 183 ms, an exposure duration to short too make directed eye-movements. On trials in which a response error was made or no response was given after 2 s, the computer beeped to inform the subjects that they had committed an error. Consecutive trials were separated by a blank inter-trial interval of 1200 ms.

Subjects performed a single block of 832 trials in which there were equal number of trials at each of the 4 levels of red elements (1, 2, 4, 8), equal number of trials at each of the levels of greens elements (1, 2, 4, 8) and equal number of target present/absent trials. Rests were allowed after every 104 trials when subjects received feedback about their performance (percentage errors and mean reaction time) on the preceding trials.

Prior to the start of the experiment subjects were instructed to search for the vertical red line segment and to press the appropriate response keys with the index fingers of the left and right hand. While explaining the experiment, sample displays showing a typical trial were shown to the subjects. Both speed and accuracy were emphasized. Subjects received one block of 416 practice trials in which they received feedback about their performance on after every 42 trials.

2.2 Results

Response times longer than 1 s were counted as errors, which led to a loss of well under 1% of the trials. Fig. 2 presents the subjects' mean RT for target present and absent trials as a function of the number of red elements for the grouped (Panel A) and random (Panel B) condition.

Fig. 3 presents the same data when plotted as a function of the number of green elements. Mean correct RTs of target present and absent trials of the grouped and the random condition were submitted to separate ANOVAs with number of reds (1, 2, 4, 8), number of greens (1, 2, 4, 8) as main factors.

Grouped condition

For target present trials in the grouped condition there was a main effect on RT of the number of red elements [$F(3,21)=29.6$; $p<.01$] (see Fig. 2A) but not for the number of green elements (see Fig. 3A). A post-hoc Tukey-test revealed that the 1 red element condition differed significantly from the 2, 4, and 8 red element condition. There were no differences between these latter conditions, indicating the main effect on RT of the number of red elements was completely due to the relatively fast response times for display size 1 (see Fig. 2A). An additional ANOVA in which the 1 red element condition was excluded confirmed this notion. This analysis reveals, as is evident in Figs 2A and 3A, that there was no effect of neither the number of red nor the number of green elements, suggesting that the time to find the target was independent of the number of elements in the display.

For target absent trials, there was a main effect on RT of the number of green elements [$F(3,21)=52.3$; $p<.01$] (see Fig. 3A) but not for the number of red elements (see Fig. 2A). This analysis indicates as is evident in Fig. 3A that RT increases with the number of green elements.

Overall, there was not a significant difference between present and absent responses.

Since the post-hoc analysis above revealed that the *1 red element condition* should be considered as an outlier, the data from the 1 red condition were not included in the display size slope calculations. Target present responses gave mean slopes of 2.7 ms/element for the red elements (excluding 1 red element) and 0.8 ms/element for the green elements. The target present slope for red elements just differed significantly from a zero slope [$t(7)=1.89$, $p=.05$]. Both slopes were very small suggesting preattentive parallel search across *all* elements.

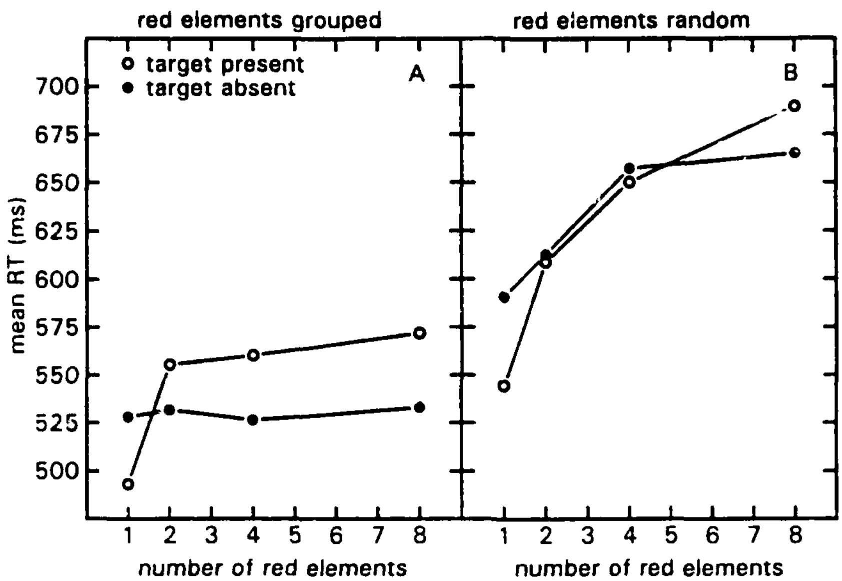

Fig. 2 Experiment 1: Mean reaction time for target present and absent trials, as a function of the number of red elements for both the grouped (Panel A) and random condition (Panel B).

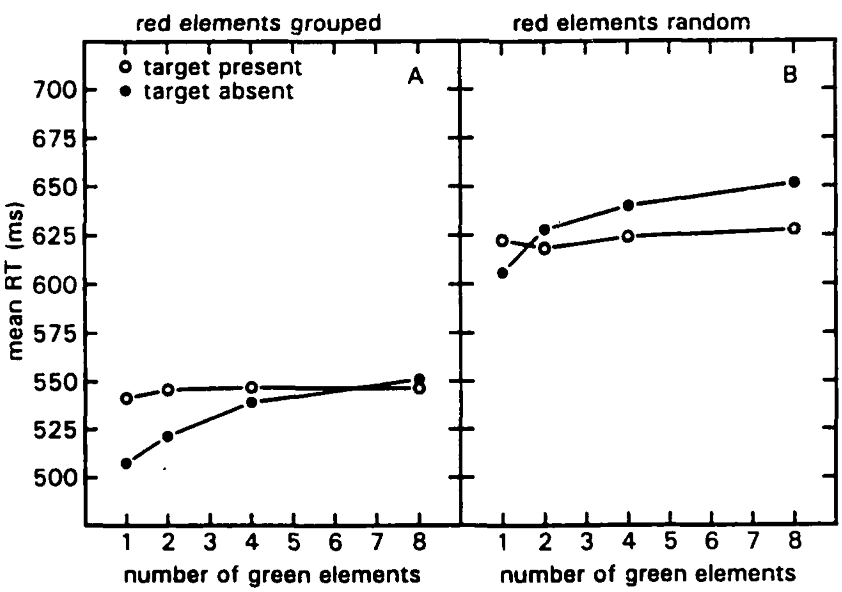

Fig. 3 Experiment 1: Mean reaction time for target present and absent trials, as a function of the number of green elements for both the grouped (Panel A) and random condition (Panel B).

For target absent responses, the slopes were 0.4 ms/element for red and 6.5 ms/element for green elements. The target absent slope for green elements was significantly different from zero [$t(7)=7.55$, $p<.01$].

Fig. 4 presents the data of the grouped condition in an different way. Mean RTs are plotted against the number of red elements, separately for each number of green elements, both for target present (Panel A) and target absent (Panel B).

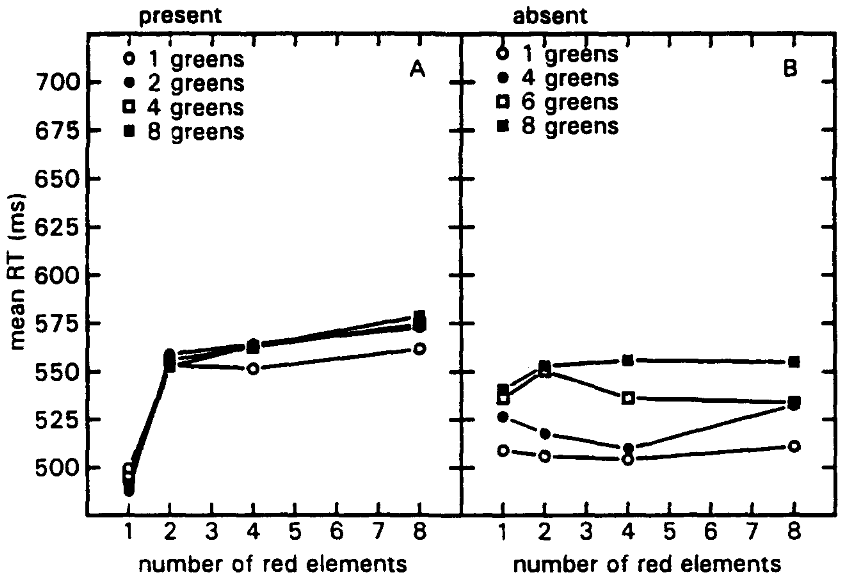

Fig. 4 Experiment 1, Grouped condition: Mean reaction time as a function of the number of red elements, separately for each number of red elements, for both target present (Panel A) and target absent trials (Panel B).

The mean overall error score in the grouped condition was 6.8%. Error rates for each display size condition are shown in Table I. To achieve homogeneity of the error rate variance, the mean error scores were transformed by means of an arcsine transformation. For target present trials, there was a main effect of the number of red elements [$F(3,21)=16.0$; $p<.01$]. As is evident from Table I, subjects tend to make more errors with increasing number of red elements. For target absent trials there was both an effect of the number of green and the number of red elements [$F(3,21)=4.3$; $p<.05$] for green and [$F(3,21)=8.2$; $p<.01$ for red]. For target absent responses, subjects tend to make more errors with increasing number of green elements. A post-hoc Tukey-test revealed that the main effect of the number of red elements was completely due to the large error rate (10.5%) at the 1 red condition. This indicates that in case only one red element is present, subject tend to respond "target present" to displays containing a single nontarget element. The overall pattern of errors suggests that subjects wait until the vertical red target line segment pops-out from the red nontarget elements. Especially in case the target line segment is surrounded by 7 red nontarget elements, it happens that the target line segment does not pop-out giving rise to a large proportion of erroneous "target not present" responses.

Table I Experiment 1: Mean Error Rates (%) for target present and absent trials for the grouped condition for each display size.

number reds	target present				target absent			
	1	2	4	8	1	2	4	8
1 green	2.4	4.3	8.1	10.1	8.6	4.3	2.4	3.8
2 greens	5.7	9.1	8.1	14.4	9.6	3.8	1.9	4.8
4 greens	1.4	8.2	9.6	13.0	13.4	3.3	5.3	4.8
8 greens	1.9	6.7	6.2	12.5	10.6	7.7	8.6	4.8

Random condition

For target present trials in the random condition there was a main effect on RT of the number of red elements [$F(3,21)=108.0$; $p<.01$] (see Fig. 2A) but not for the number of green elements (see Fig. 3A). The interaction between the number of red and green elements was also significant [$F(9,63)=2.4$; $p<.05$]. As is evident in Figs 2B and 3B, RT increases with the number of red elements but not with the number of green elements.

For target absent trials, there was a main effect on RT of both the number of green elements [$F(3,21)=37.5$; $p<.01$] and the number of red items [$F(3,21)=28.1$; $p<.01$]. Also, the interaction between these variables was significant [$F(9,63)=2.1$; $p<.05$].

Overall, there was not a significant difference between present and absent responses.

Target present responses gave mean slopes of 18.4 ms/element for the red elements and 1.0 ms/element for the green elements. The target present slope for red elements was significantly different from zero [$t(7)=12.1$, $p<.01$]. The absence of a slope on the number of green elements suggests that subjects have limited their search to only the red items, confirming the findings of Kaptein et al. (1993).

For target absent responses, the slopes were 10.2 ms/element for red and 5.7 ms/element for green elements. Both slopes differed significantly from zero (both $p<.01$), findings similar to Kaptein et al. (1993).

Fig. 5 present the mean RTs against the number of red elements, separately for each number of green elements, for target present (Panel A) and target absent (Panel B).

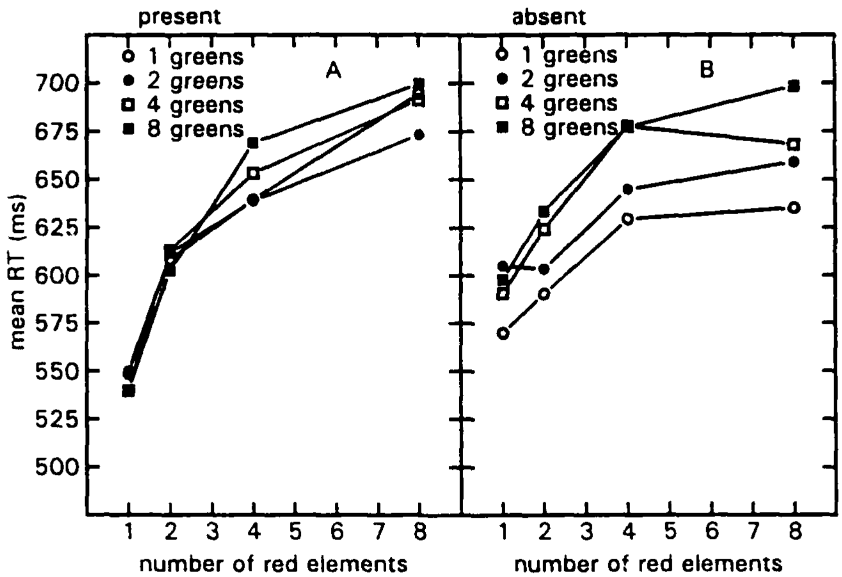

Fig. 5 Experiment 1, Random condition: Mean reaction time as a function of the number of red elements, separately for each number of red elements, for both target present (Panel A) and target absent trials (Panel B).

The mean overall error score in the random condition was 6.3%. Error rates for each display size condition are shown in Table II. To achieve homogeneity of the error rate variance, the mean error scores were transformed by means of an arcsine transformation. For target present trials, there was a main effect of the number of red items [$F(3,21)=25.1$; $p<.01$]. As is evident in Table II, subjects tend to make more response errors with increasing number of red elements. For target absent trials there was both an effect of the number of green and the number of red items [$F(3,21)=3.2$; $p<.05$] for green and [$F(3,21)=4.7$; $p<.01$ for red]. Overall, the effects on the error scores tend to mimic the effects on RT.

Table II Experiment 1: Mean Error Rates (%) for target present and absent trials for the random condition for each display size.

	target present				target absent			
number reds	1	2	4	8	1	2	4	8
1 green	0.4	4.3	6.2	13.9	4.8	3.8	2.4	5.7
2 greens	3.3	4.3	5.7	13.4	1.9	1.9	6.2	5.8
4 greens	3.3	4.3	7.2	19.7	2.8	5.2	7.2	8.2
8 greens	1.9	5.2	5.3	21.1	2.9	4.8	8.6	10.6

Traditional search functions

Traditionally in conjunction search there is always an equal number of different distractor types. In order to compare the present data with earlier studies, mean RTs were calculated for those conditions in which there was an equal number of different distractor types (equal number of red and green elements). When calculating the mean slopes, display size 2 (1 red and 1 green) was excluded from the analysis because, as noted above, the 1 red condition should be considered as an outlier. The slopes for the target present and absent trials in the grouped condition were 1.7 and 2.0 ms/element, respectively, suggesting preattentive parallel search across all elements. For the random condition, these figures were 9.2 ms/element and 8.1 ms/element, respectively, suggesting serial search through the display. Note that these traditional "serial" search functions are comparable to those obtained by Treisman (1991) in a similar task and have been interpreted as evidence for serial search through all items. It is clear for the present data that in the random condition this is not the case: subjects limited search to only the red items (see Kaptein et al., 1993, for a similar argument).

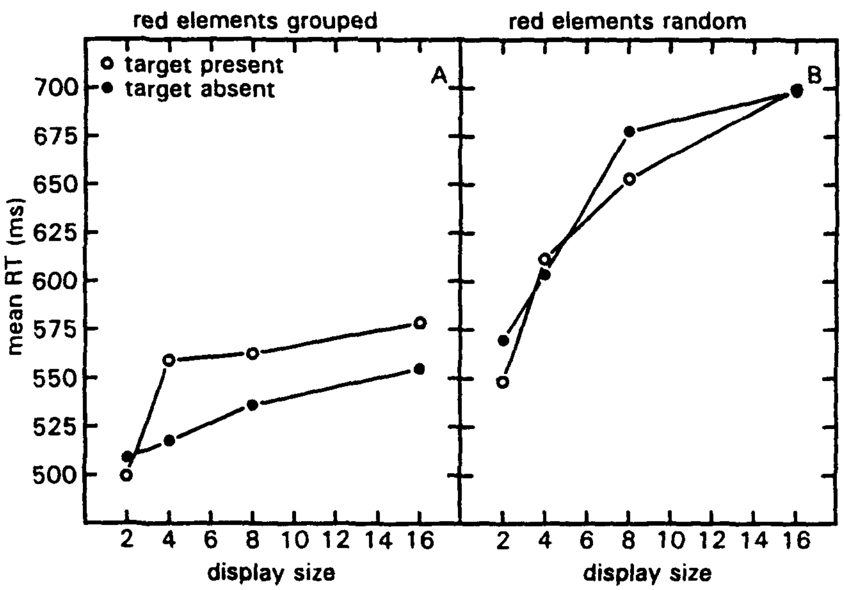

Fig. 6 Experiment 1, traditional search functions: Mean reaction time with equal number of red and green elements, as a function of display size for target present and absent trials in both the grouped and random condition.

2.3 Discussion

The present results indicate that parallel detection of a conjunction target is possible when the target is located within a group of homogenous elements. Except for the 1 red condition, search time for target present trials did neither increase with the number of green nor the number of red elements. Target absent trials were as fast as target present trials furnishing further evidence against serial processing (e.g., Pashler, 1987). The results are interpreted as evidence for sequential preattentive parallel processing: the first parallel stage detects the red elements between the green elements, followed by a second parallel stage in which the vertical red item is detected between the slightly tilted red elements. Focal attention directed to the target location allows to make a decision whether the target is present and will activate the response.

The relatively fast response to 1 red item suggests that this is a special case. Given the considerations above, it is plausible that the reaction time is short because only one preattentive parallel process (parsing the red from the green elements) is necessary in order to detect the target. In other words, one pop-out is enough to detect the target.

In the random condition, search time linearly increased with the number of red but not with the number of green items confirming the findings of Kaptein et al. (1993) suggesting that in case of conjunction search, subjects may limit their search to only the elements in the target color (see also Egeth et al., 1984). The present findings indicate that the results of Kaptein et al. (1993) do not stem from their use of circular displays.

3 EXPERIMENT 2

Pashler (1987) suggested that subjects can search in parallel up to 8 elements at a time. Between clumps of 8 items search was assumed to be serial. Experiment 1 of the present study used a maximum of 8 red elements, which matches Pashler's maximum that enables parallel search. Experiment 2 was designed to investigate whether the proposed parallel-to-parallel sequential processing is indeed limited to a maximum of 8 elements are suggested by Pashler. In Experiment 2 subjects searched displays up to 49 elements in which there were equal number of red and green nontarget elements. Again, the red elements were presented spatially grouped.

3.1 Method

Subjects

Eight subjects ranging in age between 17 and 26 years participated in the Experiment.

Apparatus

The apparatus was identical to Experiment 1. The display elements were either green or red (same CIE xy-chromaticity as in Experiment 1) and had a luminance of 9.2 cd/m^2.

Stimuli

The stimulus field consisted of 4, 8, 18, 32, or 49 elements. Half of these elements were red clockwise tilted line segments and the other half were vertical green line segments (in case of 49 elements 25 were red and 24 were green). In case a target was present, one of these red clockwise tilted elements was replaced by the vertical target line segment. The elements were presented on positions of a 7×7 array ($7.0° \times 7.0°$). Within this array the red elements always occupied adjacent positions forming a perfect square. Thus, in case of display size 49, the red elements were positioned in a 5×5 array, in case of display size 32 in a 4×4 array, in case of display size 18 in a 3×3 array; and in case of display size 8 in a 2×2 array. In case of display size 4 the red elements were located in a rectangle either 2×1 or 1×2. The target line segment could appear at any position within the red subset. The green elements were allocated randomly to the remaining empty locations of the 7×7 stimulus array.

Procedure

The task was identical to Experiment 1. Subjects performed two blocks of 300 trials in which there were equal numbers of trials in each of the 5 levels of display size (4, 8, 18, 32, 49) and equal number of target present/absent trials. Rests were allowed after every 75 trials when subjects received feedback about their performance (percentage errors and reaction time). Subjects received 300 practice trials.

3.2 **Results**

Response times longer than 1 s were counted as errors, which led to a loss of well under 1% of the trials. Mean RTs are shown in Fig. 7.

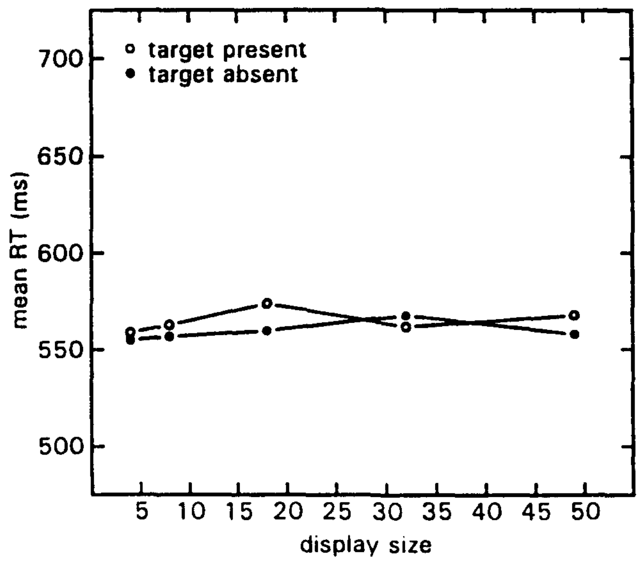

Fig. 7 Experiment 2: Mean reaction time as a function of display size for target present and absent trials.

The individual mean RTs were submitted to an ANOVA with display size and target present/absent as main factors. None of the effects were significant. As is evident in Fig. 7, search was independent of the number of elements in the display suggesting that the target element could be detected by preattentive parallel search. The mean search slopes were 0.60 ms/element for target present trials and 0.21 ms/element for target absent trials. Neither slope was significantly different from zero ($t(7)<.60$).

Error rates are shown in Table III. The mean overall error rate was 9.5%. An ANOVA with display size and target present/absent as factors showed a significant effect on the arcsine transformed error data on display size [$F(4,28)=10.7$; $p<.01$] and target present/absent [$F(1,7)=13.1$; $p<.01$]. Also the interaction between these variables was significant [$F(4,28)=8.5$; $p<.01$]. Subjects tend to make more errors when a target is present especially at large display sizes. This might suggest that in a number of cases at larger display sizes subjects do not see the target and respond "target not present" when in fact the target is present.

Table III Experiment 2: Mean Error Rates (%) for target present and absent trials.

display size	4	8	18	32	49
target present	3.9	5.2	10.6	16.4	17.7
target absent	6.7	5.6	5.0	5.8	10.2

3.3 Discussion

The results of this experiment are clear: parallel processing within groups is not limited to a maximum of 8 elements. The results suggest that there are hardly any limits to detect a conjunction target when it is located within a group of homogenous nontarget elements. The tendency of making more response errors at large display sizes in case a target is present might be indicative of some structural limitation: at large retinal eccentricities, the presence of a target may not be signalled by the fast and error-prone parallel stage because of lateral masking.

4 GENERAL DISCUSSION

The present findings have important implications for theories on visual selection. The results suggest that the first stage parses the field into a group of red and a group of green items, the attentional window is then allocated to the group of red elements, followed by a second parallel stage which enables a segmentation of a vertical element from slightly tilted elements. After this second segmentation, attention is allocated to the vertical target line segment. In other words, the first "global" parallel stage allows the rejection of the green elements, while the second "local" parallel stage allows the rejected of slightly tilted line segments within the subgroup of red elements. The results provide evidence for the notion that preattentive parallel search occurs within a variable size window (e.g., Theeuwes, 1992, in press a, in press b; Treisman & Gormican, 1988). The first window encompasses the whole visual field allowing preattentive segmentation within this window, followed by a zooming in of this attentional window to a smaller group allowing preattentive segmentation within this window (see also Theeuwes, in press b).

The results can be reconciled with the theory of Duncan & Humphreys (1989) which suggests that the first stage in visual processing consists of a resource-free parallel hierarchical segmentation and grouping process. It is assumed that an image is hierarchically segmented into linked groups and subgroups producing structural units. Parts that are described within the same whole are linked together. Each structural unit contained by its own boundary, is further subdivided into parts by the major boundaries within it. At the top of the hierarchy may be a structural unit corresponding to the whole scene. At the next level down, a new structural unit described with its own properties. Each structural unit is described within a set of elementary properties such as relative location, motion, color, surface texture, etc. As long as these units do not compete for access to the visual-short-term-store (VSTM) there are no capacity limitations.

In line with Duncan and Humphreys (1989), elements which are perceptually linked can be rejected together by a process which has been called *spreading* *suppression*. Because of "weight linkage" perceptually grouped nontargets do not have to compete independently for VSTM access. In the present experiment, the nontarget green elements are linked by similarity in color and the nontarget red elements are linked by similarity in orientation. In the random condition of Experiment 1, weight linkage in the color dimension is strong enough to obtain search times which are independent of the number of green elements. Search times linearly increased however with the number of red elements suggesting that linkage by orientation *within* the subgroup red elements was not possible. Grouping of the red elements as in Experiment 2 and the grouped condition of Experiment 1, enabled linkage by orientation within the group of red nontarget elements, giving search times which were independent of both the number of green and red elements. As noted above, it is assumed that this grouping with its subsequent spreading suppression occurs sequentially from a global (color) to local (orientation) level.

The present results are in line with the findings reported by Nakayama and Silverman (1986) who found parallel search functions for conjunctions consisting of combinations of different features (motion and color) involving stereoscopic depth (see also Steinman, 1987). Because subjects could direct their attention to particular plane in depth, a target defined by a conjunction of features becomes, within that particular plane, a target defined by a single primitive feature. Along similar lines McLeod et al. (1988) showed that search for a target defined by a conjunction of movement and form (e.g., an X moving up in a display of intermingled Os moving up and stationary Xs) could be performed in parallel. The results suggested that subjects can direct attention to particular planes of moving stimuli giving feature search within such a plane (see also McLeod, Diver, Dienes & Crisp, 1991). In the present study subjects could direct their attention to a particular group of items giving feature search within that group.

The observation that effortless sequential parallel rejection of nontarget elements can only occur when the red elements are spatially grouped suggests a special mechanism of a global-to-local allocation of spatial attention. Obviously, a pop-out of orientation among the subgroup of red elements is not possible when these elements are randomly distributed within the display. Although the data of the random condition indicate that perceptual grouping by color is strong enough to obtain search times independent of the number of green elements, focal attention has to be directed serially to each red element in turn to determine whether it is the target or not. Because it is impossible to direct the attentional window to only the red elements (in the random condition green elements are placed between the red elements), a second parallel segmentation process operating within this attentional window cannot occur. Spatial grouping seems to be a prerequisite for the second parallel process to occur. This notion is in line with Treisman & Sato (1990) who claim that if the attentional window encompasses examples of both distractor types then both target features will be passed on to the object level with the possible danger of illusory conjunctions.

To avoid the occurrence of illusory conjunctions the attentional window has to be reduced giving rise to serial search.

The presently adhered idea of sequential global-to-local parallel processing casts some doubt on the strict dichotomy between parallel and serial processing. It is likely that processing always occurs in parallel with an increasing finer attentional window until the target is found. Only when the attentional window encompasses a single element, this may be considered as serial processing in the traditional sense.

The present data indicate that the attentional window directed to the red items enabling the second parallel process, can be allocated in a flexible way. For example, in the grouped condition of Experiment 1, from trial to trial, the 8 red items could appear either in a 4 × 2 horizontal array or in a 2 × 4 vertical array. Search times for 8 red elements presented in horizontally or vertically oriented rectangles is as fast as the search time for 4 red elements presented in a square indicating that subjects had no difficulty directing the attentional window in either a horizontal or vertical way to encompass the horizontally of vertically defined subgroup of red elements.

The idea that subjects can direct attention flexibly to subgroups of items is in line with the "group scanning hypothesis" (Treisman & Gormican, 1988; Treisman & Sato, 1990)—the idea that subjects search through subgroups of items, checking items within groups in parallel. The present findings demonstrate the occurrence of feature search within subgroups of elements. Note that this explanation also can account for the relatively flat search functions found in various conjunction search tasks (e.g., Duncan & Humphreys, 1989; Kaptein et al., 1993; Wolfe, Cave & Franzel, 1989). In these tasks, search functions may vary between 5 to 20 ms/item suggesting serial to almost parallel search. If the visual field is parsed preattentively into different groups of items, and attention is serially directed to these separate groups of items within which feature search occurs, then search times are related to the number of preattentively grouped subset of items rather than to the actual number of items in the visual field. Therefore the search function obtained with conjunction targets probably never represent an item-by-item serial scan, but serial search between and parallel search within subgroups of elements.

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The present study shows that search for a conjunction of color and orientation can be performed in parallel when the target is embedded in a homogeneous colored subgroup of nontarget elements. The results provide evidence for the notion of sequential global-to-local parallel processing in which the first global stage allows the rejection of one subgroup of elements followed by a second local stage which rejects the local subgroup of elements. Experiment 1 shows that parallel search for a conjunction target can only occur when the elements are spatially grouped. Experiment 2 shows that parallel processing of a conjunction target is not limited to small display sizes but also occur in displays consisting of 49 elements. Implications of the present findings for current theories of visual search are discussed.

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