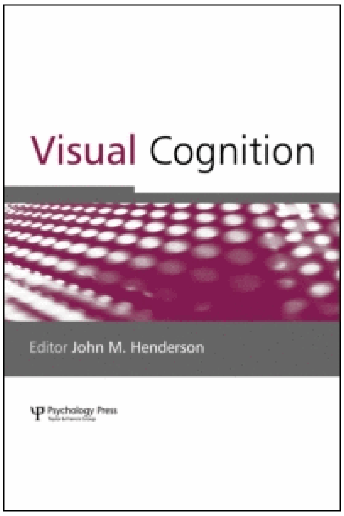

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Temporal and spatial Characteristics of preattentive and attentive processing

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Temporal and Spatial Characteristics of Preattentive and Attentive Processing

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In the present experiment, subjects searched multielement displays for a colour singleton. With a variable display-to-onset SOA, on some trials an abrupt onset was presented at three possible distances from the target location. The interference effect caused by the abrupt onset as a function of SOA and its relative position revealed the distinctive characteristics of preattentive and attentive processing. During preattentive parallel processing (processing occurring within the first 100 msec), any abrupt onset that occurred within the visual field captured attention. During attentive processing (processing occurring after 100 msec), however, focused attention prevented the abrupt onset from capturing attention. The finding that abrupt onsets interfere with selective search for a colour singleton provides additional evidence for the theory of inadequate top-down control at the level of preattentive processing.

Most current accounts of human vision suggest that there are two distinguishable and functionally distinct forms of visual information processing (e.g. Broadbent, 1958, 1982; Neisser, 1967; Treisman & Gelade, 1980). One form is typically characterized as being *preattentive*, which implies an unlimited-capacity system capable of spatial parallelism in information processing. The other form is termed *attentive* (focal) processing because it requires the allocation of attentional resources to a location in visual space. This latter system has a limited capacity and processes information serially.

It is generally assumed that in visual search these two processes operate sequentially: preattentive processes perform some basic analyses, segmenting the visual field into functional perceptual units, followed by the attentive

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stage, which deals with one item (or a few) at a time. The present study investigates the temporal and spatial characteristics of preattentive and attentive processing.

There is one prevalent difference between preattentive and attentive processing: preattentive processing is spatially parallel, operating simultaneously at various locations across the visual field (e.g. Posner & Snyder, 1975), whereas attentive processing operates on a limited spatial location (e.g. Treisman & Gelade, 1980).

In tasks in which subjects are instructed to attend to a limited spatial location indicated by a highly vaid cue there is a remarkable ability to process only elements appearing at that location, without interference of elements appearing at "nonattended" locations (e.g. Kahneman & Treisman, 1984; Yantis & Johnston, 1990). Attention is thought to operate like a spatial filter, assuming that inside the focus of attention everything is attended to, and outside the focus everything is unattended to (Yantis & Johnston, 1990). This has led to the conceptualization of visual attention as something like a spotlight (e.g. Broadbent, 1982; Posner, 1980), or a zoom lens (e.g. Eriksen &Yeh, 1985).

Yantis and Jonides (1990) and Theeuewes (1991b) showed the ability of spatial attention to filter out irrelevant singletons. When search was eliminated by advance cueing with absolute certainty of the spatial location of the impending target, onset and offset singletons elsewhere in the visual field did not affect performance. It was concluded that abrupt onsets and offsets ceased to capture attention because focusing of attention on a particular location blocks out information from elsewhere in the visual field.

In visual search tasks in which the target can appear at any location within the visual field, rather than endogenously focusing attention on a particular location, subjects may divide attention over the visual field in order to attend to all elements simultaneously. Typically, when the target is defined by some primitive feature such as colour, shape, or brightness, it can be detected equally fast, irrespective of the number of elements in the display (e.g. Egeth, Jonides, & Wall, 1972; Treisman & Gelade, 1980). This finding suggests that the complete display is encoded in parallel along a set of primitive features at the early preattentive stage of processing.

As recognized by Kahneman and Treisman (1984), tasks in which multiple elements are processed simultaneously typically show the *un*successful attempt of subjects to resist distraction. Feature registration at the preattentive stage is thought to occur automatically (Treisman & Schmidt, 1982). In other words, if search is performed in parallel, then it is impossible to resist distraction of irrelevant singletons. Theeuwes (1991a, 1992, 1994a) demonstrated both effects: in visual search tasks, the time to detect a featural singleton (i.e. search for a red item among green nontarget items) did not depend on display size, suggesting preattentive parallel search. Yet, under these circumstances subjects did not have the ability to resist distraction: An irrelevant featural singleton in a different dimension than the relevant one disrupted performance.

Theeuwes (1991a, 1992, 1994a, 1994b) concluded that in tasks in which subjects endogenously divide their attention in order to detect a featural singleton in parallel, they no longer have the ability to control what elements are selected for further processing. In other words, the ability to process several elements simultaneously has the consequence that top-down selectivity is lost (see also Theeuwes, 1993). These findings have led to the conjective that when searching for a featural singleton, there is no top-down control at the level of preattentive processing. Attention is assumed to be captured automatically and involuntarily by the most salient singleton, irrespective of what subjects are looking for (for an extensive review, see Theeuwes, 1994b). Note, however, that recent evidence (Bacon & Egeth, 1994) indicates that in conditions in which subjects do not search for a "popping-out" singleton but for a particular feature on a given dimension (the so called "feature search" mode), search can be guided by top-down information.

In the studies reviewed in the preceding paragraphs, subjects either endogenously focused attention on a particular limited spatial location before display onset, or they divided their attention over the visual field in order to process several elements simultaneously. The present study explores the hypothesis that these two types of selection normally occurring in focused and divided attention tasks take place sequentially in visual search for a feature singleton. If this hypothesis holds, then it is expected that processing during the early preattentive parallel stage will show the typical characteristics occurring during divided attention tasks, whereas processing during the attentive stage will show the typical characteristics occurring during focused attention tasks. If this is the case, then it can be inferred that the endogenous allocation of attention to a particular location occurring in typical focused attention tasks is comparable to attentive processing following preattentive segmentation occurring in a typical visual search task (see also Briand & Klein, 1987; Theeuwes, 1993).

It is hypothesized that in visual search for feature singletons, the two sequential processes (i.e. preattentive parallel processing and attentive serial processing) have the properties of *divided* and *focused* attention, respectively. Preattentive processing should show the ability to process multiple stimuli at the same time—that is, the featural singleton should be detected irrespective of the number of elements in the display. Because at this stage, processing occurs in parallel (divided attention), top-down selectivity is not possible, suggesting that an irrelevant featural singleton should disrupt search for the relevant target singleton.

It is presumed that stimuli entering the second stage of attentive processing are selected for further processing. The basis of selection is thought to be spatial—that is, during the second stage of attentive processing attention is spatially allocated to the location of a featural singleton. Consequently, because attention is now focused on a location, the attentional system should show the properties of a filtering mechanism. Stimuli well outside the focus of attention should not affect performance. If this filtering operates spatially, then it is expected that the efficiency of filtering depends on the distance between target and interfering stimulus (Yantis & Johnston, 1990).

The task used in the present study was similar to the one used by Theeuwes (1994a). Subjects had to search for a colour singleton embedded among 2 or 5 non-target items in the visual field (a grey circle embedded among red circles). On some trials another location contained an irrelevant onset (i.e. a red circle presented with abrupt onset). The distance between the grey target circle and the irrelevant abrupt onset was systematically varied. In addition, the interval between search display and irrelevant abrupt onset was systematically varied (display-to-onset Stimulus Onset Asynchrony of 0, 50, 100, and 150 msec).

Theeuwes (in press a) showed that in a similar task selective search for a colour singleton was disrupted when an irrelevant abrupt onset was presented simultaneously with the colour target singleton. Those results provided evidence that salient abrupt onsets will capture attention irrespective of the attentional set of the observer. The present experiment uses the disruption of performance caused by the abrupt onset as a tool to assess the characteristics of preattentive and attentive processing.

If preattentive and attentive serial processing have the properties of *divided* and *focused* attention, several results are expected. (a) If the abrupt onset is presented during preattentive processing, then it is expected that the interference caused by the onset is independent of the distance between target and onset. Because attention is divided over the visual field, onsets from any location within the attended area will attract attention. (b) If the abrupt onset is presented during attentive processing, then it is expected that onsets close to the location of the target singleton will disrupt performance, whereas onsets further from the target location will no longer affect performance. This latter result is expected given the conjecture that the second stage of attentive processing entails the allocation of attention to the location of the featural singleton. Stimuli close to the focus of attention will interfere, but stimuli away from the focus of attention will not affect performance. As it is unclear how long preattentive processing takes, the exact time course of the predicted effects is unclear. The only plausible hypothesis that can be inferred is that at 0-msec SOA preattentive processing is in operation, and at 150-msec SOA attentive processing is (most probably) in operation.

Method

Subjects

Eight right-handed subjects, ranging in age from 18 to 28 years, participated as paid volunteers. All had normal or corrected-to-normal vision and reported having no colour-vision defects.

Apparatus and Stimuli

A NEC Multisync 3D VGA colour CRT (resolution 640 × 350) controlled by a SX-386 Personal Computer (G2) was used for presenting the stimuli. The computer using the 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, with the head resting on a chinrest. The CRT was located at eye level, 115 cm from the chinrest.

The display elements consisted of grey (CIE *x/y* chromaticity coordinates of 0.283/0.341) or red (coordinates of 0.408/0.397) outline circles, which were matched for luminance (10.1 cd/m^2). The fixation cross and the line segments were presented in white (31.0 cd/m^2) on a black background (0.5 cd/m^2). The colorimetric and photometric measurements were carried out by means of a spectro-radiometer (Photo Research, type: PR 703 A/M). The detector head of this device was directed towards colour patches displayed at the centre of the computer screen.

Procedure

The task was similar to that in Theeuwes (1991b, 1992), consisting of a visual search task in which there is a clear separation between the defining and reported attribute of the target. Subjects responded to the orientation (horizontal or vertical) of a line segment appearing inside a grey circle embedded among red circles. Because subjects responded to the orientation of a target line segment located among slightly tilted non-target line segments, the task required focal attention (Theeuwes, 1991b; Treisman & Gormican, 1988) but not a high spatial acuity. The onset stimuli were constructed similar to Theeuwes (1994a), in which onset stimuli were presented in previously blank locations, and no-onset stimuli were camouflaged by premasks.

The trial events are shown in Figure 1. At the beginning of a trial a central dot appeared, upon which subjects remained fixated throughout a trial. After 700 msec, a premask was presented consisting of 3 or 6 grey outline circles (1.2° in diameter), which were equally spaced around the fixation point on an imaginary circle whose radius was 3.4°. The 6 circles formed a hexagon; the 3 circles formed either an upward-pointing or a downward-pointing equilateral triangle. Each circle contained 6 line segments (0.5°): one vertical, one horizontal, and four tilted 20° to either side of the horizontal and vertical plane. After a 1000-msec premask the stimulus field was presented. At the end of the 1000-msec premask period, 5 of the 6 line segments in each of the circles were extinguished, revealing line segments that were tilted 20° to either side of the horizontal or vertical plane. The orientations were randomly distributed in a display. In one of the circles, the extinguished line segments revealed a line

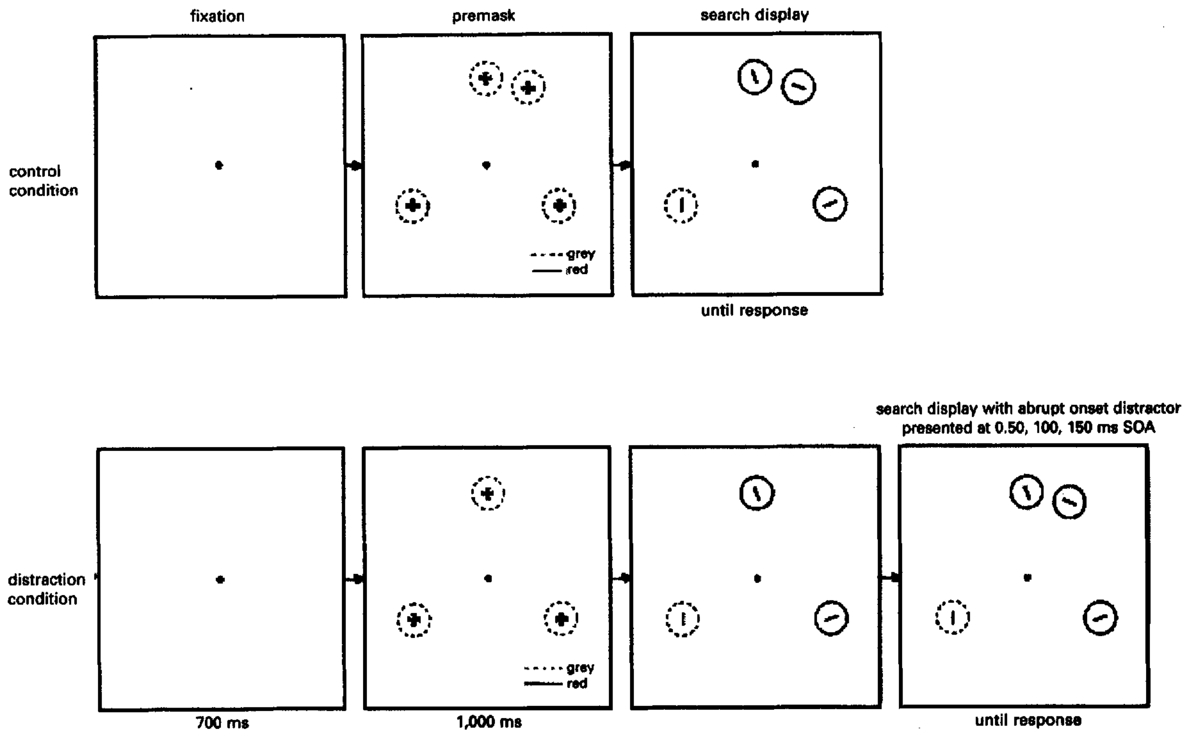

FIG. 1. Trial events in which subjects search for a uniquely coloured grey circle in the control (panel above) and distractor condition (panel below). In this example, the distractor is an irrelevant circle presented with abrupt onset at 7.1° of visual angle (150 degrees of arc) from the grey target circle. The abrupt onset is presented with variable display-to-onset SOAs; the target line segment is vertical and located in the uniquely coloured grey circle. In the control condition, the irrelevant circle is already present during the presentation of the premask.

segment oriented either horizontally or vertically; the orientation determined the appropriate response key (the"/"-key for vertical and the "z"-key for horizontal). At the end of the 1000-msec premask period, the colour of all circles except the circle containing the target line segment changed into a nominally equiluminant red (i.e. we did not measure the point of equiluminance for each subject individually). The one circle that remained grey contained the horizontal or vertical target line segment. In the distractor condition, at the end of the 1000-msec premask period, a circle of the same red colour as the other non-target circles was presented at one of the 6 previously blank locations of the 3.4° imaginary circle. In the control condition, in which no circle with abrupt onset was presented, an additional non-target circle was presented, along with the premask, at one of the blank locations at the beginning of the premask period. The stimulus field remained present for a maximum of 2 sec until a response was emitted.

Subjects received two conditions: (a) a control condition in which the grey circle containing the target line segment was presented with 3 or 6 red circles, and (b) a distractor condition in which one of the 3 or 6 red circles had abrupt onset. These abrupt onsets were presented with four possible display-to-onset SOAs: 0, 50, 100, or 150 msec, which were varied within blocks of trials. The abrupt onset in the distractor condition and the additional circle in the control condition were presented at 3 possible distances from the great target circle. On the imaginary circle with the fixation dot as its centre, the abrupt onset was presented next to the target describing an angle between target and distractor of 30 degrees of arc, somewhat further away from the target describing an angle of 90 degrees of arc, or presented almost opposite the target describing an angle of 150 degrees of arc (as in Fig. 1). In euclidian distances, these figures correspond to 2.0°, 5.0°, and 7.1° of visual angle, respectively. This factor was varied within blocks of trials. As will be clear, when searching for a uniquely coloured grey circle, the distracting element was a red circle with abrupt onset, which was presented simultaneously (at SOA 0 msec) or slightly later than the search display (at 50-, 100-, or 150-msec SOA). The grey target circle was presented equally often at each location. The location was randomized from trial to trial. It always replaced one of the circles from the premask display. The position of the onset circle was also randomized, but it was presented equally often at one of the six blank locations.

There were three blocks of 288 trials in the distractor condition and one block of 288 trials in the control condition. Each subject performed both distractor and control conditions. Half of the subjects started with the distractor condition, the other half with the control condition. The practice session consisted of 72 distractor and 72 control trials. Display size (4,7) was randomized within blocks. In the distractor condition subjects performed 864 trials—that is, a total of 36 trials in each display size (4,7), distance (30, 90, and 150 degrees of arc, corresponding to 2.0°, 5.0°, and 7.1°) and SOA (0, 50, 100, and 150 msec) condition.

In the control condition, subjects performed a total of 288 trials—that is, a total of 48 trials in each display size (4,7) and distance (30, 90, and 150 degrees of arc, corresponding to 2.0°, 5.0°, 7.1°) condition.

Each block of trials lasted approximately 20 min, followed by a 20-min break. Within each block, there were short breaks after 72 trials in which subjects received feedback about their performance (percentages of errors and mean reaction time) on the preceding trials. Prior to the start of the experiment subjects were instructed to search for the horizontal or vertical target line segment and to press the appropriate response key ("/" or "z") with the index finger that was resting on it. Before each session, the subjects were informed about the relationship between the location of the target line segment and the unique display element. They were told that the target line segment was always located in the uniquely coloured grey circle. They were instructed to use this information. It was emphasized that subjects should fixate the central dot and not move their eyes during the course of any trial. It was stressed that a steady fixation would reduce reaction time (RT) and make the task easier. Both speed and accuracy were emphasized. A warning beep informed subjects that an error had been committed. If no response was made after 2 sec, subjects were informed that they had committed an error.

Results

Response times longer than 1 sec were counted as errors, which led to a loss of about 1.9% of the trials. The data of control and distractor conditions were subjected to separate ANOVAs. The distractor condition, using distance (2.0°, 5.0°, 7.1°), display size (4,7), and SOA (0, 50, 100, 150 msec) as factors showed main effects on RT for distance, display size, and SOA: $F(2, 14) = 35.2$, $p < 0.01$, for distance; $F(1, 7) = 23.0$, $p < 0.01$, for display size; and $F(3, 21) = 18.5$, $p < 0.01$ for SOA. The Distance × SOA interaction was also significant, $F(6, 42) = 4.9$, $p < 0.01$. The control condition using distance (2.0°, 5.0°, 7.1°) and display size (4,7) as factors, showed main effects on RT for both distance and display size: $F(2, 14) = 8.5$, $p < 0.01$, for distance; and $F(1, 7) = 69.1$, $p < 0.01$, for display size. Planned comparisons show that, in the control condition, the presence of an item close to the target item (i.e. at 2.0°) gives reliably longer RTs than when this item is located at a position further away from the target item: that is, for 5.0°, $F(1, 7) = 10.3$, $p < 0.05$, and for 7.1°, $F(1, 7) = 10.0$, $p < 0.05$, respectively. There is no difference between these latter RTs. Figure 2 gives the mean RTs for distractor and control conditions collapsed over display size.

For each distance, the distracting effect of the onset for each SOA was calculated relative to its own control (see Table 1). The results of subsequent planned comparisons are indicated in Table 1.

As is clear from Table 1, relative to the control condition, for each distance at 0-msec SOA there is a reliable distracting effect. In addition, at 0-msec SOA the

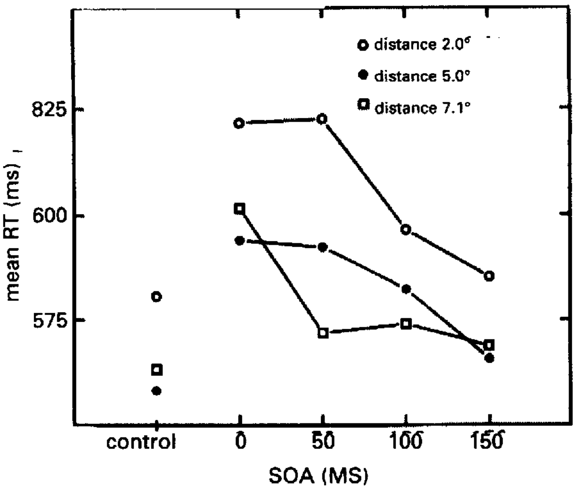

FIG. 2. Mean reaction time for search for a colour singleton as a function of display-to-onset distractor SOA for the different distances (2.0°, 5.0°, 7.1°) between the target colour singleton and the onset distractor.

distracting effect caused by the onset is the same for all distances between target and distractor, $F(2, 14) = 0.21$. At 50-msec SOA, the onset 7.1° from the target item no longer causes any interference. Onsets at 2° and 5° from the target item still give a reliable distracting effect. There is no difference in distracting effect between an onset at 2° and 5°, $F(1, 7) = 0.93$. At SOAs of 100 msec and 150 msec there is no longer a reliable effect of the onsetting item.

TABLE 1
Distracting Effect Calculated Relative to Control Condition for Each Distance between Target Item and Distractor (in Visual Angle) as a Function of Abrupt-onset SOA

	SOA			
Distance	*0*	*50*	*100*	*150*
2.0°	41**	43*	16	6
5.0°	36*	34*	25	8
7.1°	39**	9	11	6

* $p < 0.05$
** $p < 0.01$
Note: Asterisks indicate effects that differ significantly from the control condition.

TABLE 2
Error Rates for Each Distance (in Visual Angle) between Target Item and Distractor for Control and Diastractor Conditions for Each SOA

		SOA			
Distance	*Control*	*0*	*50*	*100*	*150*
2.0°	5.5	8.9	6.6	6.1	5.4
5.0°	3.8	5.7	7.5	5.6	3.3
7.1°	2.9	5.0	6.6	5.2	4.7

Note: Error rates are given in percentages.

Error rates are shown in Table 2. Overall, the error rate was 5.9% for the distractor condition and 4.0% for the control condition. In order to achieve homogeneity of the error-rate variance, the mean error rates per cell were transformed by means of an arcsine transformation. The same planned comparison as performed on the RT data shows that relative to the distractor condition at 0-msec SOA and 50-msec SOA significantly fewer errors were made in the control condition when the distractor was located 7.1° from the target: for 0-msec SOA, $F(1, 7) = 8.8$, $p < 0.05$, and for 50-msec SOA, $F(1, 7) = 27.6$, $p < 0.05$, respectively. In addition, relative to the distractor condition, at 50-msec SOA significantly fewer errors were made in the control condition when the distractor was located 5° from the target, $F(1, 7) = 6.2$; $p < 0.05$. As this analysis indicates that error differences are non-significant or tend to mimic RT, differences in response times cannot be attributed to a speed-accuracy trade-off.

In order to check whether parallel search across all items occurred, the RTs collapsed over distance and SOA were submitted to a linear regression analysis. The mean slopes for the distractor and control condition were 8.5 and 8.6 msec/item, respectively. Both slopes were small (less than 10 msec/item) and in the range generally assumed to reflect parallel processing (Treisman & Gormican, 1988).

DISCUSSION

The present experiment provides independent evidence for the notion that visual information processing consists of two functionally independent processes: an early pre-attentive parallel process segmenting the visual field into basic units, followed by an attentive process involving focal attention that operates on one item (or a few) at a time. The interference effect caused by the abrupt onset as a function of SOA and its relative position reveals the distinctive characteristics of these two processes (see Table 1). At 0-msec SOA, attention is spread over the visual field in order to allow the parallel detection of the colour singleton. In this mode of parallel processing, any abrupt onset occurring within the attended field captures attention automatically and unintentionally, causing an inference effect that does not depend on the position of the abrupt onset relative to the target position. It is assumed that attention is then switched to the target location in order to respond to the line segment located in the colour singleton. In line with earlier research (i.e. Kwak, Dagenbach & Egeth, 1991; Sagi & Julesz, 1985), it is assumed that shifting attention from the location of the abrupt onset to the location of the target occurs time-independently, suggesting that attention can index locations in the visual field independent of the distance between these locations (Eriksen & Webb, 1989).

At 50-msec SOA it is likely that focal attention has started to zoom in at the location of the colour singleton. Because attention is not yet closely focused on the location of the colour singleton, abrupt onsets presented relatively close to the singleton (distances of 2° and 5°) fall within the attended area and can therefore cause interference. The abrupt onset farthest away from the singleton (at 7.1°) no longer affects performance because it falls outside the attended area.

At 100-msec and 150-msec SOA it is assumed that attention is fully and closely focused on the location of the singleton, preventing attentional capture by onsets outside the attended area. This suggests that the process involving the parallel segmentation of the visual field and the subsequent zooming-in on the location of the colour singleton takes somewhere between 50 msec and 100 msec.

The observed pattern of results provides evidence for the assumption that preattentive and attentive processing have the characteristics of divided and focused attention, respectively. In order to allow the preattentive and parallel detection of the featural singleton, attention has to be spread over the visual field (unfocused attention) at the expense of losing selectivity within that area. Irrespective of the attentional set of the observer (i.e. subjects were looking for a colour singleton), the abrupt onsets captured attention and disrupted search for the task-relevant singleton—results confirming earlier findings (Theeuwes, 1991a, 1992, 1994a). At the second stage of processing, attention, in its focused mode encompassing the colour singleton, operates like a spatial filter, blocking out all information outside the attended (spotlight) of attention.

The idea that focusing attention can operate as a spatial filter is supported by cueing studies showing that when subjects endogenously focus their attention on a cued location, irrelevant abrupt onsets and offsets presented elsewhere in the visual field no longer capture attention (Yantis & Jonides, 1990; Theeuwes, 1991b). This interpretation suggests that attentive processing occurring during visual search is equivalent to directing spatial attention as in location-cueing experiments (see also Theeuwes, 1994b).

The present study confirms earlier theories (Theeuwes, 1991a, 1992, 1994a, 1994b) that suggested that top-down selection can only operate *spatially*—that is, the only strategic control over visual selection is through varying the span of spatial attention in the visual field. If attention is spread out over the visual field (the divided attention mode), it is possible to process multiple stimuli at the expense of losing selectivity within that area. If attention is focused on a restricted area (the focused attention mode), processing has to occur serially; yet it is then possible to filter out stimuli located outside the attended area.

The present study replicates findings of an earlier study (Theeuwes, 1994a), which showed that search for a colour singleton was disputed when an irrelevant onset was presented simultaneously (the present 0-msec SOA condition) with the colour target singleton. Theeuwes' previous study (in press a) tested the contingent capture hypothesis, which claimed that the occurrence of attentional capture is contingent on the attentional control setting induced by the task demands (Folk, Remington, & Johnston, 1992). In Folk et al.'s experiments, subjects had to ignore cues immediately prior to the presentation of the target display. It was demonstrated that an onset singleton serving as a cue did not capture attention when observers adopted an additional set for colour singleton targets. On the other hand, when observers were set to identify a colour singleton with a colour singleton serving as a cue, the time to identify the colour singleton increased, suggesting that subjects could not ignore another colour singleton (the cue) known to be irrelevant. Folk et al. (1992) claim that these findings suggest that capture of attention was contingent on top-down control settings. Theeuwes (in press a) and the present study show that the contingent capture hypothesis does not hold: independent of the attentional set of the observer (i.e. subjects searched for a unique colour singleton), attention was captured by the irrelevant onset distractor. Note that the present study indicates that attention can be shifted rapidly between distractor and target locations when these locations contain elements consisting of different stimulus dimensions (i.e. colour and abrupt onset). As noted earlier (Theeuwes, in press a), rather than showing that attentional capture is contingent on internal control setting, Folk et al.'s (1992) study might reveal difficulties in the disengaging of attention from the cue location to the target location when target and distractor share the same target-defining property (i.e. searching for a unique colour with a cue that also contains a unique colour).

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