TNO Institute for Human Factors IZF

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J. Theeuwes

PERCEPTUAL SELECTIVITY FOR COLOR AND FORM: ON THE NATURE OF THE INTERFERENCE EFFECT

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J. Theeuwes

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Dr. ing. J. Theeuwes
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TNO Technische Menskunde[1], Soesterberg

MANAGEMENT UITTREKSEL

Uit vorig onderzoek is gebleken dat het zoeken naar een unieke vorm verstoord wordt de aanwezigheid van een unieke kleur (Theeuwes, 1991b, 1992). Deze resultaten suggereerden dat de aandacht van de waarnemer automatisch getrokken wordt naar de plaats van het object met de grootste opvallendheid. Volgens deze hypothese wordt door middel van pre-attentieve parallelle verwerking lokale verschillen in features berekend. De identificatie van deze features vindt plaats door het serieel richten van focale aandacht naar de plaatsen waar de grootste lokale feature verschillen gedetecteerd zijn. Deze hypothese werd getest door middel van twee visuele zoekexperimenten waarbij proefpersonen zochten in multi-element displays naar een groen vierkant. Proefpersonen dienden de letter die in het vierkant verscheen te rapporteren. Wanneer de letter "R" in het vierkant verscheen dienden proefpersonen de rechter knop in te drukken; wanneer de letter "L" verscheen dienden proefpersonen de linker knop in te drukken. Tijdens een aantal aanbiedingen werd naast het target vierkant ook een rode distractor cirkel gepresenteerd. In deze cirkel was een letter gepresenteerd die of compatibel of incompatibel was met de letter in het target vierkant. De resultaten laten zien dat het reageren op de letter in het target vierkant beïnvloed werd door de identiteit van de letter in de rode distractor cirkel. Dit resultaat kan alleen verklaard worden wanneer er vanuit gegaan wordt dat de rode distractor cirkel de aandacht van de waarnemer automatisch en ongewild naar zich toe trekt. De resultaten geven evidentie voor de hypothese dat, ongeacht de intenties van de waarnemer, selectiviteit afhangt van de opvallendheid van de objecten in het visuele veld.

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[1] Per 1 februari 1994 is de naam Instituut voor Zintuigfysiologie TNO gewijzigd in TNO Technische Menskunde.

CONTENTS

Report No.: TNO-TM 1994 B-11

Title: Perceptual selectivity for color and form: on the nature of the interference effect

Author: Dr. Ing. J. Theeuwes

Instiiuie: TNO Human Factors Research Institute
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SUMMARY

Previous research has shown that search for a shape singleton is disrupted by the presence of an irrelevant color singleton (Theeuwes, 1991b, 1992). These findings have been treated as evidence for the hypothesis that, irrespective of a goal-directed attentional set on part of the observer, attention is unintentionally captured by the most salient singleton. This hypothesis was tested in two experiments in which subjects searched multi-element displays for a shape singleton. Subjects reported the letter that always appeared inside the target shape singleton (a green diamond). On some trials an irrelevant color singleton was present which contained a letter that was compatible or incompatible with the letter inside the target shape. As reported earlier, the presence of an irrelevant color singleton distracted goal-directed search for the shape singleton. The finding that the identity of the letter inside the distractor affected responding to the letter inside the target shape, provides support for the hypothesis that attention is captured by the most salient singleton. The identity of the letter inside the distractor can only affect responding when it is assumed that attention is involuntarily drawn to the location of the distracting singleton.

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TNO Technische Menskunde[1]
Soesterberg

Selectief zoeken naar kleur en vorm: een nadere analyse van het interferentie effect

J. Theeuwes

SAMENVATTING

Uit vorig onderzoek is gebleken dat het zoeken naar een unieke vorm verstoord wordt de aanwezigheid van een unieke kleur (Theeuwes, 1991b, 1992). Deze resultaten suggereerden dat de aandacht van de waarnemer automatisch getrokken wordt naar de plaats van het object met de grootste opvallendheid. Deze hypothese werd getest door middel van twee visuele zoekexperimenten waarbij proefpersonen zochten in multi-element displays naar een groen vierkant. Proefpersonen dienden de letter die in het vierkant verscheen te rapporteren. Tijdens een aantal aanbiedingen werd naast het target vierkant ook een rode distractor cirkel gepresenteerd. In deze cirkel was een letter gepresenteerd die of compatibel of incompatibel was met de letter in het target vierkant. De resultaten laten zien dat het reageren op de letter in het target vierkant beïnvloed werd door de identiteit van de letter in de rode distractor cirkel. Dit resultaat kan alleen verklaard worden wanneer er vanuit gegaan wordt dat de rode distractor cirkel de aandacht van de waarnemer automatisch en ongewild naar zich toe trekt.

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1 INTRODUCTION

Among the most fundamental issues of visual attention research is the extent to which visual selection is controlled by properties of the stimulus or by the intentions, goals and beliefs of the observer (see e.g., Theeuwes, in press a; Yantis, 1993). Before selective attention operates, preattentive processes perform some basic analyses segmenting the visual field into functional perceptual units. The crucial question is whether the allocation of attention to these perceptual units is under the goal-directed control of the observer (intentions, goals, beliefs) or under stimulus-driven control of stimulation. Goal-directed or endogenous control is referred to as top-down selection and is said to occur when the observer intentionally selects only those objects required to perform the task at hand. Stimulus-driven or exogenous control is referred to as bottom-up selection and is said to occur when attention is captured by the properties of the stimulus, irrespective of the intentions or goals of the observer.

Visual selection is thought to be involved when simultaneous sources of information compete for *selection*. Selective attention controls which perceptual units embedded in an array of other units are selected for further processing. Selection determines which perceptual unit is processed first, second, third, etc. A unit is thought to be selected, if spatial attention is endogenously directed to, or exogenously captured by, such a perceptual unit (Broadbent, 1958, 1982).

Clear evidence for top-down control is provided by Posner (1980; Posner, Snyder & Davidson, 1980), in tasks in which a central cue (e.g., an arrowhead) indicates the likely target location. Spatially valid cues typically result in benefits (shorter latencies) and spatially invalid cues result in costs (longer latencies) indicating that subjects are capable of endogenously directing spatial attention to a limited spatial location. These findings led to the conceptualization of visual attention as something like a spotlight (e.g., Posner, 1980; Eriksen & Yeh, 1985), which can move serially through visual space encompassing a small limited region at a time. The notion that attention can endogenously be directed to a spatial location is relatively undisputed and confirmed by various studies using various paradigms (e.g., Bashinski & Bacharach, 1980; Jonides, 1981; Theeuwes, 1989, 1991a; Yantis & Jonides, 1990; Van der Heijden, Wolters, Groep & Hagenaar, 1987).

In all studies showing endogenous control of attention, in anticipation of the target event, subjects focus their attention on a particular limited spatial region. Because spatial attention is directed to the location of the impending target, it has been claimed that *visual selection*—controlling which object embedded in an array of other objects is selected for further processing—takes place *before* the search display comes on (e.g., Theeuwes, in press a, in press b). Because the cuing procedure eliminates spatial uncertainty and therefore search, it is not necessary to select a target object among other objects. Consequently, it is not necessary to divide attention over the visual field implying that the preattentive parallel segmentation stage that breaks up the visual field into functional units *does not occur*. Note that focussing of attention before display onset results in a serial attentional deployment of the visual field (i.e., serial search).

Recently, a considerable debate has erupted regarding the extent to which attention can be endogenously directed to non-spatial stimulus features available at the early preattentive level such as such as color, shape, brightness, size, etc (e.g., Bacon & Egeth, in press; Duncan & Humphreys, 1989; Folk, Remington & Johnston, 1992, 1993; Theeuwes, 1991b, 1992, 1993, in press a, in press b; Yantis, 1993; Wolfe, Cave & Franzel, 1989). The crucial question is whether it is possible to exert top-down control over the preattentive stage so that only those objects having task-relevant stimulus features are selected.

In a series of studies, Theeuwes (1991b, 1992, in press b, in press c) accomplished to pit goal-directed selection against stimulus-driven selection in a search task in which a singleton target could appear at any location in the visual field. Rather than focusing attention onto a restricted area, subjects were required to divide attention over the visual field and select only the object necessary to perform the task. Typically, in singleton search tasks (i.e., the defining attribute of the target is a featural singleton) time to detect the target is independent of the number of elements in the display (e.g., Egeth, Jonides & Wall, 1972; Treisman & Gelade, 1980), suggesting that the complete display is encoded in parallel along a set of primitive features at the early preattentive stage of processing. The singleton target is said to "pop-out" of the display without effort on part of the observer.

In these type of singleton search tasks, Theeuwes (1991b, 1992) showed that even when observers adopt a clear top-down attentional set to search for a singleton (i.e., the defining attribute of the target was a featural singleton), performance was disrupted by an irrelevant featural singleton in a different dimension as the relevant singleton. These experiments showed that top-down selection of a particular known-to-be-relevant singleton cannot override bottom-up interference from a known-to-be-irrelevant distractor singleton. For example, in Theeuwes (1992), observers had an attentional set for a shape singleton because they searched for a green circle among green diamonds. When on some trials, an irrelevant color singleton was present (i.e., one of the diamonds was red) response latencies to find the target singleton increased. Even though observers had a clear attentional set to attend to a particular shape singleton (a green circle), the presence of an irrelevant singleton caused interference. It was shown that selectivity depended solely on the relative saliency of the stimulus attributes: when the shape singleton was more salient than the color singleton (yellowish red v. yellowish green), the shape singleton interfered with search for the color singleton, and vice versa. It was concluded that in singleton search tasks in which a preattentive segmentation process is used to detect the target, top-down control cannot override the stimulus-driven capture that arises due to the appearance of a more salient stimulus attribute. Theeuwes (1991b, 1992) claimed that in visual tasks in which the defining attribute is a singleton, selection occurs in a purely stimulus-driven fashion.

Recently Bacon & Egeth (in press) showed that this type of stimulus-driven selection only occurs in *singleton* search in which subjects have the opportunity to look for the odd-man-out (referred to a the "singleton search mode"). When subjects have to search for a specific shape (e.g., search for a green circle between green diamonds *and* green triangles) the distracting effect of the singleton disappeared suggesting that when a so called "feature search mode" is applied, top-down control at the early preattentive stage seems possible. Note however that in Theeuwes (1992, in press b) subjects had the opportunity to apply this feature search mode since they knew the exact shape and color of the singleton they were looking for. If the "feature search mode" as suggested by Bacon & Egeth (in press) is viable then for some reason, subjects did not apply this strategy in Theeuwes' (1992, in press b) studies although it would have been beneficial because it would have attenuated the distraction effect.

Although alternative hypotheses are viable in conditions in which the target is not a singleton as in Bacon & Egeth (in press), the basic finding that goal-directed selection towards a particular known singleton cannot override the stimulus-driven attraction caused by an irrelevant singleton has been confirmed by various studies (Theeuwes, 1991b, 1992, in press b; Bacon & Egeth, in press, Experiment 1; Pashler, 1988, Experiment 6). In order to understand the mechanisms underlying goal-directed vs stimulus-driven selection it is important to consider the basis for this interference.

On the one hand, Theeuwes (1991b, 1992, 1993, in press b) has claimed that the interference effect in singleton search is due to involuntary *capture of attention* by the irrelevant singleton. Since Theeuwes (1991b, 1992, in press b) showed that selectivity completely depended on the relative saliency of target and distractor singleton, he suggested that attention is always first captured by the most salient singleton irrespective of whether the "popping-out" singleton is a target or a distractor. According to this notion, the presence of the irrelevant singleton causes *spatial distraction*, in the sense that irrespective of what subjects are looking for (i.e., irrespective of any top-down control), spatial attention is automatically and involuntary captured by the most salient singleton. If this singleton is the target, a response is given. If it is not the target, attention is automatically switched to the next salient singleton. It has been suggested that the preattentive process simply calculates differences in features within dimensions and the most salient singleton gets focal attention first. The source of the pre-attentively calculated difference signal (whether it is caused by a color singleton or a form singleton) can only be recognized after attention has moved to the location of the difference signal. In other words, the subject only knows whether the singleton was the target after selecting the location having the large difference signal. Obviously, given this account, the interference effect is due to the stimulus-driven capture of attention.

The alternative view is that there is top-down control at the preattentive level suggesting that observers intentionally select only the task-relevant singleton. Irrespective of the saliency of the singletons present in the visual field, attention is immediately directed towards the singleton relevant for the task at hand. In this view, the increase in reaction time in trials in which an irrelevant singleton is present is due to *non-spatial* distraction (e.g., Folk & Remington, 1993). For example, it is possible that the signal that codes the presence of the target singleton is less strong in case a singleton in an irrelevant dimension is present implying that it simply takes somewhat longer to shift attention to the location of target singleton (see e.g., Theeuwes, 1992). Alternatively, it is possible that the preattentive stage segments the visual field into two possible "objects", the target and the distractor singleton, and the mere presence of another irrelevant perceptual object slows down shifting of attention to the relevant object. According to this idea, when two distinct perceptual objects compete for attention, "filtering costs" in the sense of for example Treisman, Kahneman and Burkell (1983) may cause an increase in the time to find the target singleton. Note that a non-spatial distraction explanation is compatible with the notion that top-down control at the preattentive level can selectively guide spatial focal attention to the target singleton (e.g., Bacon & Egeth, in press; Hoffman, 1978, 1979; Treisman & Sato, 1990; Wolfe et al., 1989).

The present study was designed to test whether the distraction effect in singleton search is due to *spatial* distraction (i.e., attention is *exogenously captured* by the irrelevant singleton) or due to *non-spatial* distraction (i.e., attention is *endogenously shifted* to the location of the target singleton, yet due to the irrelevant singleton this shifting takes longer). The task employed in the present study was similar to that of Theeuwes (1992) in which subjects always searched for a green diamond among green circles. In one condition, a colored distractor singleton was present (i.e., one of the circles was red). Theeuwes (1992) has shown that in this type of tasks, the red distractor singleton is so salient that it slows down search target shape singleton (see also Bacon & Egeth, in press). Unlike discriminating a line inside the target shape as in Theeuwes (1991b, 1992, in press b; Bacon & Egeth, in press) in the present study, subjects responded to a letter centered in the target shape. When the letter was an "R" they responded with the right hand, when it was an "L" they responded with their left hand, a response assignment which can be considered as highly compatible. The letters in all other non-target shapes were randomly Rs and Ls. There was a clear separation between the defining (the diamond) and reporting (the letter inside the diamond) attributes of the target (Duncan, 1985) which guarantees that the stimulus information available at the preattentive level separating target from nontarget elements (the singleton diamond between circles) tells nothing about which response to choose (R or L). Such a separation enables to disentangle perceptual factors from response selection factors (see Theeuwes, 1992, in press b, for a discussion).

In order to test the hypotheses described above, the letter inside the distracting singleton was systematically manipulated. On half of the trials the letter inside the distractor and target singleton were identical ("compatible" condition; e.g., in both shapes an L or in both shapes an R), in the other half of the trials they were different ("incompatible" condition; e.g., in the target singleton an R and in the distractor singleton an L, and vice versa). If the distracting effect is *spatial* in the sense that attention is always first captured by the (more salient) irrelevant singleton, then one expects that incompatible letters centered inside the irrelevant singleton give longer response latencies than compatible letters. Because attention is captured by the irrelevant singleton, the singleton receives focal attention first resulting in the mandatory processing of all attributes of that object (e.g., Kramer & Jacobson, 1991). In line with the work of Eriksen and colleagues (Eriksen & Eriksen, 1974; Eriksen & Hoffman, 1972, 1973) it is expected that the processing of response-incompatible letters produces performance costs relatively to response-compatible letters.

Alternatively, if the distracting effect of the irrelevant singleton is *non*-spatial in the sense that attention is shifted only but slowed to the location of the target singleton, then it is expected that the compatibility manipulation does not have any effect. Since no focal attention is shifted to the location of the irrelevant singleton, the letter inside the irrelevant singleton does not become available and should therefore have no effect on the response to the letter appearing in the target singleton.

2 EXPERIMENT 1

Subjects viewed equi-spaced multi-element displays (7 or 9) in which they responded to the letter inside the diamond. Display size was manipulated in order to check whether search was performed in parallel ensuring that the preattentive parallel stage was involved in detecting the shape singleton. Relatively large display size were used to ensure that the saliency of target and distractor singleton was about the same in the two display size conditions. As suggested earlier (Theeuwes, in press a) the saliency of the singleton possibly depends on the density (distance between the elements) and the number of nonunique elements present in the display (see also, Green, 1991; Todd & Kramer, in press). On the other hand, larger display size were not included because a too close spatial proximity of the elements would result in typical flanker compatibility effects in the sense of Eriksen and/or effects lateral masking.

2.1 Method

2.1.1 *Subjects*

Eight right-handed subjects, ranging in age from 18 to 26 years, participated as paid volunteers. All had normal or correct-to-normal vision and reported having no color vision defects.

2.1.2 *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, 100 cm from the chinrest.

2.1.3 *Stimuli*

The stimulus display consisted of seven or nine colored shapes which were equally spaced around the fixation point on an imaginary circle whose radius was 3.6°. The target shape was a diamond (45° rotated square) 1.37° on a side presented in green (CIE x,y chromaticity coordinates of .309/.597). The nontarget shapes were circles 1.26° presented in the same color. In the distractor condition, one of the circles was presented in red (coordinates of .572/.399). The colors were matched for luminance (16.0 cd/m^2). Centered inside each shape was a white capital Roman letter L or R (0.57° × 0.29°) having a luminance of 45.0 cd/m^2. In the compatible distractor condition, the letter inside the target shape (the diamond) matched the letter inside the red circle distractor (e.g., an R in the green diamond and an R in the red circle or an L in the green diamond and an L in the red circle). In the incompatible distractor condition, the letter inside the diamond was different from the letter inside the red circle distractor (e.g., an L in the green diamond and R in the red circle or an R in the green diamond and L in the green circle).

The closest separation between the letters was 2.5° center-to-center at display size nine. The closest of the nearest contours of the outline shapes was 1.2° at display size 9.

The fixation cross was presented in white (45.0 cd/m^2) on a gray background (2.5 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 patches of the colors used in this experiment. The patches were displayed at the center of the computer screen. Fig. 1 shows examples of the displays with display size seven both for the no-distractor, compatible distractor and incompatible distractor conditions.

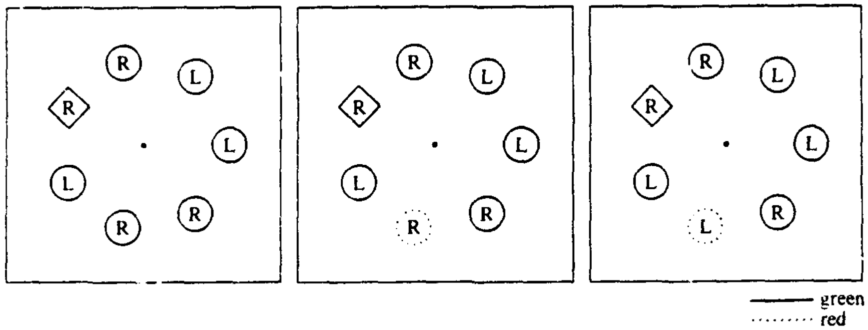

Fig. 1 Sample stimulus displays (with display size 7). In the no-distractor condition (left panel) the green diamond target shape appears among green circles. In the compatible distractor condition (middle), the letter inside the green diamond target shape (in this case the letter "R") is identical to the letter inside the red circle distractor. In the incompatible distractor condition (right), the letter inside the green diamond target shape is different from the letter inside the red circle distractor.

2.1.4 *Procedure*

Subjects were instructed to report the letter (R or L) inside the green diamond, and press with their left index finger the "Z"-key for L and with their right index finger the "/"-key for R; A response mapping that can be considered as highly compatible.

Each subject performed 208 trials in both the no-distractor and distractor condition. Half of the subjects started with the no-distractor, the other half with the distractor condition. Subjects first received a practice half-block of 104 trials in each condition. In the distractor condition, in half of the trials, the letter *inside the green diamond target matched* the letter inside the red circle distractor (compatible condition). In the other half of the distractor trials, the letter inside the green diamond target was different from the letter inside the red circle distractor (incompatible condition). Target and distractor were positioned at random locations within the display. There were equal numbers of R and L targets. Rs and Ls inside nontarget circles were randomly distributed with a display. Display size (7 or 9) was randomized within blocks.

Within a session, there were short breaks after every 52 trials in which subjects received feedback about their performance (percentage errors and mean reaction time) on the preceding block of trials. Prior to the start of the experiment subjects were instructed to search for the R and L located inside the diamond and to press the appropriate response key with their index fingers each of which were resting on "/" and "z"-keys. 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 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 s, the trial was counted as an error.

2.2 Results

Response times longer than 1 sec were counted as errors, which led to a loss of 0.82% of the trials. Fig. 2 presents the subjects' mean RTs and error percentages. The individual mean correct RTs were submitted an ANOVA with distractor (no-distractor v distractor) and display size (7,9) as factors. There was a main effect on RT of distractor [$F(1,7)=6.6$; $p<.05$], indicating that response times in the no-distraction condition were reliably faster than in the distractor condition, a result which confirms earlier findings (Theeuwes, 1992).

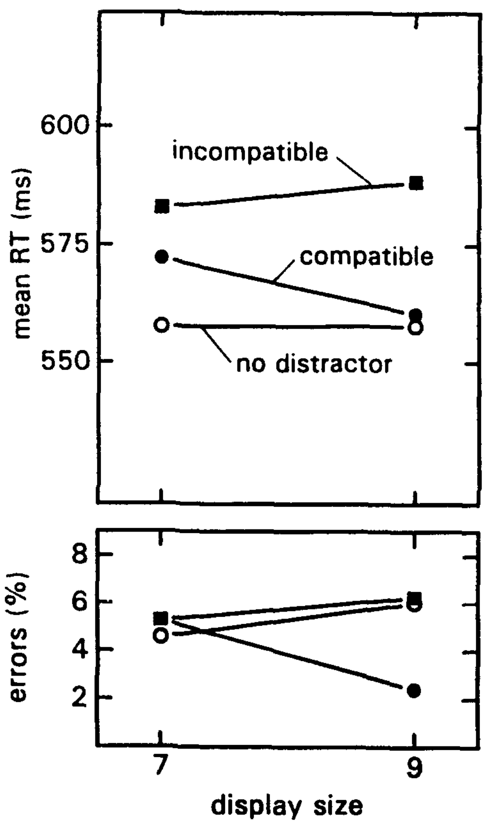

Fig. 2 Mean RTs and error percentages as a function of display size for search without a distractor and search with a compatible or incompatible distractor.

The individual mean correct RTs of the distractor condition were entered into an ANOVA with compatibility (compatible, incompatible) and display size (7,9) as factors. There was only an main effect on RT of compatibility [$F(1,7)=5.9$; $p<.05$]. The factor display size and the interaction display size × compatibility failed to reach significance. This analysis shows, as clear from Fig. 2, that the RTs in the incompatible condition were significant slower than in the compatible condition.

Planned comparisons showed that the mean RT of the incompatible condition was reliably slower than the mean RT of the no-distractor condition ($p<.05$). There was no difference between the compatible and the no-distractor condition.

The mean slopes for the no-distractor, compatible and incompatible conditions were 0.0, -5.9, 2.8 ms. None of the slopes were significantly different from zero [$t(7)<0.33$], indicating preattentive parallel search across all items in the display (e.g., Treisman & Gormican, 1988).

In order to achieve homogeneity of the error rate variance, the mean error rates per cell were transformed by means of an arcsine transformation. Individual mean arcsine transformed error rates were entered into the same ANOVAs as performed on the response latencies. None of the effects were significant, indicating that differences in response latencies are not due to a speed-accuracy trade-off.

2.3 **Discussion**

The results of this experiment are fairly clear: the identity of the letter inside the distractor singleton does have an effect on responding to the letter appearing inside the target singleton. When the letter inside the distractor is identical to the letter inside the target singleton, it is compatible with the response giving relatively fast RTs. In fact, the finding that RTs the compatible condition are as fast as the no-distractor condition suggests that there is a redundancy gain: the identical letter in the distractor speeds up processing of the letter in the target singleton. When the letter inside the distractor is different from the letter inside the target singleton, it is incompatible with the response, causing slow response times. The present findings are entirely consistent with the hypothesis that the distracting effect is *spatial* in the sense that attention is *exogenously captured* by the more salient, yet irrelevant singleton.

3 EXPERIMENT 2

Although results of the previous experiment clearly support the hypothesis that attention is captured by the most salient singleton, other support for the hypothesis is desirable. To test whether the present findings are robust, Experiment 2 used a different display lay-out, a different procedure and a limited exposure duration. The display consisted of a 4 × 4 rectangular stimulus array containing 16 shapes. Rather than presenting the distraction factor in separate blocks, in Experiment 2 the distraction condition was mixed within blocks. Unlike in Experiment 1, this does not allow subjects to adopt a different strategy on different blocks. This manipulation makes it possible to ensure that the compatibility effect as found in Experiment 1 is not due to adapting a different strategy on distraction blocks. Finally, exposure duration of the display was limited to 200 ms, a duration too short to make directed eye movements. This manipulation ensures that the effects reported are due to *attention capture*, not confounded by directed eye movements towards the target or distractor location.

3.1 Method

3.1.1 *Subjects*

Eight subjects ranging in age between 17 and 25 years participated in the experiment.

3.1.2 *Stimuli and Procedure*

The task was identical to Experiment 1, except that the stimulus display consisted always of sixteen colored shapes (same dimensions and colorimetric values as in Experiment 1) presented on 4 × 4 rectangular stimulus array (8.2° × 8.2°) spaced around the fixation point. The center-to-center separation between the letters located inside the outlines shapes was of 2.3° of visual angle. The closest separation between the outlines shapes was 1.1°.

There was one block of 120 trials. In half of the trials there was no distractor, in the other half there was a red circle distractor. In half of the distractor trials, the letter inside the distractor was identical to the letter in the target singleton, in the other half it was different. Target and distractor were positioned at random locations within the 4 × 4 grid. Subjects received one practice block of 120 trials. There was feedback every 60 trials.

3.2 Results and Discussion

Response times longer than 1200 ms were counted as errors, which led to a loss of 1.0% of the trials. The means of response latencies and error rates are shown in Table 1. The difference of 38 ms between the compatible and incompatible condition [$t(7)=5.26$; $p<.01$] replicates the findings of Experiment 1, supporting the notion that the distractor singleton captures attention. The compatibility effect obviously does not depend on the display lay-out or the procedure used. The effects reported depict *attentional* capture that does not depend on the occurrence of directed eye movements.

Overall, the presence of a distractor does slow down responding to the target singleton [$t(7)=2.14$; $p<.05$]. The incompatible distractor condition differed significantly from the no-distractor condition [$t(7)=3.44$; $p<.01$]. There was no difference between the no-distractor and the compatible condition.

An analysis performed on the arcsine transformed error rate indicated that none of the effects were significant, indicating that differences in response latencies are not due to a speed-accuracy trade-off.

Table I Mean RTs (in ms) and Errors for search without a distractor and search with a compatible or incompatible distractor.

	no distractor	compatible	incompatible
mean RT	590	599	637
% Error	6.2	6.6	5.8

4 GENERAL DISCUSSION

Both experiments clearly show that the identity of the letter inside the irrelevant distractor singleton does have an effect on the latency of responding to the letter appearing inside the target singleton. These findings can only be explained by assuming that attention is *captured* by the irrelevant singleton, at least on a larger part of the trials. Because capturing of attention implies that focal attention is directed to the irrelevant singleton, the identity of the letter becomes available thereby affecting the speed of responding to the target letter. If attention would not have been captured by the irrelevant singleton, then there no plausible explanation how the identity of the letter in the irrelevant singleton could have affected responding to the target letter.

The present findings support the notion that the preattentive process calculates differences in features within dimensions (see e.g., Theeuwes, in press a, in press b), resulting in a pattern of activations at different locations. For example, at the location of the red distractor singleton a large "difference" signal arises because the singleton differs from all other nontargets in color. At the location of the diamond singleton, a large "difference" signal arises because the diamond differs from all other elements in shape. Previous results (Theeuwes, 1991b, 1992) have shown that it takes less time to find a color singleton than a shape singleton suggesting that the red color singleton produces a larger difference signal than the diamond shape singleton. Because focal attention is automatically and unintentionally shifted to the location in the display having the largest local feature difference, the color singleton is selected first. It is assumed that the source of the pre-attentively calculated difference signal (whether it is caused by a color singleton or a form singleton) can only be recognized after focal attention is moved to the location of the difference signal. In other words, the subject only knows whether the singleton was the target after selecting the location having the large difference signal. In the present experiment, selecting the location of the distractor singleton results in mandatory processing of the letter inside the distractor singleton. After re-shifting attention from the distractor location to the target location, the previously identified letter inside the distractor affects responding to the letter in the target singleton, similar as irrelevant and to ignore flankers affect responding to a relevant letter in flanker compatibility experiments (e.g., Eriksen & Eriksen, 1974).

In this view, the salience of the singleton, and not its identity, its color, its shape, its brightness, etc., will determine which element captures attention. Obviously, given this account, selection operates irrespective of the task demands. The automatic shifts of attention are considered to be the result of relatively inflexible, "hardwired" mechanism that is triggered by the presence of these difference signal interrupts. In line with for example Sagi and Julesz (1985) and Ullman (1984) it is assumed that the parallel process in singleton search performs a *local-mismatch* detection followed by a serial stage in which the most mismatching areas are selected for further analysis.

The present results, indicating that the identity of the letter inside the distractor does affect processing of the letter inside the target element, suggest that the capture of attention to the location of the distractor results in mandatory processing of the letter at that location. Note that one has to assume that this processing is *mandatory* because the distractor element (the red circle) that has putatively drawn attention to its location tells the subject that the letter inside the distractor cannot be the target. Subjects may disengage attention quickly and refocus attention to the next salient singleton which in the present experiments is the target. It should be realized that the rapid disengagement of attention from the distractor- to the target location based on the knowledge that the letter in the red circle cannot be the target, does represent top-down effects. Yet, these top-down effects do not operate on selection, but on processes occurring after the distractor was selected (see e.g., Theeuwes, in press b for a similar explanation of the results of Folk et al., 1993).

The present results cannot be explained by assuming that attention to the target singleton "leaks over" to an adjacent letter, which typically is used as an explanation for the flanker compatibility effect (e.g., Eriksen & Eriksen, 1974; Yantis & Johnston, 1990). In the present experiments, only at change level the target and distractor singleton occupied adjacent locations, and even then the minimal center-to-center distance between the letters was 2.3° of visual angle (in Experiment 2). Such a distance has generally be considered as a separation sufficient to ensure no attentional spillover (e.g., Eriksen & Eriksen, 1974; Eriksen & Hoffman, 1972, 1973; but see Miller, 1991). Flanker compatibility effects tend to disappear when intervening items are placed between the relevant item and the flanker suggesting that there is hardly any spillover of attention to nonadjacent flankers (e.g., Eriksen & St. James, 1986).

In summary, the present results confirm earlier findings that in singleton search, goal-directed attentional selection is relatively ineffective. Selection seems to determined by the saliency of the elements in the display. The present findings indicate that attention is captured by the any salient singleton irrespective of whether the "popping-out" singleton is a target or a distractor.

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Previous research has shown that search for a shape singleton is disrupted by the presence of an irrelevant color singleton (Theeuwes, 1991b, 1992). These findings have been treated as evidence for the hypothesis that, irrespective of a goal-directed attentional set on part of the observer, attention is unintentionally captured by the most salient singleton. This hypothesis was tested in two experiments in which subjects searched multi-element displays for a shape singleton. Subjects reported the letter that always appeared inside the target shape singleton (a green diamond). On some trials an irrelevant color singleton was present which contained a letter that was compatible or incompatible with the letter inside the target shape. As reported earlier, the presence of an irrelevant color singleton distracted goal-directed search for the shape singleton. The finding that the identity of the letter inside the distractor affected responding to the letter inside the target shape, provides support for the hypothesis that attention is captured by the most salient singleton. The identity of the letter inside the distractor can only affect responding when it is assumed that attention is involuntarily drawn to the location of the distracting singleton.

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