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Attentional Control During Visual Search: The Effect of Irrelevant Singletons

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Four experiments investigated whether a highly salient color singleton can be ignored during serial search. Observers searched for a target letter among nontarget letters and were instructed to ignore an irrelevant, highly salient color singleton that was either compatible or incompatible with the response to the target letter. The results indicate that it was possible to prevent attentional capture by the irrelevant singleton only when both the target and the distractor color were known. When either the color of the target or the color of the to-be-ignored singleton were varied over trials, the irrelevant singleton captured attention. The ability to selectively filter singleton distractors during serial search depends on the presence of an attentional set for a specific feature value of both target and distractor. In the absence of a consistently predictable feature value of both target and distractor, top-down control is not possible.

Among the most fundamental issues of visual attention research is the extent to which visual selection is controlled by the properties of the image or by the intentions, goals, and beliefs of the observer (for recent reviews, see Egeth & Yantis, 1997; Theeuwes, 1993, 1996; Yantis, 1993, 1998). When an observer intentionally selects only those objects required for the task at hand, selection is thought to occur in a voluntary, goal-directed manner. When specific properties present in the visual field determine selection independent of the observer's goals and beliefs, selection is thought to occur in an involuntary, stimulus-driven manner.

Models of visual search assume that selection is the result of an interaction between goal-directed and stimulus-driven factors. For example, Wolfe's guided search model (Cave & Wolfe, 1990; Wolfe, 1994; Wolfe, Cave, & Franzel, 1989) assumes that attention is directed to items serially in order of priority. Attentional priority is determined by both top-down and bottom-up activation. The greater the activation at a location, the more likely it is that attention will be directed to that location. *Bottom-up activation* is a measure of how salient an item is in its context. Therefore, an item that is locally unique in some basic visual dimension—usually referred to as a "feature singleton" or simply a "singleton"—will generate a large bottom-up activation (e.g., a red item between green items). The term *top-down activation* refers to the extent to which an item matches the current attentional set. For example, when instructed to search for a red target among red and green nontargets, all elements that are red will receive a high top-down activation. These two sources of activation are combined to produce an "attentional map" that determines the order in which objects are visited during visual search.

Visual search models assume that the attentional serial stage is guided by information that is available at the early preattentive level. According to the guided search model (Wolfe, 1994), top-down guidance is achieved by activation of those features that match the target. Thus, when searching for a red target among red and green nontargets, all red elements receive a high top-down activation. Along similar lines, the revised feature integration theory (Treisman & Sato, 1990) postulates that inhibition is applied to features that match the distractors. Thus, when searching for a red target among red and green nontargets, the activation of the green elements is inhibited. In either case, search is restricted to a particular set of elements either by guidance toward particular target features (Wolfe, 1994) or by guidance away from distractors (Treisman, 1988).

Various studies have demonstrated that knowledge of the specific task demands may guide attention only to those locations that match the target-relevant feature. For example, Kaptein, Theeuwes, and Van der Heijden (1995), among others, showed that observers can limit their search only to a particular subset of elements (see also Bacon & Egeth, 1997; Egeth, Virzi, & Garbart, 1984). Kaptein et al. demonstrated that participants restricted their search for a color-orientation conjunction target to a color-defined subset. Thus, when searching for a red vertical line segment between red tilted and green vertical line segments, partici-

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pants searched serially among the red items and that they completely ignored the green line segments. In addition, Kaptein et al. showed that participants could flexibly (from trial to trial) change the subset they were searching, demonstrating the flexibility of top-down settings in visual search. Thus, on one trial participants searched serially among the red items and ignored the green, whereas on the next trial they searched the green items and ignored the red.

Although the results of previous studies have demonstrated the efficacy of top-down information in guiding attention selectively only to those locations containing task-relevant features, to our knowledge the limits of this top-down guidance have never been explored. In most cases, top-down guidance is demonstrated in conjunction search in which there are about an equal number of distractor types present in the visual field (see, e.g., Treisman & Gelade, 1980; Treisman & Sato, 1990). In these types of displays, there is typically not a single element (i.e., a feature singleton) that stands out from the background in a basic visual dimension. The question addressed in the present study is the extent to which observers have the ability to ignore a salient feature singleton when searching serially through a display. In other words, when engaged in serial search, do participants have the ability to block out a highly salient element that is irrelevant for the task? In terms of visual search models, what is the extent to which top-down activation to the relevant items can overcome the large bottom-up activation caused by the irrelevant salient element?

It has been demonstrated in several studies that when observers are engaged in parallel search for a particular singleton (e.g., search for an element with a unique color), an irrelevant singleton having a higher saliency than the singleton for which observers are looking interferes with search (Bacon & Egeth, 1994; Theeuwes, 1991, 1992, 1994). The results of these experiments showed that when participants searched in parallel for a singleton, top-down guidance could not override the stimulus-driven activation that arose from the more salient stimulus attribute. Even though participants knew that they had to ignore the salient singleton, they were unable to do so. More recently, Joseph and Optican (1996) corroborated these results by applying a different paradigm showing that attention was drawn to the more salient singleton even though participants knew it was irrelevant. Bacon and Egeth (1994) suggested that capture by a to-be-ignored feature singleton occurred only when the task could be carried out in the so-called *singleton detection mode,* in which attention is directed to the location in the array having the largest local feature contrast (see also Northdurft, 1991, 1992). When observers adopt a *feature search mode,* attention becomes more under top-down control and is directed only to locations that match some task-defined feature (e.g., "red"). In line with the visual search models, it is assumed that in this mode, top-down control allows observers to successfully ignore salient singletons.

These conclusions are consistent with a proposal by Folk, Remington, and Johnston (1992) that the ability of a singleton to capture attention is modulated by the nature of the primary task (i.e., color cues will capture attention in color search tasks but not in tasks in which observers search for an abrupt onset). According to the contingent capture account, attentional capture is ultimately contingent on whether an attention-capturing stimulus is consistent with top-down settings that are established "off-line" on the basis of current attentional goals. According to this model, only stimuli that match the top-down control settings will capture attention; stimuli that do not match the top-down settings will be ignored. The findings of Theeuwes (1991, 1992, 1994) showing that an irrelevant singleton interferes with search for a relevant singleton are consistent with this proposal. Because the target of search is a singleton, the attentional system is set to respond to singletons. Even though participants knew that they had to ignore a particular singleton, they were unable to do so because the attentional system was set to respond to singletons in general. Therefore, any singleton, relevant or irrelevant, captured attention (Bacon & Egeth, 1994). Folk et al. (1992) suggested that attentional settings are broadly tuned. They speculated that there was a setting for a dynamic discontinuity (i.e., onset or motion) or for a static discontinuity (such as color and texture).

Consistent with this model, another series of experiments demonstrated that the mere presence of a singleton is not enough to capture attention in a stimulus-driven manner (Jonides & Yantis, 1988; Theeuwes, 1990). To assess whether a stimulus captures attention, one must devise a task in which the stimulus under investigation is not relevant to the participant's task. If such an irrelevant singleton still influences the deployment of attention, then it can be concluded that the singleton captured attention (Yantis, 1998). In previous studies, observers searched for a target letter among other letters. On each trial one letter differed from all the rest in a specific dimension, indicating that a salient singleton was present in each trial (e.g., Jonides & Yantis, 1988; Theeuwes, 1990). Although the singleton was not relevant for the task, observers knew that the unique element occasionally would be the target letter. Reaction times (RTs) to find the target did not depend on whether the unique element happened to be the target letter, suggesting that the deployment of attention was not influenced by the presence of the singleton. On the basis of these findings, it was concluded that singletons did not capture attention in a stimulus-driven fashion. Even though these studies demonstrated that salient singletons irrelevant for the task did not capture attention, they did not establish whether observers could intentionally ignore processing singletons when instructed to do so. Todd and Kramer (1994) provided evidence that task-irrelevant salient features may affect the allocation of attention within the visual field. They demonstrated that even though attention may not be captured by salient elements, attention is at least guided by salient, yet task-irrelevant features. This result, referred to as "attentional misguidance," is not considered to be the result of stimulus-driven attentional capture by the irrelevant singletons but is explained by assuming that participants deliberately choose to attend to the singletons (Yantis, 1998). Even though top-down-induced "misguidance" by salient singletons may occur, the question remains as to whether observers can intentionally ignore salient singletons when required to do so.

The present series of experiments was conducted to provide a critical test of whether the attentional system can be set intentionally to ignore a salient singleton during serial search. If observers are able to adapt an attentional set that matches that of only the target, they should be able to ignore the irrelevant singleton. To investigate this issue, we used a new technique that reveals any processing of the to-be-ignored item. This technique, referred to as "identity intrusion,"[1] not only shows that attention is directed at the location of the to-be-ignored item but also reveals that the presence of the item is associated with active stimulus processing.

The basic idea underlying this technique is similar to that of an earlier study (Theeuwes, 1996). The singleton element that observers had to ignore was either identical or different from the target element they were looking for. Participants searched for the target letter E or R among a variable number of nontarget letters. In each display there was one letter that had a unique color, constituting the singleton that had to be ignored. The singleton to be ignored was either identical to the target letter (the compatible condition; i.e., both letters were Es or Rs) or different from the target letter (the incompatible condition; i.e., the singleton was an E, and the target letter was an R or vice versa). If participants could ignore the color singleton successfully, we expected the identity of the singleton to have no effect on search for the target element. Alternatively, if participants were not capable of completely ignoring the color singleton, we expected the processing of a response-incompatible singleton to produce performance costs relative to a response-compatible singleton. This latter effect is referred to as the "identity intrusion effect."

Finding an identity intrusion effect would imply that attention was shifted to the location of the singleton and that the singleton was processed up to a level at which its identity became available. Even without an identity intrusion effect, the presence of a singleton may slow search relative to a condition in which there is no singleton. If the presence of a singleton slows search without causing identity intrusion, this would suggest something like "nonspatial distraction" (see Folk & Remington, 1993, 1998; Theeuwes, 1996). Because the visual system segments the display in potential perceptual objects, the singleton may be encoded as an object distinct from the rest of the display. Even though it does not generate a shift of spatial attention, the mere presence of another object may slow down search in the sense of "filtering costs," as described by Treisman, Kahneman, and Burkell (1983).

Note that in previous studies (e.g., Jonides & Yantis, 1988; Theeuwes, 1990; Todd & Kramer, 1994) the unique element and the target occasionally coincided. Although there was no incentive for observers to deliberately direct attention to the unique element, there were also no costs for doing so. In the current research, participants were explicitly instructed to always ignore the unique element because the unique element was never the target. If the presence of the singleton influences the deployment of attention even when it is irrelevant for the task at hand, it should be concluded that the singleton captured attention (e.g., Yantis, 1993).

Experiment 1

Participants searched for the letter E or R in displays consisting of either five or seven nontarget letters. We manipulated display size to determine whether search was serial. In each display, there was a color singleton consisting of a letter that was either compatible or incompatible with the target letter. Participants were explicitly instructed to ignore the color singleton. In the first experiment, the color of the letters and the color of the singleton switched from trial to trial. Thus, on any given trial, either all letters were green and the singleton to be ignored was red or all letters were red and the singleton was green. Exposure duration of the display was limited to 183 ms, a duration too short in which to make eye movements. This manipulation ensured that the effects reported would be due to the serial deployment of attention and not confounded by directed eye movements toward the letters.

As noted earlier, because irrelevant singletons may produce distraction effects that are independent of shifts of spatial attention and therefore independent of identity intrusion effects, we included a control condition in which all letters had the same color. If search is slowed down but without causing identity intrusion, search in which a singleton is present should be slower than search in the control condition in which no singleton is present. To ensure that in the singleton condition participants had ample opportunity to ignore the singleton, we presented control and singleton conditions in separate blocks of trials. Blocking these conditions should allow participants to optimally adapt a strategy to filter the irrelevant singleton.

Method

Participants. Eight right-handed participants (aged 20–26 years) participated as paid volunteers. All had normal or corrected-to-normal vision and reported having no color vision defects.

Apparatus. An SX-386 PC (G2) with a NEC Multisync 3-D video graphics array color screen (resolution = 640 × 350) controlled the timing of the events, generated pictures, and recorded RTs. The / key and the Z key of the computer keyboard were used as response buttons. Each observer was tested in a sound-attenuated, dimly lit room, with his or her head resting on a chin rest. The CRT was located at eye level, 80 cm from the chin rest.

Stimuli. The stimulus display consisted of five or seven letters that were equally spaced around the fixation point on an imaginary circle whose radius was 3.2°. The exact location of the equally spaced letters on the imaginary circle varied from trial to trial. In each display there was a target letter (either E or R) and nontarget letters randomly taken from the set (P, H, T, K, X, S, F, and N). In the control condition, all letters had the same color (either red or green). All letters were unique in any given display. In the singleton condition, one of the nontarget letters was replaced by a color singleton that had a color that was different from all other letters in the display. Thus, when all other letters were green, the singleton was red; when all letters were red, the singleton distractor was

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[1] This term was suggested by Roger Remington.

green. The singleton distractor consisted of a letter that was either compatible with the target letter (singleton and target both were Es or Rs) or noncompatible with the target letter (the singleton was an E and the target was an R or vice versa). In the control condition, all letters had the same color because no singleton was present. The location of the target, nontargets, and singleton letters was varied randomly from trial to trial. Figure 1 contains examples of the stimulus displays for the control, compatible, and incompatible conditions for Display Size 5.

The closest separation between the letters was 2.7° center to center at Display Size 7. The separation between the nearest contours was 2.2°. The letters were Roman capital letters (0.72° × 0.36°). The letters were either red or green (CIE x,y chromaticity coordinates of 0.57/0.38 for red and 0.31/0.58 for green) and were matched for luminance (7.4 cd/m^2). The letters were presented against a dark background (0.1 cd/m^2). The fixation dot presented in the center of the display was white (19.0 cd/m^2). The colorimetric and photometric measurements were made with a spectroradiometer (Photo Research, Type PR 703 A/M). The detector head of this device was directed toward patches of the colors used in this experiment. The patches were displayed at the center of the computer screen.

Procedure. Initially, a fixation cross was presented at the center of the screen. Seven hundred milliseconds before display onset, the cross changed into a fixation star to warn the participant of the upcoming stimulus. Along with the fixation star, the stimulus field consisting of either five or seven letters was presented for 183 ms.

Participants were instructed to ignore the singleton and to determine whether an R or an E was present among the nonsingleton letters. Participants pressed with their left index fingers the Z key for E and with their right index fingers the / key for R.

Each participant performed 128 trials in both the control and singleton conditions. Half the participants started with the control condition, and the other half with the singleton condition. Participants first received four to six practice blocks until they were able to perform the task with an accuracy of at least about 90%. In the singleton condition, in half the trials the singleton distractor matched the target letter (compatible condition); in the other half, the singleton distractor was different from the target letter (incompatible condition). The target letter and singleton distractor were positioned at random locations within the display. In half the trials, the letters were red; in the other half they were green. Color changed randomly from trial to trial. There were equal numbers of E and R targets. Display size (five or seven) was randomized within blocks.

Within a session, there were short breaks after every 34 trials, in which participants received feedback about their performance (i.e., percentage errors and mean RT) on the preceding block of trials. Participants were told to fixate on the central dot. Both speed and accuracy were emphasized. A warning beep informed participants that an error had been committed. If no response was made after 2 s, the trial was counted as an error.

Results

RTs longer than 1,300 ms were counted as errors, which led to a loss of 0.89% of the trials. Figure 2 shows the mean RTs and error percentages. The individual mean correct RTs were submitted to an analysis of variance (ANOVA) with display size (five or seven) and singleton (control vs. singleton condition) as factors. There was a main effect on RT of display size, $F(1, 7) = 27.5, p < .01$, and of singleton, $F(1, 7) = 18.5, p < .01$. This analysis showed that the mere presence of the singleton slowed down search about 50 ms. As can be seen in Figure 2, both in the singleton and control conditions search for the target letter was serial (an average of 21.7 ms/item). The absence of an interaction between these factors indicates that the way participants searched through the display was basically not affected by the presence of the singleton.

Planned comparisons on compatibility (compatible vs. incompatible singleton) showed a main effect on RT of compatibility, $F(1, 7) = 20.3, p < .01$. This analysis showed, as can be seen in Figure 2, a clear identity intrusion effect: RTs in the incompatible condition were significantly slower than in the compatible condition. This result indicates not only that the presence of a singleton slowed down search but that participants processed the identity of the to-be-ignored singleton. This result indicates that participants were unable to successfully ignore the singleton distractor.

To achieve homogeneity of the error rate variance, we transformed the mean error rates per cell by means of an arcsine transformation. Individual mean arcsine-transformed error rates were entered into the same ANOVA as performed on the mean RTs. There was a main effect of display size, $F(1, 7) = 6.7, p < .05$. The interaction between

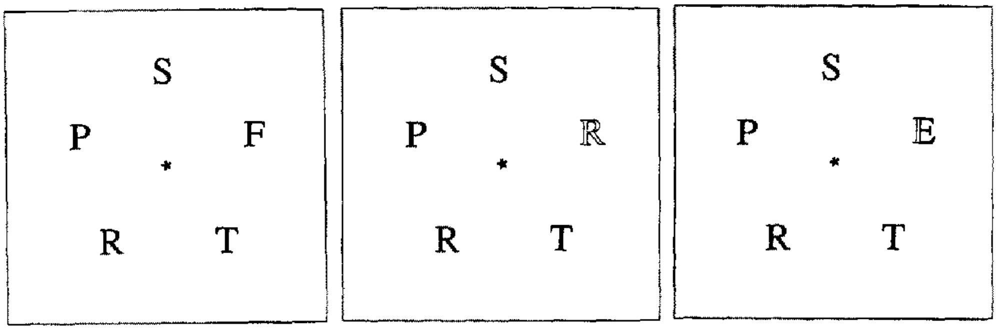

Figure 1. Sample stimulus displays (with Display Size 5). In the control condition (left panel), all letters are red (shown here as solid letters); the target is the letter R (press "right"). In the compatible condition (middle panel), the singleton to be ignored is a green letter R (shown here as a hollow letter) identical to the red target letter R. In the incompatible condition (right panel), the singleton to be ignored is a green letter E (shown here as a hollow letter) different from the red target letter R.

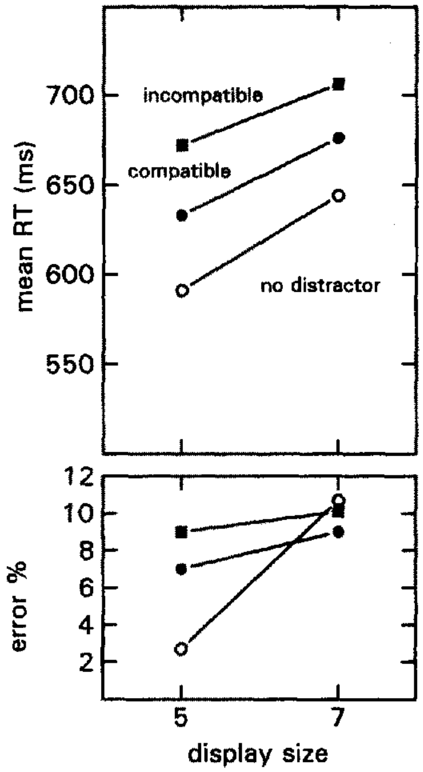

Figure 2. Experiment 1: Mean reaction times (RTs) and error percentages as a function of display size for the control, compatible, and incompatible conditions.

singleton and display size was also significant, $F(1, 7) = 11.5$, $p < .05$, mainly because of a higher error rate for the singleton condition at Display Size 5. Because this analysis showed that error differences were nonsignificant or tended to mimic RT, differences in response latencies were not attributable to a speed–accuracy trade-off.

Discussion

The results of this experiment are clear: The presence of the singleton slowed down search. There was also a clear identity intrusion effect in that the identity of the to-be-ignored singleton did have an effect on responding to the target letter. When the singleton was identical to the target letter and therefore compatible with the response, RTs were relatively fast. When the singleton was different from the target letter and therefore incompatible with the response, RTs were relatively slow. These findings indicate that participants were unable to ignore processing irrelevant yet salient singletons when they were engaged in serial search.

Note, however, that participants knew only that they had to ignore the singleton (i.e., ignore the unique element in the display), but they never knew whether this would be a red singleton between green items or a green singleton between red items. Also, participants never knew the exact features of the target they were looking for. In other words, under these circumstances, it is likely that top-down knowledge cannot guide attention to only those locations that match some task-defined feature. In terms of the visual search models, there was no opportunity to activate the features that matched the target, nor was there opportunity to inhibit the features that matched the distractor. In this sense, we expected that the irrelevant singleton would interfere with search for the target letter.

In terms of the contingent capture hypothesis, participants could adopt only an attentional control setting that could be set to ignore "something unique." Only if attention could be set to attend to something "not unique" could distraction from the irrelevant singleton have been prevented. These findings showing interference by the irrelevant unique singleton are consistent with results from a study by Remington and Folk (1994), who showed that attention cannot be set to ignore distractor properties.

Experiment 2

Although the results of the previous experiment suggest that participants cannot avoid processing irrelevant singletons during serial search, in the previous experiment, in which the color of the target and the singleton constantly switched roles, there was little chance for participants to use top-down control. In Experiment 2 the opportunity to exert top-down control was maximized: Throughout the experiment, the color of the target letter and that of the singleton were fixed. Participants knew the exact features of the element they were looking for and the exact features of the singleton they were to ignore. In terms of the visual search models (e.g., Treisman & Sato, 1990; Wolfe, 1994), participants could both activate the features that matched the target (e.g., activate all red items) and at the same time inhibit the feature that matched the distractor (e.g., inhibit all green items). In terms of the contingent capture hypothesis, these conditions should enable participants to develop a specific and selective attentional set that allows the deployment of attention only to the task-relevant stimuli. It should be possible to set attention narrowly to only the relevant stimuli because both the color of the target and the color of the singleton distractor are known and highly predictable.

Method

Participants. Twelve right-handed participants (aged 18–26 years) participated as paid volunteers. All had normal or corrected-to-normal vision and reported having no color vision defects.

Stimuli and procedure. The task was identical to that used in Experiment 1 except that the colors did not switch from trial to trial. Half the participants always searched for a green E or R and had to ignore a red singleton, whereas the other half always searched for a red E or R and had to ignore a green singleton.

Results

RTs longer than 1,300 ms were counted as errors, which led to a loss of 0.42% of the trials. Figure 3 shows the participants' mean RTs and error percentages. There was a significant effect on RT only of display size, $F(1, 11) = 66.4$, $p < .01$. This analysis showed, as can be seen in Figure 3,

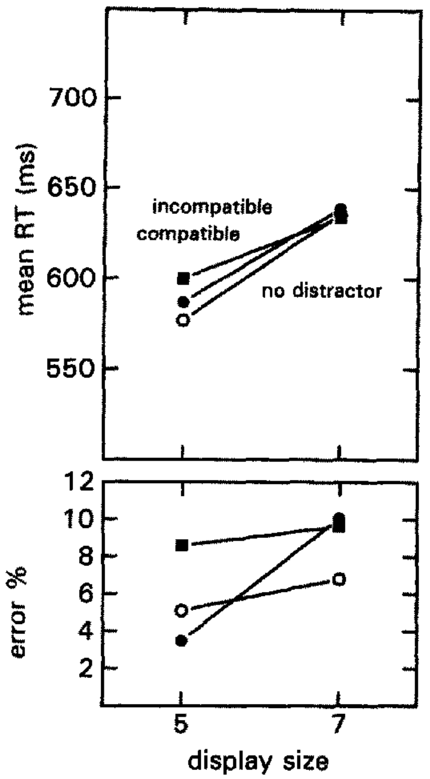

Figure 3. Experiment 2: Mean reaction times (RTs) and error percentages as a function of display size for the control, compatible, and incompatible conditions.

that search was not slowed by the presence of the singleton and that the identity of the singleton had no effect on search for the target letter. There was no evidence of an identity intrusion effect: Whether the singleton was compatible or incompatible with the target did not affect RT to the target, indicating that the singleton was ignored successfully.

There was only a main effect of display size on arcsine-transformed error scores, $F(1, 11) = 8.1$, $p < .05$. Error differences were nonsignificant and tend to mimic RT, indicating that differences in response latencies were not attributable to a speed–accuracy trade-off.

Discussion

The results of this experiment show that when participants had the opportunity to apply top-down control, they were able to direct attention only to those locations that matched the task-relevant feature. In this particular experiment, because the color of target and of the singleton distractor were fixed over trials, participants had the opportunity to selectively direct attention only to the color in which the target would be presented and, at the same time, had the opportunity to inhibit the color of the irrelevant singleton.

In terms of the visual search models (Wolfe, 1994), these results indicate that when the feature that matches the target can be activated and the feature that matches the distractor can be inhibited, search can be efficient. Highly salient singletons can be ignored successfully. Consistent with earlier studies investigating conjunction search, the current results indicate that participants can direct attention selectively only to those locations that contain task-relevant features (e.g., Egeth et al., 1984; Kaptein et al., 1995). As expected, and consistent with the contingent capture hypothesis (Folk et al., 1992), these conditions enabled participants to adopt a specific and highly selective attentional set allowing the deployment of attention only to the task-relevant stimuli.

Note that search was neither slowed down nor speeded up by the presence of the singleton. If participants can ignore the singleton without any effort and can selectively exclude the location of the singleton from search, then search in the singleton condition should have been somewhat faster. Because the location of the distractor is excluded from serial self-terminating search, one would expect participants to search, on average, half an item less. The results showed that search was not faster in the singleton condition, which may indicate that it requires effort to actively inhibit the location of the to-be-ignored singleton.

Experiment 3

In the previous experiment, both the color of the target and the color of the singleton distractor were fixed, allowing participants to both selectively direct attention to the color in which the target would be presented (e.g., attend to the red elements) and to inhibit the color of the irrelevant singleton (e.g., inhibit the green singleton). The question was whether the activation of the feature that matched the target, as assumed by Wolfe (1994), or the inhibition of the feature that matched the distractor, as assumed by Treisman and Sato (1990), was responsible for the top-down guidance through the display.

Experiment 3 was designed to determine which mechanism was responsible for the top-down control found in Experiment 2. Can participants ignore the salient singleton (e.g., the red element) because "green" is activated, or can they ignore the salient singleton because "red" is inhibited?

In Experiment 3, the letters to be searched were presented in gray, whereas the singleton to ignore was presented either in red or green, which was varied from trial to trial. Because the target color remained fixed (in this case, gray) throughout the whole experiment, we assumed that participants would have the opportunity to selectively activate the color of the target letter (e.g., activate "gray"). If activation of the target color was enough to obtain selective search, we expected that the irrelevant singleton would not affect search for the target. On the other hand, if activation of the target color was not enough to obtain complete top-down control, we expected that a singleton that varies in color randomly from trial to trial would interfere with search for the target.

Method

Participants. Twelve right-handed participants (aged 19–26 years) participated as paid volunteers. All had normal or corrected-to-normal vision and reported having no color vision defects.

Stimuli and procedure. The task was identical to Experiment 1, except that the letters to be searched were presented in gray (CIE *x,y* chromaticity coordinates of 0.29/0.31, matched for luminance to red and green). The singleton was presented in either red or green (the same CIE values as in Experiment 1). The color of the singleton varied randomly from trial to trial. Given the relatively high error scores in Experiments 1 and 2, we made the task slightly easier using Display Sizes 4 and 6 instead of 5 and 7. Because display size was reduced to six, the closest separation between the letters was now 3.2° center to center at Display Size 6. The separation between the nearest contours was 2.7°. The rest of the task was identical to Experiment 1.

Results

RTs longer than 1,300 ms were counted as errors, which led to a loss of 0.21% of the trials. Figure 4 shows the participants' mean RTs and error percentages. There was an effect on RT of display size, $F(1, 11) = 69.5, p < .01$, and of singleton, $F(1, 11) = 7.0, p < .05$. The results indicate that the presence of a singleton slowed search.

Planned comparisons on compatibility (a compatible vs. incompatible singleton) showed a main effect on RT of compatibility, $F(1, 11) = 14.3, p < .01$. This analysis indicated that the identity of the singleton did affect search for the target: When the singleton was incompatible with the response, RTs were slower than when it was compatible with the response. This finding indicates that even though the color that participants were searching for remained fixed throughout the experiment, they were unable to successfully ignore the singleton.

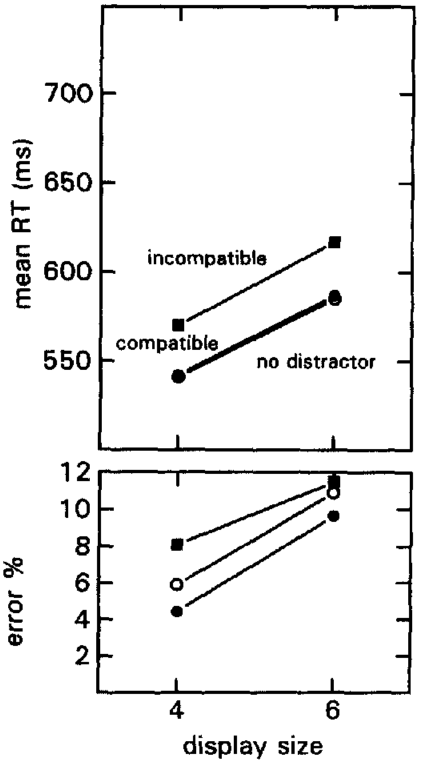

Figure 4. Experiment 3: Mean reaction times (RTs) and error percentages as a function of display size for the control, compatible, and incompatible conditions.

There was a main effect only of display size on arcsine-transformed error scores, $F(1, 11) = 14.1, p < .01$. Because this analysis showed that error differences were nonsignificant or tended to mimic RT, differences in response latencies were not attributable to a speed–accuracy trade-off.

Discussion

These findings indicate an identity intrusion effect: The identity of the singleton to be ignored had an effect on responding to the target letter, indicating that participants processed the to-be-ignored singleton. Even though participants knew what they were looking for (a gray E or R), they were unable to ignore the salient singleton distractor. Even though participants could selectively activate "gray," this was not enough to obtain selective search among the gray letters. Compared with Experiment 2, in which top-down control was found, the results of this study suggest that observers could not ignore the salient singleton because it randomly changed color from trial to trial.

In terms of the visual search models, contrary to what was suggested by Wolfe (1994), this result indicates that activation of the feature that matches the target (e.g., activate all gray elements) is not enough to obtain complete top-down control. When the salient element is unpredictable and changes from trial to trial, it will interfere with search. In terms of the contingent capture hypothesis, having an attentional set to respond only to "gray" is obviously not enough to filter salient singletons. Even though the target color was consistently predictable, attention could not be set in such a way that irrelevant singletons were filtered.

Experiment 4

Although the results of Experiment 3 clearly established that knowing what one is looking for is not enough to obtain complete top-down control, the question remains as to whether knowing what one has to inhibit will result in complete top-down control. In other words, as assumed by Treisman and Sato (1990), is inhibition of the feature that matches the distractor enough to obtain top-down guidance through the display?

In Experiment 4, the letters to be searched changed from trial to trial and were presented in either red or green, whereas the singleton was gray and remained fixed throughout the whole experiment. Because the singleton remained fixed throughout the experiment, we assumed that participants would have the opportunity to selectively inhibit "gray." If inhibition of the color singleton was enough to obtain selective search, we expected that the irrelevant singleton would not affect search. On the other hand, if inhibition of the distractor color was not enough to obtain complete top-down control, we expected that changing the color of the letter to be searched would interfere.

Method

Participants. Eight right-handed participants (aged 19–31 years) participated as paid volunteers. All had normal or corrected-to-normal vision and reported having no color vision defects.

Stimuli and procedure. The task was identical to that used in Experiment 3 except that the singleton to be ignored was presented in gray. The letters to be searched were presented in either red or green. Green, red, and gray colors were matched for luminance (11.5 cd/m^2). The color of the letters to be searched varied randomly from trial to trial.

Results

RTs longer than 1,300 ms were counted as errors, which led to a loss of 0.31% of the trials. There was an effect on RT of display size, $F(1, 7) = 60.7$, $p < .01$, and of singleton, $F(1, 7) = 18.1$, $p < .01$. These findings suggest that the presence of the singleton slowed down search.

Planned comparisons on compatibility (a compatible vs. incompatible singleton) showed a main effect on RT of compatibility, $F(1, 7) = 19.2$, $p < .01$. This analysis indicated, as can be seen in Figure 5, an identity intrusion effect: When the singleton was incompatible with the response, RTs were slower than when it was compatible with the response. This finding indicates that even though the color of the singleton was fixed throughout the experiment, participants were unable to ignore processing the singleton.

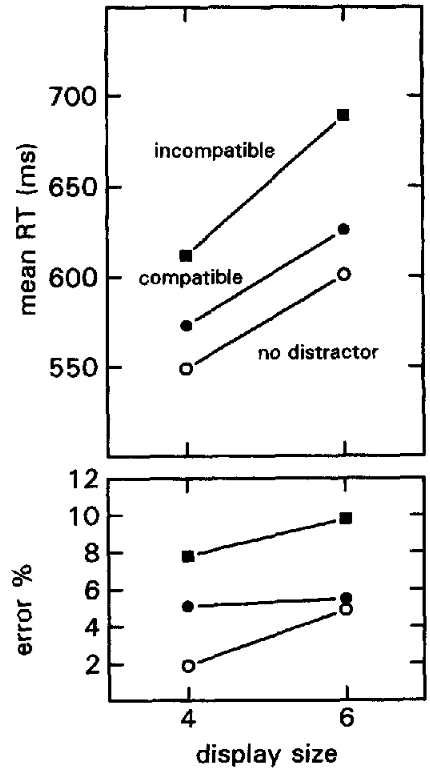

Figure 5. Experiment 4: Mean reaction times (RTs) and error percentages as a function of display size for the control, compatible, and incompatible conditions.

There was a main effect only of display size on arcsine-transformed error scores, $F(1, 7) = 7.2$, $p < .05$. Because this analysis showed that error differences were nonsignificant or tended to mimic RT, differences in response latencies were not attributable to a speed–accuracy trade-off.

Discussion

This result shows that even when participants knew what they had to ignore (i.e., "ignore the gray letter"), they were unable to do so. Compared with Experiments 2 and 3, obviously knowing what they had to ignore was not enough for participants to obtain complete top-down control. To successfully ignore the singletons, one must know both the color one is looking for and the color that has to be ignored.

General Discussion

These experiments were conducted to test the degree of top-down control over attentional capture by an irrelevant singleton during serial search. The results indicate that it is only possible to ignore processing an irrelevant singleton when both the target color and the distractor color are known and remain fixed over trials. When either the color of the target or the color of the distractor vary over trials, participants are not able to filter the distractor. The presence of the identity intrusion effect indicates that participants did actively process the to-be-ignored singleton, suggesting that attention was captured by the singleton.

Our results are consistent with some data reported earlier by Remington and Folk (1994). In that study, participants searched for an unpredictable color singleton (i.e., either an orange, green, or violet singleton). When the search display was preceded by a cue consisting of a red singleton (a color that was unlike any of the target colors), attention was captured by the cue. The reasoning was that if attention could be set to exclude everything red (i.e., a not-red setting), then the red cue would not capture attention. The results showed that participants were unable to ignore the cue, indicating that it was impossible to have an attentional set for the negation of a distractor color. Note that when the target color remained fixed over trials, participants had no trouble ignoring the red singleton, which suggests that if the color of the target and the color of the cue are known, participants are able to exclude the cue. On the other hand, when the color of the cue is known (fixed over trials) and the color of the target is unknown (varied over trials), it is impossible to exclude the cue, and attention is captured. Remington and Folk (1994) concluded that one can selectively filter distractors when one can adopt an attentional set for a specific feature value (i.e., have an attentional set to respond to green). If the target is not consistently predictable (either green, violet, or orange), attention is broadly set to respond to any singleton.

Our findings are similar to those reported by Remington and Folk (1994). Only in our Experiment 2, in which both the color of the target and the color of the singleton were fixed over trials, did we find that it was possible to ignore processing of the irrelevant singleton. This condition is similar to Remington and Folk's condition in which both the cue and the target were fixed over trials. In Remington and Folk's experiments, attentional capture was found in conditions in which the color of the target varied and the color of the cue was fixed, conditions similar to those of our Experiment 4. Like Remington and Folk, we also found that under these conditions, attentional capture by the irrelevant singleton could not be prevented. Remington and Folk did not test the conditions that were run in our Experiment 3, in which the color of the target was fixed and the color of the distractor varied. Because these conditions were not tested, Remington and Folk concluded that it was important that the target color be predictable in order to obtain top-down control. Our findings indicate that in order to obtain top-down control, both the target color and the distractor color should be predictable.

There are, however, important differences between Remington and Folk's (1994) study and our study. The most important difference is that in their study, participants had to respond to a singleton in the search display while ignoring a singleton in the cue display. In our experiments, however, participants did not search for a singleton. Instead, participants searched for a target letter among other nontarget letters while having to ignore a singleton. The failure to inhibit capture by the irrelevant singleton in Remington and Folk's study could have been due to the fact that in conditions in which the color of the target changed from trial to trial, participants had no other choice than to adopt a "singleton detection" mode (Bacon & Egeth, 1994). In this attentional setting, attention is captured by anything that stands out from the display ("odd man out"). In our experiments, it seems unlikely that participants adopted a singleton detection mode because this setting would not help in finding the target because the target was never the odd-man-out element. In fact, this particular setting would result in attentional capture by the irrelevant singleton. Even though it is counterproductive to respond to the odd man out and the opposite of what participants were instructed, it may be that this was the only attentional setting that participants were able to adopt when the color of the target or the color of the distractor varied.

In terms of the visual search models, it seems that neither the activation of the color feature that matches the target, as assumed by Wolfe's (1994) model, nor the inhibition of the color feature that matches the distractor, as assumed by Treisman and Sato's (1990) model, is enough to overcome the bottom-up activation caused by the irrelevant singleton. It appears that both mechanisms, activation of the relevant color and *at the same time* inhibition of the irrelevant color, are required to ensure complete top-down control over search. In terms of the visual search models, these results suggest that either the simultaneous inhibition of two colors (inhibition of red and green in Experiment 3) or the simultaneous activation of two colors (activation of green and red in Experiment 4) cannot be done effectively to ensure complete top-down control. Note that in Experiments 3 and 4, the colors to ignore and the colors to attend to were distinctive (i.e., red, green, and gray). In addition, in Experiments 3 and 4, the color of the target and the color of the singleton distractor never changed roles: The color to attend to (e.g., the target color) was never a color to ignore (e.g., a singleton color), and vice versa. These conditions should have allowed participants to set the appropriate top-down control settings (cf. consistent mapping; Shiffrin & Schneider, 1977).

Consistent with various visual search models, we assume that the attentional serial stage is guided by information available at the early preattentive parallel level (e.g., Wolfe, 1994). Given this notion, we also assume that color is used to guide attention serially to those locations that are likely to contain the target. For example, in Experiment 3, in which the target was a gray letter E or R and the distractor changed color from trial to trial, we assumed that first, in parallel, the display is parsed in gray and not-gray letters and that attention is subsequently selectively deployed only to the gray elements. Our results indicate that this does not occur; it is impossible to exclude the distractor from search, indicating that attention cannot be limited only to the color gray if the color of the distractor changes from trial to trial. Yet, alternatively, it may be argued that if shape information is available at the early parallel level, as assumed, for example, by the guided search model (Wolfe, 1994), then it is likely that there is some attentional deployment to the distractor because it has a shape that matches that of the target. This would suggest that there is capture of the distractor not because of its saliency but because it has a shape that matches that of the target. Consistent with this reasoning, the results of our experiments do show, however, that when the colors of the target and the distractor are known and remain fixed over trials (as in our Experiment 2), it seems to be possible to exclude the shape information at the early parallel level, so that there is no attentional deployment toward the singleton.

Along similar lines, a limited-capacity parallel model of visual search (e.g., Townsend, 1972) would also predict an identity intrusion effect when it is assumed that the distractor to be ignored will be processed along with the target and the nontarget letters. Only when both target and distractor colors are known (as in our Experiment 2) should the speed with which the distractor is processed be slower than the speed with which the target is processed, explaining the absence of an identity intrusion effect. Even though such a model is viable, given that we used a letter search task that is typically assumed to produce serial search among items (e.g., Wolfe, 1994), we focus here on models that assume that after preattentive segmentation of the visual field, attention is serially deployed to each item in turn.

Our experiments were conducted to test the degree of top-down control over the deployment of attention during serial search for a target letter. The search functions indicate that search for the target letter was indeed serial, which is a fairly typical result for these types of search tasks (see, e.g., Jonides & Yantis, 1988). In Experiments 1, 3, and 4 there was an identity intrusion effect, suggesting that at some point during search through the display, attention was directed at the location of the singleton. In principle, there are two ways to explain the identity intrusion effect observed in our experiments. First, attention may have been captured

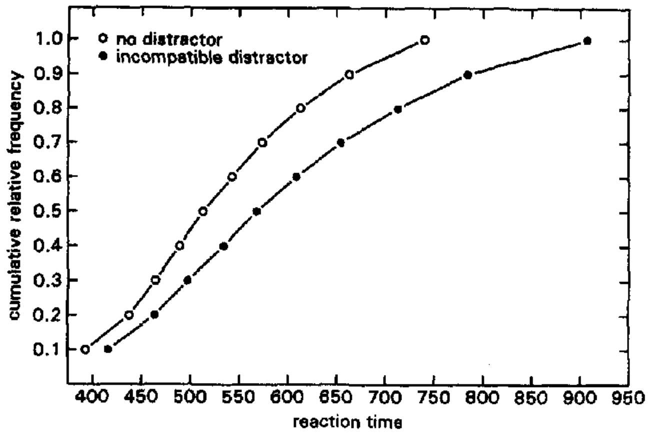

Figure 6. Vincentized reaction time distributions for the no-distractor and incompatible distractor conditions for Experiment 3.

by the singleton, suggesting that attention was directed at the location of the singleton before the other display elements were searched. Because the identity of the singleton was processed before processing of the target letter, an identity intrusion effect showed up. An alternative to this explanation would be that attention is not captured by the singleton but instead that search proceeds serially through the display and that the singleton is treated like any other element in the display. If on some trials, the target letter is found before search hits the singleton distractor, then it would be expected that for these trials the singleton has no effect. If, on the other hand, the singleton is processed before the target letter, an identity intrusion occurs. In this latter explanation, although one still has to account for why it is not possible to ignore the singleton during serial search (i.e., why not simply skip the salient element during serial search), the results would not necessarily imply that attention was captured by the singleton.

To address this issue, we analyzed the cumulative RT distributions of Experiments 3 and 4. The individual distributions for each observer and condition were averaged with the Vincentizing procedure (Ratcliff, 1979) for each experiment. If the singleton is treated as just another display element, it would be expected that at least on some portion of the trials, the target will be found before the singleton. This holds for both the compatible and incompatible distractor conditions. In fact, it does not matter whether the singleton is compatible or incompatible because the target is found and a response is emitted before the singleton is processed. Because it is not clear to what extent a compatible distractor (when processed) speeds up responding to the target we used only the incompatible distractor conditions in this analysis.

If on some portion of the trials, the target is processed before the distractor, then it would be expected that for these trials the RT for the distractor condition will be the same as the RT for the control condition, in which no distractor is present. Therefore, one would expect that the fastest RTs in the distractor condition, which supposedly represent those trials in which the target is found before the distractor, are basically the same as the fastest RT in the no-distractor condition. However, if attention is captured on each trial, then there should be no set of RTs that are particularly fast; instead, one would expect that the whole distribution would shift along the time axis. Figures 6 and 7 show the distributions for the no-distractor and incompatible distractor conditions. As can be seen in these figures, the fastest RTs in the distractor conditions were always slower than the fastest RTs in the no-distractor condition: Experiment 3, $t(11) = 7.0, p < .05$; Experiment 4, $t(7) = 14.9, p < .01$. This suggests that it is unlikely that a portion of the trials reflected serial search without processing the singleton distractor. Because the distribution of the RTs of the incompatible distractor condition of Experiments 3 and 4 did not contain a particularly fast set of RTs, it can be concluded that on each trial, attention was directed to the location of the singleton before the other display elements were searched. This analysis indicates that the identity intrusion effect as observed in Experiments 3 and 4 was attributable to capture of attention to the location of the to-be-ignored singleton.

Previous studies that have demonstrated top-down guidance in search (e.g., Egeth et al., 1984; Kaptein et al., 1995; Treisman, 1988; Wolfe, 1994) have not explored the effects on top-down guidance in the presence of salient singletons. In addition, unlike previous paradigms, our identity intrusion paradigm is highly sensitive in revealing any processing of to-be-ignored display elements. If ignoring fails, and consequently the identity of the display element becomes available because of the response-compatibility manipulation (e.g., B. A. Eriksen & Eriksen, 1974; C. W. Eriksen & Hoffman, 1972), it is likely that a compatibility effect will show up in the RT data. In a typical conjunction search task, however, in which participants have to ignore green and search the red elements, observers may process a green element (see, e.g., Kaptein et al., 1995). Yet, because processing of the identity of a green element has no consequences, attention may be withdrawn quickly, and the RT data suggest that the irrelevant green elements were successfully ignored. The data may suggest complete top-down control on the part of the observer, yet the manipula-

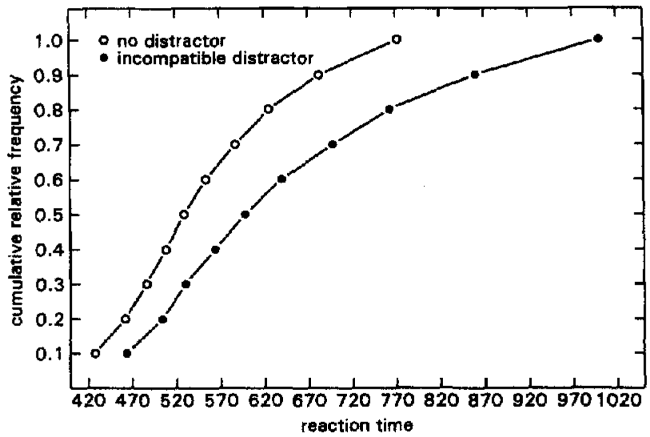

Figure 7. Vincentized reaction time distributions for the no-distractor and incompatible distractor conditions for Experiment 4.

tion was obviously not sensitive enough to reveal any processing of the to-be-ignored elements. The same reasoning may hold for conditions in which observers are able to override attentional capture by irrelevant singletons (i.e., "feature detection mode"; see Bacon & Egeth, 1994). Again, it is likely that the irrelevant singleton did capture attention, yet, because processing the singleton had no consequences, attention can be quickly withdrawn and the absence of an effect of the singleton is interpreted as evidence for complete top-down control. Because our paradigm is powerful in revealing any processing, it is also reasonable to argue that in case of our Experiment 2, in which selection was successful, the singleton was ignored and never processed. Under these circumstances, participants were able to prevent capture by the singleton.

Consistent with earlier work showing attentional capture by singletons during parallel search (Theeuwes, 1991, 1992, 1994), the present study shows that during serial search, static singletons also may capture attention. We assumed that a static salient singleton generates a large bottom-up activation, which in most cases will affect the allocation of attention (see also Koch & Ullman, 1985; Sagi & Julesz, 1985; Wolfe, 1994). As demonstrated in our Experiment 2, only with maximum opportunity to apply top-down control (i.e., knowing what to attend to and knowing what to inhibit consistently over trials) could the effect of this large activation be eliminated. Only in these circumstances can attentional capture be prevented. The results are consistent with the notion that the ability to selectively filter singleton distractors during serial search depends on the presence of an attentional set for a specific feature value of both the target and the distractor. The results suggest that in the absence of either a consistently predictable target color or distractor color, attention is captured by the singleton distractor.

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