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Bottom – up and top – down control in visual search

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Abstract. Previous research suggests that the allocation of attention is largely controlled either in a stimulus-driven or in a goal-driven manner. To date, few studies have systematically manipulated variables affecting stimulus-driven and goal-driven selection independently in order to investigate how both manners of control interrelate and affect performance in visual search. In the present study observers were presented with search displays consisting of an array of line segments rotated at various orientations. The task of observers was to indicate the presence or absence of a vertical line segment (the target) presented amongst a series of nontargets and possibly one distractor. By varying the absolute differences in orientation between the target, nontargets, and distractors, relative target – distractor salience and target – distractor similarity were independently manipulated to investigate the contribution of stimulus-driven and goal-driven control. The major result was that relative target – distractor salience and target – distractor similarity affected search performance independently. Performance was better in cases where the irrelevant distractor was not a salient item in the search display and did not look similar to the target. The results are discussed in terms of models of attentional control.

1 Introduction

A major question regarding the allocation of visual attention is whether selection is ultimately determined by the stimulus properties in the visual field or by the goals and intentions of the observer (Egeth and Yantis 1997; Theeuwes 1993, 1994; Yantis 1996, 2000). While it is generally agreed that both manners of selection influence attentional performance, few studies have simultaneously manipulated variables that independently affect stimulus-driven and goal-driven selection. Nevertheless, the independent manipulation of such variables would be important to investigate how they interrelate and influence overall attentional performance (see Kim and Cave 1999). Traditionally, search models emphasise the importance of either stimulus-driven or goal-driven selection processes.

Several studies suggest that attentional control is dominated by the stimulus properties in the visual field (Sagi and Julesz 1985; Theeuwes 1991, 1992, 1994; Theeuwes et al 2000; Wolfe 1998; Yantis 2000; Yantis and Hillstrom 1994). According to these bottom – up models of attention, selection is primarily stimulus-driven. For example, Theeuwes (1991, 1992, 1994) found that, if observers have to search for a prespecified target that is unique in a basic visual dimension (eg searching for a diamond among circles), the presence of an irrelevant distractor (such as a single red circle among the otherwise grey elements) strongly disrupts search if the irrelevant distractor is more salient than the target (Theeuwes 1991, 1992, 1994). On the basis of such results, Theeuwes claims that the allocation of attention is ultimately determined by the relative salience of the stimuli in the visual field. Goal-driven control may play a role, but only after attention has been captured by a salient element (Theeuwes 1992; Theeuwes et al 2000). Recently, Kumada (1999) also showed that knowledge of the target identity could not override the effect of the presence of an irrelevant distractor. Kumada (1999) had participants search for a rectangle tilted 45° to the left amongst multiple vertically oriented rectangles. In one condition, an irrelevant distractor was presented.

The distractor could either be a rectangle tilted 45° to the right or a rectangle tilted 22.5° to the right. Kumada's major finding was that, irrespective of the identity of the distractor, search performance was worse in the distractor condition than in a condition in which no distractor was presented. Knowledge of the target identity could not override the interference from an irrelevant distractor (Kumada 1999). These results were similar to those previously obtained by Theeuwes (1991, 1992, 1994), with the notable difference that in Kumada's study irrelevant distractors always captured attention irrespective of their salience, whereas in Theeuwes's studies (1991, 1992, 1994) only distractors that were more salient than the target captured attention. Thus, according to bottom–up models of attention, attention is primarily driven by stimulus properties. Goal-driven selection may play a role, but only after and conditioned on initial stimulus-driven selection. That is, the effect of any variable affecting goal-driven processes should depend on the efficiency of stimulus-driven processes.

In contrast to this bottom–up view, others (Bacon and Egeth 1994; Folk and Remington 1998; Folk et al 1992; Muller and Rabbitt 1989; Pashler 1988) have suggested that attentional selection is initially determined by the goals of the observers. According to this top–down view of attention, a highly salient element does not automatically capture attention. Instead, shifts of attention occur only if they are in accordance with a specific goal setting. For example, Folk et al (1992) assume that observers can confine their search to one specific feature value and are able to override interference from any element lacking this feature value. By this, the orienting of attention to a stimulus event is contingent on whether the event shares a feature property that is critical to the task at hand. This 'contingent involuntary orienting hypothesis' (Folk et al 1992) predicts that, when one looks for a target of a certain colour, capture of attention by an irrelevant distractor will happen only when the irrelevant distractor is also unique with respect to that colour and not, for example, when the irrelevant distractor is unique in another colour. Bacon and Egeth (1994) also argued that irrelevant singletons do not necessarily attract attention automatically. According to Bacon and Egeth (1994) irrelevant feature singletons may or may not cause distraction during search for a known target, depending on the search strategy employed. Observers may choose to rely on a mode of processing that identifies elements that differ from their backgrounds, a singleton detection mode, or may choose to monitor a specific feature, referred to as feature detection mode. Only when people are tuned to the singleton detection mode will irrelevant salient distractors hinder search performance (Bacon and Egeth 1994). An irrelevant distractor will not hamper performance when observers are set to search for a particular feature. While some authors (Bacon and Egeth 1994; Folk et al 1992) argue that observers are able to confine their search to a certain feature value, others (Muller et al 1995; Pashler 1988) take a less extreme position and suggest that subjects can confine their search only to a certain feature dimension. Thus, according to a top–down model of selection, initial selection is assumed to be determined by the goals and intentions of an observer. Stimulus-driven selection may take place, but only after and contingent upon goal-directed selection. That is, it is assumed that a salient stimulus will capture attention if it shares features with a target an observer is searching for.

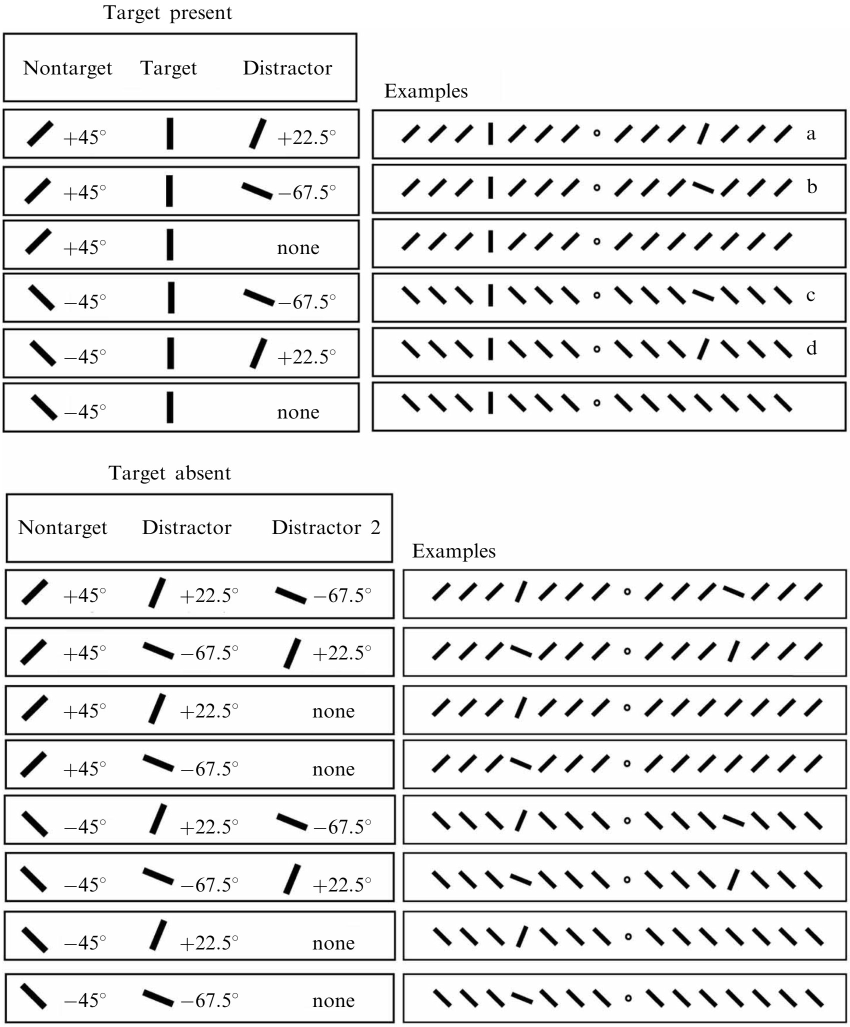
To briefly summarise, whereas bottom–up models argue that initial selection is blind to identity and is driven predominantly by the salience of elements, top–down models of attention argue that observers primarily select objects based on a certain identity (ie feature dimension or feature value). Typically, evidence in favour of bottom–up models of attention is obtained from visual-search experiments in which an irrelevant distractor singleton is either present or not (Theeuwes 1991, 1992, 1994). These studies show that the presence of a highly salient singleton distractor generally disrupts search. This finding is taken as evidence for the claim that attention is primarily stimulus-driven.

However, the results obtained in these studies do not necessarily imply that the initial allocation of attention is completely unaffected by goal-driven factors. In fact, goal-driven processing might have played a role such that the effect of the distractor might have been modified depending on the current goals of the observer. Indeed, several studies (Treisman and Gelade 1980; Treisman and Sato 1990; Yantis and Egeth 1999) have shown that if participants know the identity of a singleton target in advance, they respond faster to its presence than when the target identity is not known. These results suggest that goal-driven control influences initial selection. A top – down account of attentional selection may account for the results if one assumes goal-driven control to successfully act to select the target location on some trials, yet fail to select the target location in other trials (see Kim and Cave 1999). Nevertheless, studies that have emphasised the importance of stimulus-driven selection (Theeuwes 1991, 1992, 1994) have never considered goal-driven control to affect initial selection.

In contrast to the above, evidence for top – down models of attention has typically been obtained in cueing studies. For instance. Folk et al (1992) performed an experiment in which (150 ms) prior to the presentation of a search display an irrelevant cue was presented at one of four potential target locations. Participants had to indicate the identity of a target ('X' versus '=') that was presented as a single onset for one group of participants, or as a colour singleton amongst elements of another colour for another group of participants. The results showed that an invalid location cue disrupted search performance only if the cue possessed a stimulus property that was used to locate the target. Cues with task-irrelevant properties did not disrupt performance. Folk et al (1992) concluded that, because observers adopt an attentional set specifying the target features, cues sharing properties with the target provoke involuntary shifts of attention to their location (Folk and Remington 1998; Folk et al 1992). Recently, Theeuwes and Godijn (2001) argued that the results obtained by Folk et al did not conclusively prove that participants' performance was initially goal-driven. In fact, it is possible that, regardless of its properties, the singleton cue did capture attention. Subsequent disengagement of the cue might have been relatively fast when the cue and the target did not share the same defining property while disengagement might have been relatively slow when the cue and target shared the same defining property. As a consequence, performance was disrupted to a greater degree in the latter than the former case. Given these considerations, it is questionable whether the results obtained in cueing studies are really indicative of initial goal-driven control.

The aim of the present study was to investigate the contribution of stimulus-driven and goal-driven control of attention by independently manipulating factors that contribute to either type of control. Whereas evidence for stimulus-driven selection is obtained in cases where highly salient irrelevant items disrupt search performance, evidence for goal-driven selection is obtained in cases where search is affected by items that share target-defining properties. In order to investigate both stimulus-driven and goal-driven control simultaneously, distractor salience and target – distractor similarity were manipulated. If differences in search performance are found between those conditions where stimulus salience is high and those where stimulus salience is low, one may conclude that stimulus-driven control processes contribute to visual-search performance. In contrast, if differences are found between those conditions where target – distractor similarity is high and those conditions where target – distractor similarity is low, one may conclude that goal-driven processes affect search performance.

In the present work, observers were presented with displays containing one target, multiple nontargets, and possibly one distractor (see figure 1). The nontargets consisted of a homogenous group of elements different from the target. The distractor was a single element different from the nontargets and target. All elements consisted of line



[a] Distractor is not salient; target – distractor similarity high
[b] Distractor is salient; target – distractor similarity low
[c] Distractor is not salient; target – distractor similarity low
[d] Distractor is salient; target – distractor similarity high

Figure 1. Stimuli and conditions presented.

segments rotated along the vertical axis.(1) The task of observers was to indicate the presence or absence of the target. The irrelevant distractor presented was either a salient item in the display or was not, and either looked similar to the target or did not. Furthermore, accidental changes in distractor salience due to changes in target – distractor similarity were controlled for.

Speaking in terms of models of attention control, according to a bottom – up model selection is expected to be contingent upon salience. Target – distractor salience is predicted to affect performance. It is expected that reaction time (RT) is shorter in conditions where the target is more salient than the distractor as compared to conditions in which the distractor is more salient than the target. According to a bottom – up

(1) It should be noted that the size of an orientation difference between an element and its background is directly correlated with the salience of this element, ie the larger the difference in orientation, the faster the detection time (eg Theeuwes 1991, 1992; Wolfe and Friedman-Hill 1992).

model an effect of target – distractor similarity may exist but depends on whether or not elements were selected on the basis of salience in the first place. In this case, one predicts a larger effect of target – distractor similarity when the distractor was the most salient item in the search display as compared to when the target was the most salient item. Thus, a bottom – up view predicts a main effect of relative target – distractor salience and possibly an effect of target – distractor similarity depending on salience.

A top – down model of attention assumes attentional selection to be contingent on target – distractor similarity. Selection is identity based. Reaction times are predicted to be longer when a distractor similar to the target is presented than when a distractor dissimilar to the target is presented. In addition, the relative salience of the target and distractor might also affect visual selection behaviour. However, the extent of the effect is assumed to depend on the target – distractor similarity. If the distractor is similar to the target, the effect of distractor salience is assumed to be larger than if the distractor is dissimilar to the target.

2 Method

2.1 *Participants*

Eight students of the Vrije Universiteit Amsterdam participated as paid volunteers in a 45 min session. Two participants were replaced due to poor accuracy ($\geqslant$11% errors). Participants ranged in age from 22 to 30 years and all reported having normal or corrected-to-normal vision.

2.2 *Apparatus*

A Celeron 400 mHz 128 kb PC with a 19 inch colour monitor (ATI Rage 4 mB card) controlled the timing of the events and the generation of the stimuli. Display resolution was 1280×1024 pixels. The '/' key and the 'z' key of the computer keyboard were used as response buttons. All subjects were tested in a sound-attenuated, dimly lit room with their heads resting on a chin-rest. The monitor was located at eye level 95 cm from the chin-rest.

2.3 *Task and stimuli*

Participants performed a visual-search task in which they had to indicate whether or not a target was present. The target was always a vertical line (ie 0° relative to the vertical). The target was presented in 50% of the trials. In the target-present trials, displays consisted of 1 target, 108 nontargets (oriented +45° or −45° relative to the vertical) and 1 distractor (oriented −67.5° or +22.5° relative to the vertical) or of 1 target, 109 nontargets and no distractor. The stimuli were presented in 5 rows of 22 items each. If present, the target was presented in the middle row of elements. The target-absent trials were identical to the target-present trials except that the target was replaced by a nontarget (oriented +45° or −45° relative to the vertical) or an element oriented −67.5° or +22.5° relative to the vertical. The orientation of the element replacing the target was always different from that of the distractor (see figure 2).

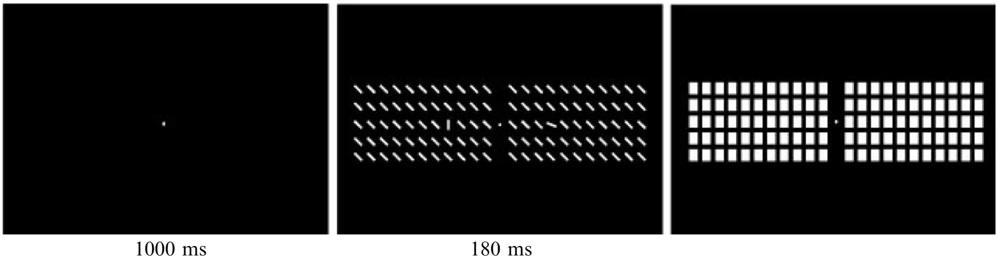


Figure 2. Example of display as presented.

The absolute difference in orientation between the target and the nontargets was always 45°. The absolute difference in orientation between the two types of distractors and the nontargets was either 22.5° or 67.5°. Salience was taken as the amount by which an element's orientation differs from that of the nontarget. When the absolute difference in orientation between the distractor and the nontargets was 67.5° the distractor was more salient than the target than when this difference was 22.5°.[(2)] Target – distractor similarity was high when the distractor was oriented at +22.5°, and target – distractor similarity was low when the distractor was oriented at −67.5°.

Items had an approximate height of 0.60 deg of visual angle and approximate width of 0.24 deg. Items were white (CIE *x*, *y* coordinates of 0.278, 0.316; 43.70 cd m^{-2}) and were presented on a black background. The stimuli were presented in 5 rows of 22 items each (5 × 22 raster). In each row 11 items were presented on each side of central fixation. Stimuli were presented in a region that subtended 18.5 deg × 4.22 deg. Distractors were always presented on the opposite side of fixation relative to the target (or opposite to the element replacing the target) at an equidistant location from the central fixation point. Targets could be presented either at the fourth or the eighth position relative to the fixation point (retinal eccentricity of 3.61° and 6.90°, respectively). Eccentricity was varied to prevent an attentional bias to certain locations. Targets were presented to the left or right side of fixation with equal probability, but they could only appear at the horizontal midline (middle row out of 5). In order to exclude the effects of eye movements, stimuli were presented for 180 ms and were masked after presentation by bright-white squares (CIE *x*, *y* coordinates of 0.278, 0.316; 43.70 cd m^{-2}).

2.4 *Design and procedure*

A within-subjects design was used. Each participant performed 64 practice trials and 640 experimental trials. Target presence (target present and target absent), target position (retinal eccentricity of 3.61° and 6.90° left of fixation and 3.61° and 6.90° right of fixation), and distractor presence (distractor present and distractor absent) were independently manipulated. The order of trials was randomised. 25% of the total number of experimental trials (ie 160 trials) were trials in which both a target and a distractor were presented. Within those trials, there were two possible distractor identities (+22.5° or −67.5°) and two possible nontarget identities (−45° or +45°) resulting in four different combinations of relative target – distractor salience and target – distractor similarity (see figure 1). The remaining 75% of the trials consisted of 160 target-present – distractor-absent trials and 320 target-absent trials. In order to avoid subjects responding on the basis of global appearance, and to match the appearance of the target-absent trials with the target-present trials, two types of target-absent trials were presented: 160 target-absent – 1 distractor-present trials, and 160 target-absent – 2 distractors-present trials. In the target-absent – 2 distractors-present trials the 2 distractors presented were never identical to one another.

To make sure participants understood the task correctly, they were given both written and oral instruction. To start a trial, participants pressed the space bar, after which a fixation point was presented for 1000 ms, followed by the stimulus array, which was presented for 180 ms. Stimuli were masked by white cubes following presentation.

[(2)] A small pilot study was carried out to test whether the target – distractor similarity as such did not affect relative item salience. Four participants reported the presence or absence of a deviant line (lines either had an orientation of 0°, +22.5°, or −67.5° relative to the vertical) amongst nontargets oriented at either −45° or +45°. Depending on the nontargets presented, the deviant line segments were relatively salient or not. Participants showed an effect of relative salience only. Participants were faster to report the presence of a salient element than of a nonsalient element. Moreover, no significant difference in performance was found between the +22.5° and the −67.5° line element when they were presented either as salient or as not salient. This suggests that type of distractor (ie +22.5° or −67.5°) did not affect the relative salience of the distractor.

Subjects were instructed to respond as quickly as possible while maintaining a high level of accuracy. Participants were explicitly instructed to keep their eyes fixated on the central fixation cross. Feedback was presented every 40 trials. Participants were free to take a break every 120 trials.

3 Results

Response times (RTs) longer than 2000 ms were counted as errors and excluded from the RT analysis. This resulted in the removal of 0.51% of all observations and an average of 6.0% overall error rate. Participants more often erroneously reported the target to be absent when it was present (8.2% misses) as compared to present when it was absent (3.8% false alarms; $t_7 = 2.53$, $p < 0.05$). There were no systematic differences in errors across conditions. Only the correct responses in target-present trials are included in the RT analysis.

A three-way analysis of variance (ANOVA) was performed on the correct RTs for the target-present – distractor-present trials only with eccentricity (high and low), target – distractor similarity (low and high), and relative target – distractor salience (target most salient and distractor most salient) as factor variables. All main effects were significant (eccentricity: $F_{1,7} = 19.52$, $p < 0.01$; target – distractor similarity: $F_{1,7} = 6.65$, $p < 0.05$; relative target – distractor salience: $F_{1,7} = 7.79$, $p < 0.05$). RTs were longer when the eccentricity was high than when it was low. RTs were longer when the target and distractor looked alike (ie if the distractor had an orientation of 22.5°) than when they did not look alike (ie if the distractor had an orientation of −67.5°). Furthermore, RTs were longer when the distractor was the most salient item in the display than when the distractor was not the most salient item in the display. No interactions were found between eccentricity, target – distractor similarity, and relative target – distractor salience. Importantly, there was no interaction between target – distractor similarity and relative target – distractor salience ($F_{1,7} = 0.1$). The mean correct RTs and the error percentages for the target-present trials, collapsed over eccentricity, are plotted in figure 3.

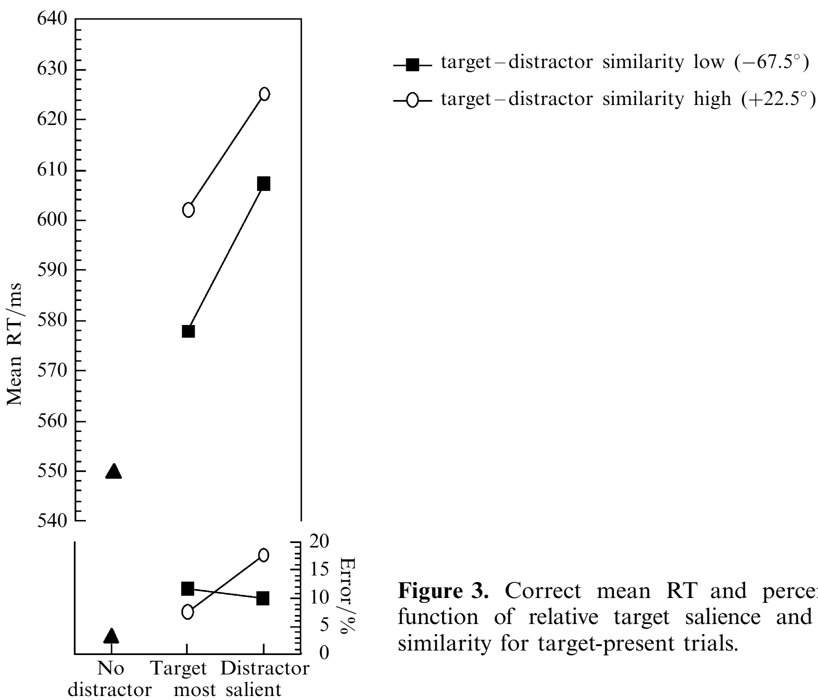


Figure 3. Correct mean RT and percentage error as a function of relative target salience and target – distractor similarity for target-present trials.

As eccentricity did not interact with target – distractor similarity nor with target – distractor salience, for the remainder of closer analysis, trials were collapsed over eccentricity. Comparison of the mean correct RTs of target-present – distractor-present trials (mean 603 ms) with target-present – distractor-absent trials (mean 550 ms) showed a significant effect of distractor presence ($t_7 = 5.78$, $p < 0.01$). Even in the case of a low-salience distractor dissimilar to the target (mean 578 ms), a significant effect of distractor presence was found ($t_7 = 3.79$, $p > 0.01$). In general, RTs were shorter when no distractor was present than when a distractor was present.

An ANOVA was performed on the distractor-absent trials where only one distractor was presented, with target – distractor similarity (low and high) and distractor salience (distractor not salient and distractor salient) as factors. A main effect of target – distractor similarity was found ($F_{1,7} = 15.83$, $p < 0.01$), as well as an effect of distractor salience ($F_{1,7} = 6.11$, $p < 0.05$). No interaction was found between target – distractor similarity and distractor salience ($F_{1,7} = 2.37$, $p > 0.1$). Participants took longer to make an "absent" response when the single distractor presented was not salient. Furthermore, participants took longer to make an "absent" response when the single distractor presented looked similar to the target.

4 Discussion

The major result is that relative target – distractor salience and target – distractor similarity affected search performance independently. Participants took longer to respond when the distractor was a salient item in the display than when the distractor was not a salient item. When the irrelevant distractor looked similar to the target, participants took longer to respond than when it was dissimilar to the target. Finally, the presence of a distractor always affected search even if the distractor was not salient.

In line with a bottom – up model, the present study shows that responses were faster in trials where no distractor was presented than in trials where distractor was presented concurrently. Furthermore, relative target – distractor salience influenced performance in the sense that observers were slower to respond to the presence of the target if the concurrently presented distractor was higher in salience than the target, as compared to when the distractor was lower in salience than the target. Previous studies have also demonstrated that relative target salience influences search performance. For example, Theeuwes (1992) showed that the extent to which an irrelevant distractor hinders search strongly depends on the relative target – distractor salience. However, in contrast to the present findings, Theeuwes (1991, 1992, 1994) failed to find any interference of an irrelevant distractor when this distractor was less salient than the target. It is important to point out that in Theeuwes's study the target always was unique in one dimension whereas the distractor was unique in another dimension. In our study, both target and distractor were unique in the same dimension, ie orientation. Possibly, a less salient distractor only disrupts search if its salience is defined in the same feature dimension as the target. If distractor and target are unique in different dimensions, interference may only occur if the distractor is more salient than the target [for a similar account see Kumada (1999)].

That we found additive effects of target – distractor similarity is in disagreement with the predictions of a bottom – up model. Bottom – up models of attention (Theeuwes 1991, 1992, 1994) predict that an effect of target – distractor similarity may exist but depends on whether or not elements were selected on the basis of salience in the first place. The effect of target – distractor similarity should be larger if the distractor is more salient than the target. This was not the case. Target – distractor similarity influenced search independently from target – distractor salience. It should be noted that in the present study target – distractor similarity was varied completely separately from relative target – distractor salience. As a result, a change in the target – distractor similarity was not accompanied by an accidental change in relative target – distractor salience. Nevertheless, responses were faster if the target and distractor were dissimilar than when they were similar. Thus, while bottom – up models assume identity information only to affect search performance contingent on the efficiency of stimulus-driven selection, the present results show that identity information affects search performance independently of stimulus-driven selection.

The finding that target – distractor similarity affected overall search performance is in line with top – down models of attentional control. Observers have more difficulty correctly selecting the target when an irrelevant distractor resembling the target is present than when a distractor dissimilar to the target is present. This suggests that attentional selection is influenced by goal settings. However, current top – down models of attentional selection cannot fully explain our results. For example, Folk et al (1992) argue that an irrelevant distractor will capture attention only when the distractor is defined by the same *feature value* as the target. The present results, however, show that elements defined by feature values other than the target draw attention. This suggests that, in contrast to the claims of Folk et al (1992), the allocation of attention is not contingent upon goal settings defined in terms of *exact* feature values. In comparison, if an observer could have an attentional set for a certain dimension, as suggested by other authors (Muller et al 1995; Pashler 1988), observers should have been indifferent to various feature values within a dimension. By this, the two types of distractors, characterised by different feature values within the same feature dimension, should yield similar results. Contrary to this, however, the present results show that target – distractor similarity had a profound effect on search performance. This suggests that observers' attentional set is defined neither in terms of exact feature values nor in terms of general feature dimensions. The present results show that the allocation of attention is contingent upon goal settings that are defined in terms of imprecise feature values. Despite the work of Folk et al (1992), feature values do not seem to be defined in an all-or-none manner. Instead, goal settings appear to be specified in a graded fashion in which feature values closer to the target value have a larger chance to be selected than feature values that are very different from the target value.

We see, then, that, whereas bottom – up models of attentional selection account for the effects of relative target – distractor salience, top – down models explain why target – distractor similarity affects search performance. However, neither type of model is able to account for the additive effects of relative target – distractor salience and target – distractor similarity. In fact, the finding that relative target – distractor salience and target – distractor similarity influenced search independently is not in line with any model assuming a contingency of one type of control upon another type of control. Because no interaction was found between relative target – distractor salience and target – distractor similarity, it is unlikely that stimulus-driven selection is contingent upon goal-driven selection or the other way round. Instead, stimulus-driven and goal-driven control seems to independently affect the allocation of attention.

The results of the present study strongly suggest that attentional selection occurs on the basis of two independent processes that do not interact (see van Zoest et al 2004). While, indeed, several models of visual search suggest that this is the case, these models generally fail to be explicit about the exact way in which stimulus-driven and goal-driven control jointly influence the selection process. For example, the Guided Search 2.0 model by Wolfe (Cave and Wolfe 1990; Wolfe 1994; Wolfe et al 1989) and Treisman's feature-integration theory (Treisman and Gelade 1980; Treisman and Sato 1990) suggest that stimulus-driven and goal-driven control affect search equally in that their effects add up to jointly influence the allocation of attention. However, the precise manner in which this occurs remains unclear, as is evident in Cave and Wolfe (1990) who claim "a more thorough understanding of the relationship between bottom – up and top–down processing will allow more precise prediction" (page 261). The results of the present study suggest that stimulus-driven and goal-driven control affect search additively, at least when target and distractor are defined within the same feature dimension. Whether both types of control are also independent when target and distractor are defined across different dimensions remains an open question.

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