VISUAL COGNITION, 2006, 14 (4/5/6/7/8), 466–489

Psychology Press
Taylor & Francis Group

Visual search for featural singletons: No top-down modulation, only bottom-up priming

Jan Theeuwes
Vrije Universiteit, Amsterdam, Netherlands

Brit Reimann
Dresden University of Technology, Germany

Karen Mortier
Vrije Universiteit, Amsterdam, Netherlands

The present study investigated the effect of top-down knowledge on search for a feature singleton (a "pop-out target"). In a singleton detection task, advance cueing of the dimension of upcoming singleton resulted in cueing costs and benefits (Experiment 1). When the search for the singleton stayed the same but only the response requirements were changed, advance cueing failed to have an effect (Experiments 2 and 3). In singleton search only bottom-up priming plays a role (Experiments 4 and 5). We conclude that expectancy-based, top-down knowledge cannot guide the search for a featural singleton. Bottom-up priming that does facilitate search for a featural singleton cannot be influenced by top-down control. The study demonstrates that effects often attributed to early top-down guidance may represent effects that occur later in processing or represent bottom-up priming effects.

Every day we spend a lot of time searching for important things such as a traffic sign at a busy crossroad, or one of our kids in a busy shopping centre. When searching for an object we have to keep in mind what we are looking for. A target template describing the target (its colour, its shape, its location, etc.) is kept in memory to guide our search process. For example when searching for one of our lost kids in a shopping centre, we try to remember

Please address all correspondence to Jan Theeuwes, Dept. of Cognitive Psychology, Vrije Universiteit, van der Boechorststraat 1, 1081 BT Amsterdam, The Netherlands. E-mail: J.Theeuwes@ psy.vu.nl

We would like to thank Hermann Müller for valuable comments on an earlier draft of this paper.

http://www.psypress.com/viscog DOI: 10.1080/13506280500195110

what the child was wearing that day so that colour may guide our search process.

It appears to be obvious that knowledge of what we are looking for helps our search process. Indeed almost all theories of visual search assume that preknowledge may generate top-down activation that can guide the search process. 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 green nontargets, the red element will receive high top-down activation. Visual search models assume that attentional serial search is guided by information that is available at the early preattentive level (Wolfe, 1994). Various studies have demonstrated that knowledge of the specific task demands may guide attention to only those locations that match the target-relevant feature. For example, Kaptein, Theeuwes, and van der Heijden (1995) showed that participants can restrict search for a colour-orientation conjunction target to a colour-defined subset. Thus, when searching for a red vertical line segment between red tilted and green vertical line segments, participants searched serially among the red items while they completely ignored the green line segments.

Even though it may be obvious that top-down knowledge can guide search in environments that require effortful serial search (e.g., when searching for a conjunction target), it is not clear whether top-down knowledge guides search when the target is unique in a basic feature dimension. When confronted with a display in which one element is unique in a basic feature dimension (such as a red element surrounded by green elements) the element pops out from the display. Without any effort one is able to detect such a *feature singleton*. The question is whether top-down knowledge can affect search for a singleton target (i.e., a "pop-out target").

When confronted with a display, it is first segmented into basic stimulus attributes in different dimension-specific "modules" (such as colour, orientation, etc.). For each stimulus location, each module computes a bottom-up saliency signals indicating the feature difference between one particular item relative to all other items represented within the same module. The more dissimilar an item is, the greater its saliency (see, e.g., Cave & Wolfe, 1990; Theeuwes, 1992, 1994; Wolfe, 1994). Maps of saliency signals are computed in parallel in all modules, and these signals are summed onto a master map of activations. The activity on the master map guides focal attention to the most active location. Focal attention gates the passage of information to higher stages of processing (visual object recognition and response systems). The question we address is whether top-down knowledge can affect the already high bottom-up activity generated by the singleton.

There is evidence that top-down knowledge speeds up search even when one is searching for a feature singleton. While knowing the actual feature value of the target (whether it is blue, red, or white between green nontargets) hardly speeded search, Treisman (1988) showed that knowing the dimension of the target (whether it would be a unique colour or a unique shape) speeded search with about 100 ms. Treisman (1988) suggested that there is no top-down selectivity within dimensions; yet, across dimensions knowing in what dimension the target will be presented speeds up search significantly. More recently, Müller and colleagues (e.g., Found & Müller, 1996; Müller, Heller, & Ziegler, 1995; Müller, Reimann, & Krummenacher, 2003) also provided evidence that knowing for which dimension one is looking speeds up search even when one is searching for a singleton target.

Müller et al. (1995) investigated search for singleton targets within and across stimulus dimensions. Typically, in these experiments, participants search for three possible targets, which all are defined within one dimension (e.g., orientation) or are defined across dimensions (e.g., orientation, colour, and size). In their Experiment 1, the detection of a common right-tilted target was 60 ms slower in the cross-dimension relative to both the intradimension condition and the control condition. In addition, Müller et al. reported dimension-specific intertrial effects: There was an RT advantage when the previous trial contained a target defined in the same dimension relative to a target defined in a different dimension (see also, Found & Müller, 1996).

To account for data like these, Müller and colleagues developed a "dimensionweighting" account of visual selection (Found & Müller, 1996; Müller et al., 1995). In cross-dimensional singleton feature search, observers have to detect the presence of an odd-one-out target object (a feature singleton). Because the target-defining dimension varies from trial to trial, the target is not known in advance. In these conditions, the target does not simply "pop out" from the background in a purely bottom-up fashion. Rather it is claimed that that target detection involves "an attentional mechanism that modifies the processing system by allocating selection weight to the various dimensions that potentially define the target" (Müller et al., 2003, p. 1021). According to the dimension-weighting account, there is a limit to the total attentional weight available to be allocated at any one time to the various dimensions of the target object. It is assumed that potential target-defining dimensions are assigned weight in accordance with their instructed importance and their variability across trials. The greater the weight allocated to a particular dimension, the faster can the presence of a target defined in that dimension be discerned. Dimensional weighting is similar to Guided Search (Wolfe, 1994) except that it focuses specific on dimension specific signals.

Recently, Wolfe, Butcher, Lee, and Hyle (2003) conducted experiments similar to those of Müller and colleagues and Treisman (1988). For example, in Wolfe et al. participants searched a whole block of trials for a red target between green nontargets (i.e., colour singleton) or for a vertical line between horizontal line segments (i.e., shape singleton). These blocked conditions were compared to mixed conditions consisting of blocks of trials in which the target could either be red, green, vertical, or horizontal. On the basis of these data Wolfe et al. concluded "top-down information makes a substantial contribution to RT even for the simplest of feature searches. Fully mixed RTs are about 80 ms slower than are blocked RTs" (p. 485). Wolfe et al. explain these experiments in the same vein as Müller and colleagues: In a blocked condition in which the target is always the same, as much weight as possible can be placed on one dimension (e.g., orientation), allowing for a strong signal to guide search. In a mixed condition, all features have some weight. When in the mixed condition the target happens to be an orientation singleton, there is a weaker signal to guide search, and noise from other dimensions (colour and size) may slow search. Note that both in Müller's and Wolfe's accounts top-down knowledge guides the search process, i.e., top-down knowledge influences the selection process of the featural singleton.

In general, studies demonstrating top-down effects on singleton search use the same straightforward approach. In Treisman (1988) participants either know or did not know in which dimension the target singleton would pop out. Not knowing the dimension of the target generated a large cost. Similarly, in Wolfe et al.'s (2003) experiments participants know which target they are looking for because they search a whole block for the same singleton (for example a red line). This performance is compared to mixed blocks in which the target singleton can either be the same red line or a singleton unique in another dimension (e.g. orientation, size, shape). In Müller's experiments participants typically search for three possible targets that all are defined within one dimension (e.g., orientation) or are defined in one of several possible dimensions (e.g., orientation, colour, and size). Typically, search time in conditions in which the target dimension (or feature) is known are faster than those in mixed blocks in which the target dimension (or target feature) is not known (cross-dimensional search costs).

Even though on the face of it this approach seems valid, it may appear to be impossible to determine whether the effects reflect knowledge, expectancy-based top-down effects, or merely passive bottom-up priming (cf. Maljokovic & Nakayama, 1994). As outlined by Müller et al. (2003) the design of experiments in which mixed versus blocked conditions are compared introduces intertrial effects that may have nothing to do with top-down effects. For example, showing faster RT when one type of singleton is presented throughout a whole block of trials relatively to a condition in which the type of singleton varies from trial to trial would not necessarily imply top-down modulation. In other words, participants may not be faster in a blocked condition because they actively prepare for the upcoming target singleton (as a top-down approach would assume) but are faster because the target singleton on the current trial is simply the same as the one on the previous trial. Indeed, Maljkovic and Nakayama's (1994) research demonstrated that it is impossible to counteract the priming of a previous trial. Intertrial facilitation could not be abolished or reduced even when participants knew exactly which target would be presented on the next trial. Participants could not actively set themselves for a target that was different from that of the previous trial (but see Hillstrom, 2000).

To rule out the possibility that the effects are due to passive bottom-up priming, instead of using a blockwise cueing procedure, Müller et al (2003) employed a trial-by-trial cueing procedure. Before each trial, a verbal cue (the word "colour" and "shape") indicated the likely target-defining dimension. It is assumed that the cue allows participants to actively set themselves for the likely upcoming stimulus dimension. In terms of the dimensional weighting account (Müller et al., 2003) or guided search (e.g., Wolfe et al., 2003) it is assumed that participants use the advance cue to allocate attentional weight to the likely target dimension. In the current experiments, we used the same trial-by-trial cueing procedure as Müller et al. In addition to examining the attentional set induced by the cue it allows an analysis of the intertrial effects to examine the bottom-up priming effects.

EXPERIMENT 1

To ensure that the task was a singleton task we used the same displays as used by Theeuwes (1992). For the current shape and colour singleton, Theeuwes (1992) demonstrated flat search functions indicating parallel (preattentive) search.

Experiment 1 consisted of a singleton search task in which participants had to respond to the presence or absence of a shape or colour singleton. On each trial participants were cued regarding the dimension of the singleton that was most likely to be presented (cue validity of 83%).

Method

Participants. Twelve participants ranging in age between 18 and 30 years participated as paid volunteers. All had self-reported normal or corrected-to-normal vision and reported having no colour vision defects.

Apparatus. A Dell Pentium Optiplex GX-1 with a Dell SVGA colour monitor controlled the timing of the events, generated stimuli and recorded reaction times. The "/" key and the "z" key of the computer keyboard were used as response buttons.

Stimuli. The visual field consisted of nine green elements equally spaced around the fixation point on an imaginary circle (3.4° radius). The search displays were identical to Theeuwes' (1992) "display-size-nine" displays consisting of outline circles (1.4° in diameter) and possibly one diamond of 1.4° side length, each element containing a line segment (0.5°) that was tilted 22.5° to either side of the horizontal or vertical plane. These oriented lines (which were irrelevant in Experiment 1) were randomly distributed in the display. In the colour target-present condition one of the green circles was replaced by a red circle. In the shape target-present condition, one of the green circles was replaced by a green diamond shape. The target-singleton position was randomly chosen among the nine possible element positions. In the target-absent conditions all nine circles were green.

Initially, a centre fixation cross was presented for 900 ms. This was replaced by a verbal cue presented at the centre of the screen indicating with an 83% probability the dimension of the upcoming singleton. In other words, if a singleton was present then the cue indicated this with an 83% probability. For example, if the cue indicated "colour" and a target was present, in 83% of the trials a colour singleton was presented (valid cue condition) and in 17% of the trials a shape singleton (invalid cue condition) was presented. If the cue indicated "shape" and a target was present, in 83% of the trials a shape singleton was presented and in 17% of the trials a colour singleton. In the neutral condition the word "equal" was presented as a cue indicating that there was an equal probability of receiving a shape or a colour singleton appearing on the upcoming trial. After 700 ms the cue was replaced by the centre fixation point. After an ISI of 850 ms the display consisting of the nine elements along with the fixation point was presented. The search display remained on until a response was given (with a maximum of 2 s). Figure 1 gives an example of the displays.

Design and procedure. Each participant performed both the cue and neutral conditions which were varied between blocks. Half of the participants started with the neutral condition, the other half with the cue condition. Each participant performed 360 cue trials and 180 neutral trials. In half of the trials were target-present trials. Half of the participants responded with the "z" key for target present and "/" key for target absent. This response assignment was reversed for the other half.

Participants were told to keep their eyes fixated at the fixation cross. Participants received 270 practice trials prior to the experimental trials. Participants were told to respond to the presence of a singleton regardless of type of singleton. They were informed that the cue would indicate with a high probability the dimension of the upcoming singleton target.

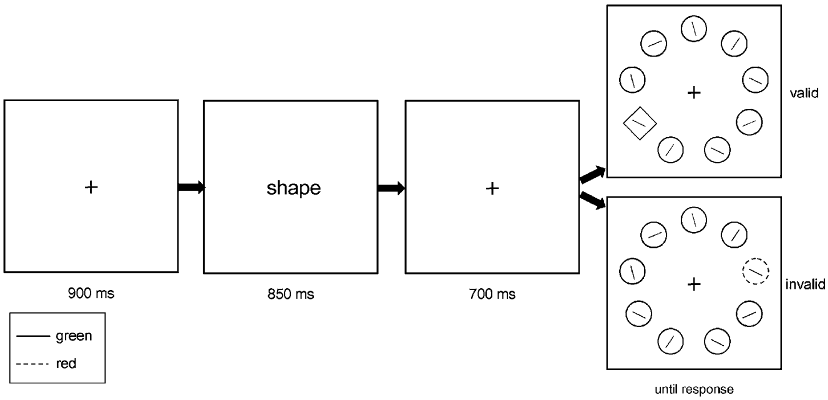

Figure 1. An example of a trial sequence. A verbal cue indicated with 83% validity the dimension ("shape" or "colour") of the upcoming colour or shape singleton target. Participants responded to the presence of a singleton regardless of the type of singleton.

Results

All RTs lasting longer than 750 ms were counted as errors, which led to a loss of well under 1% of the trials.

Figure 2 presents the mean RTs for target-present trials. The individual mean RTs for target-present trials were submitted to an analysis of variance (ANOVA) with cue validity (valid, invalid, or neutral) and singleton type (colour singleton or shape singleton) as factors. There were main effects of

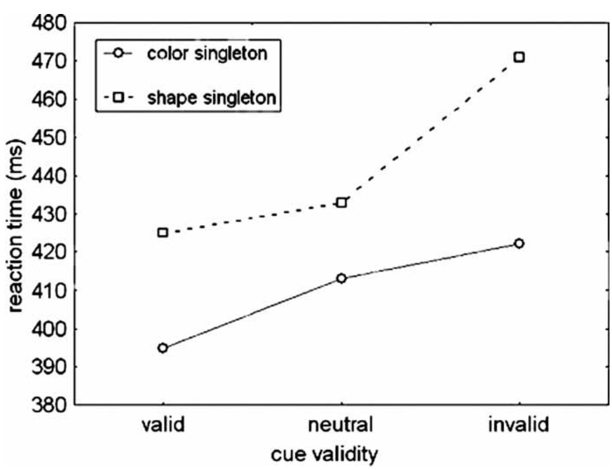

Figure 2. Experiment 1: Mean reaction time as a function of cue validity in a feature detection task when searching for a colour singleton and when searching for a shape singleton.

cue validity, $F(2, 22) = 11.3$, $p < .001$, and of singleton type, $F(1, 11) = 39.2$, $p < .0001$. The interaction was also reliable, $F(2, 22) = 7.4$, $p < .01$. Additional planned comparisons showed that the response times in the valid cue condition were significantly faster than those in the neutral cue condition (411 ms vs. 423 ms; $p = .005$). In addition, the neutral cue condition generated faster RTs than the invalid cue condition (423 ms vs. 447 ms; $p = .019$). As is clear from Figure 2, identical to Theeuwes (1992), colour singleton generated faster response times than shape singletons.

Present responses were not faster than absent responses (418 vs. 425 ms; $F < 1$) providing additional evidence that the current task was a singleton detection task (see Theeuwes, Kramer, & Atchley, 1999).

To determine whether there were any intertrial facilitation effects (cf. Found & Müller, 1996; Maljkovic & Nakayama, 1994), we determined for target-present trials the mean RTs to a target on trial N dependent on the dimensional definition of target on trial $N-1$ (dimension not switch versus dimension switched). An ANOVA showed a main effect of switch (dimension not switch vs. dimension switch: 410 ms vs. 444 ms), $F(1, 11) = 11.4$, $p = .006$. It is important to note that the factor switch did not interact with singleton type or with cue validity, $F(2, 22) = 1.27$, $p = .30$, indicating that the above reported validity effects are not modulated by any passive, bottom-up, priming (cf. Maljkovic & Nakayama, 1994) and do not depend on the singleton type one has to respond to.

An ANOVA on the error rates for target-present trials showed a main effect of validity, $F(2, 22) = 4.0$, $p < .05$. Since error rates mimicked the validity effect on RT (valid 2.4%, neutral 3.6%, and invalid 7.5% errors), differences in response latencies cannot be attributed to a speed–accuracy tradeoff.

Discussion

The present findings show dimension-specific cueing effects and basically represent a replication of the experiments conducted by Müller et al. (2003). Relative to the neutral condition there were reliable benefits for valid cue and reliable costs for invalid cue conditions. The results indicate that advance knowledge regarding the dimension of the upcoming singleton affects the speed of responding. The present results are in line with theories that assume that top-down knowledge can improve visual search for a singleton target. For example, in line with the dimension-weighting account of Müller et al. (1995, 2003; Found & Müller, 1996) or the guided search account of Wolfe et al. (2003), the present results seem to indicate that target selection is modulated by intentional, knowledge-based processes. Because processing is tuned to a specific dimension (i.e., the cued dimension), it is assumed that visual search for the relevant feature dimension is speeded.

The observation of an intertrial facilitation effect that does not interact with any top-down cueing conditions is in line with Maljokovic and Nakayama (1994), who argued that intertrial facilitation is a passive bottom-up priming effect, which cannot be modulated by top-down processing. Priming is a process that is assumed to be cognitively inaccessible (see also Kristjansson, Wang, & Nakayama, 2002).

EXPERIMENT 2

Experiment 2 was identical to Experiment 1 except that participants responded to the orientation of the line segment located in the target singleton. In such a "compound" search task (cf. Duncan, 1985), there is a clear separation between perceptual and response selection factors (see also Theeuwes, 1991, 1992). Employing this task makes it possible to determine whether the cueing effect reported in Experiment 1 represents cueing effects operating at perceptual or response selection levels. Participants searched for exactly the same singletons as in Experiment 1 yet they responded to the line segment inside the singleton. Identical to Experiment 1 the dimension of the upcoming target singleton was cued with a validity of 83%.

Method

Participant. Fourteen participants ranging in age between 18 and 30 years participated as paid volunteers.

Stimuli. The stimuli and trial sequence were identical to those in Experiment 1 except that the line segment inside the target singleton was either vertical or horizontal, the orientation determining the appropriate response keys (left for vertical and right for horizontal).

Design and procedure. Cue validity was again 83%. Participants performed 360 trials (200 valid, 40 invalid, and 120 neutral). Cue and neutral conditions were again varied between blocks of trials. Participants received a block of 180 practice trials. Again, they were informed that the cue would indicate with a high probability the dimension of the upcoming singleton in which the target line segment was located. It was made explicitly clear that they should use the cue as much as possible to reduce reaction time. Note that unlike in Experiment 1 there were no target-absent trials.

Results

All RTs lasting longer than 1200 ms were counted as errors, which led to a loss of less than 1% of the trials.

Figure 3 presents the mean RTs. The individual mean RTs were submitted to the same analysis of variance with cue validity (valid, invalid, or neutral) and singleton type (colour singleton or shape singleton) as factors. There was only a main effect of singleton type, $F(1, 13) = 35.0$, $p < .0001$. Identical to Experiment 1, colour singletons generated faster responses than shape singletons. There was no effect of cue validity, $F(1, 13) = 0.06$. The mean RT in the valid cue condition was 585 ms, in the neutral cue condition it was 585 ms and in the invalid cue condition it was 589 ms. Cue validity did not interact with singleton type, $F(2, 26) = 0.65$. As in Experiment 1 we did find a reliably intertrial effect, $F(1, 13) = 4.74$, $p < .05$. Participants responded faster (mean of 582 ms) when the target did not switch dimensions than when it did switch (mean of 592 ms).

Error rates (about 8.3%) were slightly higher than in Experiment 1. More errors were made in the shape singleton condition (9.4%) than in the colour singleton condition (7.2%), $F(1, 13) = 6.9$, $p < .05$, effects that mimic the effects on RT.

Discussion

The current experiment clearly indicates that the same cue that was able to generate cue benefits and costs in Experiment 1 failed to produce cueing

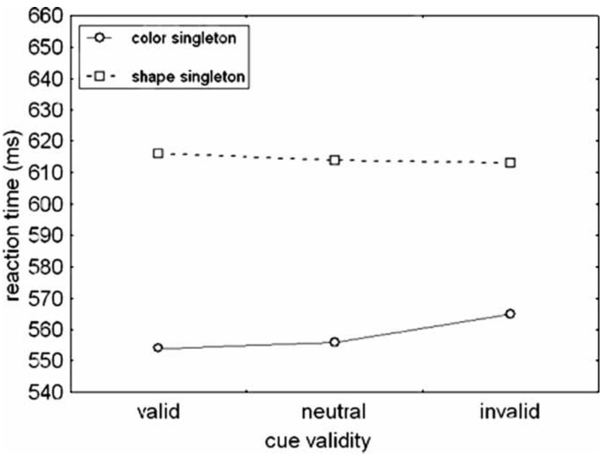

Figure 3. Experiment 2: Mean reaction time as a function of cue validity in a compound search task when searching for a colour singleton and when searching for a shape singleton.

effects in Experiment 2. Unlike Experiment 1 in which participants responded to the presence or absence of the singleton, in Experiment 2 participants searched for the singleton but responded to the line segment located in it.

Experiment 2 was identical to Experiment 1 (i.e., same type of cues, same targets, same cue validity) except that now participants responded to the line segment located inside the singleton. Just by changing the response requirement the reliable cueing effect of Experiment 1 was not present anymore. If the cue would affect (preattentive) search processes for the odd-one-out singleton as many theories of visual search assume (cf. Muller et al., 2003; Wolfe et al., 2003) then one would expect a validity effect in Experiment 2 as well. The results clearly show no sign of cue validity whatsoever. The differential cueing effects between Experiment 1 and 2 demonstrates that effects that typically have been attributed to early top-down visual modulation (e.g., Found & Müller, 1996; Müller et al., 1995; Wolfe et al., 2003) represent effects that occur much later in processing.

EXPERIMENT 3

One may argue that the verbal cue in Experiment 2 did not have a cueing effect because participants did not actively process the cue. Since it may have been difficult to establish a top-down set for a cued dimension and at the same time hold the response mapping for the orientation task, participants may simply have ignored the cue altogether. To determine whether participants actually processed the cue, in Experiment 3 we interleaved some "validation" trials with the search trials. In these validation trials, the cue was presented as in a search trial but instead of presenting the search display, the participant was probed with a question "the cue, was it SHAPE or COLOUR?" Participants gave a nonspeeded response to this question. To ensure that the response requirements were as simple as possible, instead of using an arbitrary response mapping involving line orientations, participants had to respond to the letter that appeared inside the singleton target. If the letter inside the singleton was an "R" participants pressed with their right hand; if it was an "L" the pressed with their left hand.

Method

Participant. Ten participants participated as paid volunteers.

Stimuli. The stimuli and trial sequence were identical to those in Experiment 2 except that there were capital "R"s and "L"s placed inside each of the elements (see Theeuwes, 1995, in which exactly the same task was used). The letter that appeared inside the singleton (which was either colour or shape) determined the appropriate response keys (left for "L" and right for "R"). In case of a validation trial, instead of presenting the search display a question was displayed in the middle of the screen saying "SHAPE or COLOUR?" Participants made a nonspeeded response, typing the "S" key when the verbal cue said SHAPE and a "C" when the verbal cue said COLOUR. If they made an error, they received feedback stating "please process the cue".

Design and procedure. For search trials cue validity was 80% (160 valid cues and 40 invalid cues). Forty validation trials were randomly interleaved.

Results

The first trial following a validation trial was considered a warm-up trial and was therefore excluded from the analysis. Figure 4 presents the mean RTs. There was only a main effect of singleton type, $F(1, 9) = 35.3$, $p < .0001$. As in Experiments 1 and 2, colour singletons generated faster responses than shape singletons. Even though numerically there appears to the be some effect in the right direction (valid cue condition: 586 ms vs. invalid cue condition: 598 ms), statistically cue validity, $F(1, 9) = 1.7$, was not reliable. Cue validity did not interact with singleton type, $F(1, 9) = 0.0004$. Intertrial analyses were not performed since there were not enough trials in the invalid cue condition.

Of the 400 validation trials participants were wrong on only 3 trials ($<1\%$), suggesting that they processed the verbal cue correctly. Error rates

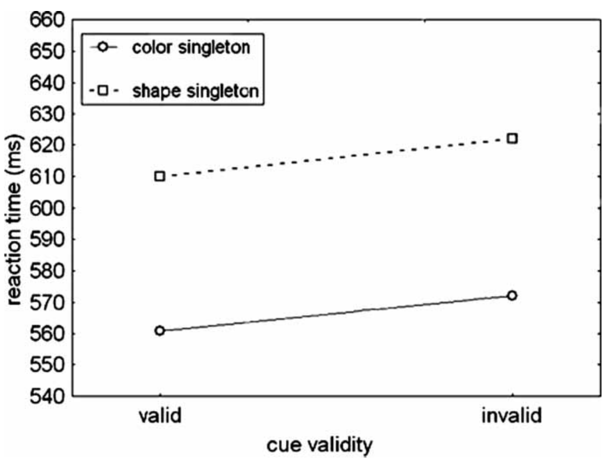

Figure 4. Experiment 3: Mean reaction time as a function of cue validity in a compound search task when searching for a colour singleton and when searching for a shape singleton.

in the search task were very low (about 2.8%) and were therefore not further analysed.

Discussion

Experiment 3 clearly demonstrates that participants processed the cue. Participants correctly identified the cue in 99.2% of the trials. Also, the task, which required participants only to press right when a "R" was presented and press left when an "L" was presented, was slightly easier. Even though participants did not respond faster they made significantly less errors in Experiment 3 than in Experiment 2 (2.8% vs. 8.3%). Even though the response requirements were fairly simple and there was evidence that participants processed the cue (i.e., they did not simply ignore the cue), the results basically replicate those of Experiment 2: Dimension cueing does not affect search for a feature singleton. The finding that cueing had no effect suggests that the cue cannot speed up or slow down the actual search for the odd-one-out singleton.

EXPERIMENT 4

Given the results of Experiments 1–3, one may ask the question whether there can be any top-down guidance of visual search when searching for a featural singleton (i.e., pop-out target). In other words, is it possible to design an experiment that results in reliable cueing effects that operate on the actual search processes. As noted above there have been demonstrations that cueing may speed up the response when participants search for the presence or absence of a feature singleton (e.g., Müller et al., 1995, 2003). Experiments 1–3 suggest, however, that these effects that typically have been attributed to early top-down visual modulation (e.g., Found & Müller, 1996; Müller et al., 1995, 2003; Wolfe et al. 2003) may represent effects that occur later in processing.

The question arises which conditions, if any, would allow top-down guidance for singleton search. One argument may be that the verbal cues used in Experiments 1–3 may be less optimal to obtain early modulation of visual search processes. Even though verbal cues may be effective when the design of the experiments is such that it allows response bias (as for example in Müller et al., 2003), they may be less effective when response bias is taken out as an explanatory mechanism (as in Experiments 2 and 3).

In Experiments 4 and 5, instead of a verbal cue, we used the actual singleton as a cue presented at the centre of the screen. The cue (e.g., a red circle or a green diamond) was identical to the target singleton that was most likely to be presented on the upcoming trial (80% validity). As in

Experiments 2 and 3, participants searched a target singleton and responded to the orientation of the line segment therein. If we find any cueing effects, these conditions ensure that possible cueing effects represent facilitation at the perceptual selection level and not at the response selection level.

Method

Participants. Twelve participants participated as paid volunteers.

Stimuli. The stimuli and trial sequence were identical to those in Experiment 2 except that, instead of using a verbal cue, a symbolic (direct) cue was used. The symbolic cue, which was presented in the centre of the display, was identical to the shape singleton (i.e., the green diamond) or the colour singleton (i.e., the red circle) participants had to search for in the search display. The cue was presented just as in Experiment 1 for 850 ms followed by a 700 ms ISI before the search display was presented.

Design and procedure. The cue indicated with a probability of 80% the target singleton for the upcoming trial. If the cue was a green diamond, there was an 80% probability that the target singleton was a green diamond and a 20% probability that the target singleton was a red circle. If the cue was a red circle, there was an 80% probability that the target singleton was a red circle and a 20% probability that the target singleton was a green diamond. Each participant performed 240 experimental trials consisting of 200 validly and 40 invalidly cued trials. Participants performed 240 practice trials. Participants were told to respond to the presence of a singleton regardless of type of singleton. They were informed that the cue would indicate with a high probability the dimension of the upcoming singleton target.

Results

All RTs lasting longer than 1200 ms were counted as errors, which led to a loss of less than 1% of the trials. There were main effect of cue validity, $F(1, 11) = 6.3$, $p < .05$, and of singleton type, $F(1, 11) = 27.0$, $p < .001$. The interaction was not reliable ($F < 1$). In line with previous experiments, responses to the colour singletons were faster (586 ms) than responses to shape singletons (617 ms). The results indicate that cueing was effective. In case of a valid cue participants were faster than when the cue is invalid (593 ms vs. 610 ms).

There was a reliable Intertrial $\times$ Cue validity interaction, $F(1, 11) = 6.5$, $p < .05$. The validity manipulation had a much larger effect (582 ms for valid vs. 612 ms for invalid) when the target dimension did not switch than when it switched from one dimension to another (603 ms for valid vs. 610 ms for invalid).

Error rates were low (6.3%) and were not systematically related to any of the variables manipulated.

Discussion

The present results suggest that there is top-down guidance of visual search for featural singletons. Even when it is ensured that cueing can only operate on the search process itself (and not on the response selection process) a clear cueing effect was found.

One may argue that the absence of a cueing effect in Experiments 2 and 3 may have been due to the fact that a verbal cue may not be effective in generating a top-down set that can guide search for the featural singleton. Even though on the face of it these results suggest that top-down knowledge can help attentional selection of a featural singleton, it remains a question whether this cueing effect is genuinely top-down. Indeed, the SOA between cue and target display was 1.5 s. which seems enough to cognitively prepare for the upcoming target singleton. Also, participants had every reason to prepare themselves for the upcoming singleton because most of the time the cue was correct (80% of the trials).

Even though this seems to be a reasonable interpretation, it is also possible that this cueing benefit is a bottom-up priming effect that is independent of any top-down set. This is in line with Maljkovic and Nakayama (1994), who showed that intertrial facilitation in visual search is most likely a passive bottom-up priming effect that cannot be influenced by any top-down processing.

In line with such a bottom-up priming account is the interaction between cue validity and intertrial target switches. The analysis suggests that the validity effect was due to fast response times when both the cue and the previous trial contained the same singleton. Only in this condition RT was fast (mean RT of 582 ms) while in all other conditions RTs were relatively slow and had about the same value (612 ms for no switch invalid, 603 ms for switch valid, and 610 ms for switch invalid). In all these latter conditions there was always a singleton as a cue or as a target in the previous trial that did not match the target singleton of the current trial. If bottom-up priming extends to several previous instances of the stimulus (see, e.g., Hillstrom, 2000) then these results can be expected. The fact that there are basically no cue validity effects when the previous trial contained a singleton that was different from the current trial suggests that actively preparing for the upcoming trial on the basis of the cue cannot counteract the bottom-up priming effect from the previous trial.

EXPERIMENT 5

Experiment 5 was designed to determine whether the cueing effect obtained in Experiment 4 is a top-down attentional set effect or a bottom-up priming effect. The cue indicated the upcoming target singleton with a low probability of only 16.6%. For example, when a colour singleton was presented as a cue, in 16.6% a colour target singleton would be presented and in 83.4% a shape singleton would be presented. If with this low validity, a valid cue still would result in faster response times, one would have strong evidence for bottom-up priming.

Method

Participants. Twelve new participants participated as paid volunteers.

Stimuli. The experiment was exactly the same as Experiment 1 except that now there were 40 validly cued trials and 200 invalidly cued trials implying that the cue was only valid on 16.6% of the trials. Participants were informed about these probabilities. Again there were 240 practice and 240 experimental trials.

Results

RTs lasting longer than 1200 ms were counted as errors, which led to a loss of less than 1% of the trials. There were main effects of cue validity, $F(1, 11) = 5.5$, $p < .05$, and of singleton type, $F(1, 11) = 16.9$, $p < .001$. The interaction was not reliable ($F < 1$). Again, RTs to the colour singletons were faster (555 ms) than responses to shape singletons (586 ms). Even though the cue did not have predictive value regarding the upcoming target singleton, cueing was effective. Where the cue happened to be valid (which was only in 16.6% of the trials), RTs were faster (565 ms) than when the cue was invalid (577 ms).

Again there was a reliable Intertrial × Cue validity interaction, $F(1, 11) = 7.8$, $p < .05$. The validity manipulation had a larger effect when the target dimension was switched (561 ms for valid vs. 584 ms for invalid) than when it was not switched (569 ms for valid vs. 570 ms for invalid. Error rates were low (5.2%) and not systematically related to any of the variables manipulated.

Discussion

The results of Experiment 5 are quite striking. Even though the cue had no predictive value, there was a reliable cueing effect for the valid versus invalid cue condition. In fact, an additional analysis with "Experiment 4 vs. 5" as a between-subject factor confirmed the notion that the cueing effect was not altered by the predictive value of the cue: The factor "experiment" was not reliable ($F < 1$) and did not interact with any of the other variables (all Fs <1). Figure 5 gives the cueing effects for Experiments 4 and 5.

The current findings indicate that the cueing effect in Experiment 4 is not due to a top-down attentional set. Indeed the current data indicate that there is no top-down control to actively prepare for the upcoming dimension. If observers had been able to set themselves in a top-down fashion to search for the appropriate target singleton then one would expect to find a reverse cueing effect. For example, seeing a diamond as a cue predicts with 83% validity that a colour target singleton (a red circle) would be presented. Also, seeing a red circle as a cue predicts with 83% validity that a shape singleton (a green diamond) would be presented. If observers had been able to exert top-down control then invalidly cued trials should have been faster than validly cued trial. We found the opposite, providing evidence for bottom-up priming effects in visual search.

The intertrial analysis also suggests that bottom-up priming plays a major role. In this experiment the slowest RT is found when both the cue preceding

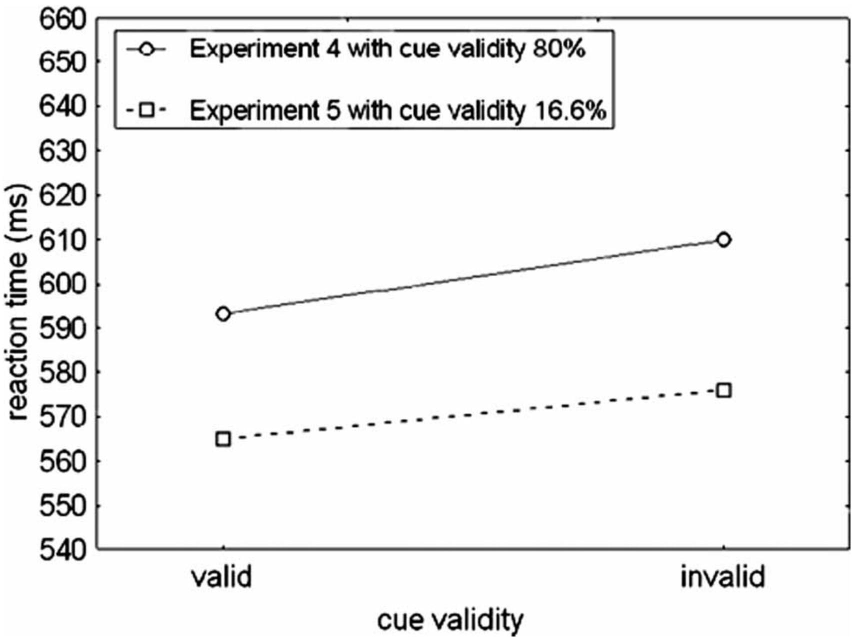

Figure 5. The cueing effect for Experiment 4 in which the cue had a validity of 80% and Experiment 5 in which the cue had a validity of 16.6%.

the trial and the target singleton of the previous trial are the same and both are different from the target singleton of the current tri al (mean RT of 584 ms). In all other conditions either the cue or the target in the previous trial matched that of the target in the current trials. These RTs are all relatively fast (569ms for no switch valid; 570 ms for no switch invalid; 561 ms for switch valid). It seems that in this experiment participants became very slow when both the cue and the previous trial did not match the singleton of the current trial regardless of the actual validity.

GENERAL DISCUSSION

The current results are important in our thinking regarding top-down control in visual search for featural singletons. It is intuitively plausible to assume that observers can set themselves to search for a particular feature in a top-down knowledge-based way. Indeed most theories of visual search assume that top-down knowledge guides the actual search process for the featural singleton (e.g., Müller et al., 2003; Wolfe et al., 2003). The current study shows, however, that:

1. Expectancy-based, top-down knowledge induced by a verbal cue that is assumed to guide the search process (e.g., Müller et al., 1995, 2003) may represent effects that occur after visual selection has taken place (i.e., postselective).
2. Cueing that does affect the actual search for the featural singleton is not due to expectancy-based, top-down settings but is due to bottom-up priming.
3. Deliberate top-down control cannot counteract the bottom-up priming effects of the cue and of previous trials.

Experiment 1, which uses a verbal cue to induce expectancy-based top-down settings, basically replicates the main findings of Müller et al. (2003). Like Müller et al. we show that knowledge of the upcoming target dimension affects the speed of responding. When the verbal cue induced the correct expectations regarding the upcoming stimulus dimension participants were fast; if expectations were incorrect participants were slow. The typical explanation for these findings is that top-down modulation can guide search for a singleton target (e.g., Müller et al., 1995, 2003; Treisman, 1988; Wolfe, 1994; Wolfe et al., 2003). For example, according to the dimensional weighting account of Müller et al. (2003; see also Wolfe et al., 2003), knowing the dimension in advance allows attentional weight to be assigned to the relevant (known, precued) dimension. According to Müller et al., assigning weights according to the known likelihood of a target appearing in a particular dimension permits a rapid search. Experiment 2 was identical to Experiment 1 (i.e., same type of cues, same targets, same cue validity) except that now participants responded to the line segment located inside the singleton. Just by changing the response requirement the reliable cueing effect of Experiment 1 was not present anymore in Experiment 2. If the cue would guide search processes for the odd-one-out singleton, as many theories of visual search assume, then one would expect a validity effect in Experiment 2 as well. The results clearly show no sign of cue validity whatsoever. Experiment 3 demonstrated that participants did not simply ignore the cue: Participants processed the cue and knew exactly which cue was presented; yet they were not able to use this knowledge to speed up the search process. Experiment 1 shows that a verbal cue can have an effect on the speed of responding when searching for a singleton; Experiments 2 and 3 show that when one ensures that this advance cueing cannot affect response selection processes but only the actual search processes, cueing effects are no longer present. Our Experiments 1–3 suggest that effects that have been attributed to early top-down visual guidance (e.g., Müller et al., 2003; Wolfe et al., 2003) may represent effects that occur much later in processing.

Experiments 4 and 5 show that it is possible to obtain cueing effects that operate on the actual search process. As in Experiments 2 and 3, a compound search task was used in which the target one is searching for is different from what one has to respond to. Instead of using verbal cues, Experiment 4 demonstrated that a symbolic cue showing the actual singleton that would be the most likely target on the upcoming trial resulted in a cueing effect. On the basis of this finding one could conclude that participants used the cue to actively prepare for the most likely target singleton. Indeed the cue indicated with an 80% probability the upcoming target singleton. However, Experiment 5 shows that predictability of the cue did not alter the size of the cueing effect, suggesting that the cueing effect is not due to actively preparing for the most likely target singleton but may represent bottom-up priming. Indeed, if participants are able to actively set themselves for the most likely target singleton one would have expected a reversed cueing effect. Seeing one particular cue (e.g., a red circle) should have allowed participants to actively prepare for the shape dimension (the shape singleton) because in 83% of the trials a colour cue was followed by a shape singleton. The results suggest that participants did not and presumably could not set themselves for the most likely target singleton. The cueing effect was not reversed but basically identical to the cueing effect of Experiment 4 in which the cue was predictive of the upcoming target singleton. The fact that the size of the cueing effect is not modulated by its validity suggests that top-down processing cannot counteract bottom-up priming.

Our claim that in feature search only bottom-up priming occurs, which cannot be counteracted by top-down, expectation-based modulation, is in line with the findings of Maljkovic and Nakayama (1994), who investigated intertrial effects in feature search. Even when a target on a given trial was 100% predictable (e.g., target definition changed in an AABBAABBAA . . . manner), knowledge-based expectations could not modulate feature-specific intertrial effects. Maljkovic and Nakayama conclude that their intertrial effects reflect passive priming that are not top-down penetrable. This conclusion is completely in line with our study that used cues to induce top-down expectancies: In feature search there is no top-down modulation, only bottom-up priming. Maljkovic and Nakayama referred to this findings as "priming of pop-out". Kristjansson et al. (2002) found priming effects in conjunctive visual search. They show, similar to our Experiment 5, a counterintuitive result: Knowing what the target is on a given trial does not facilitate conjunction search. More importantly, they argue that, in addition to priming, there are no benefits for top-down guidance. They conclude, "the role of priming in visual search is underestimated in current theories of visual search and that differences in search times often attributed to top-down guidance may instead reflect the benefits of priming" (p. 37).

The effects reported in our Experiments 4 and 5 (and those reported by Kristjansson et al., 2002; Maljkovic & Nakayama, 1994) should be considered as the result of priming and not of some form of top-down processing. Wolfe et al. (2003) referred to the intertrial effects revealed in their study as being top-down in nature. Even though it is generally agreed that priming is basically a bottom-up process (e.g., Posner, 1978), Wolfe et al. (2003) called these effects top-down because "it relies on what the observer has learned about the prior trial and does not rely solely on the state of the stimulus" (p. 483). Even though the intertrial effects reported by Wolfe et al. are due to bottom-up priming in the sense of Maljokovic and Nakayama (1994, 1996; Kristjansson et al., 2002) given their definition that priming is top-down, it is not surprising that Wolfe et al. called his intertrial effects the results of *top-down guidance* in terms of Guided Search. Calling these effects top-down because they rely on what an observer has learned may be problematic. The word "learning" may be misleading because the change of state that priming induces has nothing to do with conscious effort or explicit knowledge. In fact priming effects may represent the most important example of effects that are impervious to prior knowledge and/or top-down processing. In line with others (Kristjansson et al., 2002; Maljkovic & Nakayama, 1994), we consider the intertrial effects the results of passive bottom-up priming that is not top-down penetrable.

In line with the notion that priming is impervious to prior knowledge or top-down processing our Experiments 4 and 5 show that top-down processing has no effect on priming. Our Experiment 5 shows that even when the cue was highly unpredictive (i.e., it indicated with 83% that the other singleton would be presented) it still caused priming effects. If there had been any top-down processing (i.e., preparing for the upcoming singleton) that could have counteracted the bottom-up priming one should have at least expected some attenuation of the priming effect. The results show that there is basically no difference in priming dependent on whether the cue was predictive (Experiment 4) or not (Experiment 5). In line with Kristjansson et al. (2002) we conclude that indeed "there are no benefits for top-down guidance over and above the effect of priming" (p. 49).

If one adheres the position that there should be top-down guidance in singleton search, one may argue that in experiments in which cueing effects are found participants actively processed and used the cue to set up top-down expectations, and in experiments in which there are no cueing effects participants just ignored the cue and did not bother to actively set-up top-down expectations. In other words, according this line of reasoning top-down effects on visual search are assumed even when cueing has no effect. If no effects of the cue are found it is assumed that observers did not bother to use it. This may especially be true for singleton search because this type of search is easy and of low effort. There are, however, arguments that do not seem to fit this interpretation. First, the claim that participants do not bother to set up top-down expectations when the task is very easy is not consistent with studies investigating location cueing. For example, in Remington and Pierce (1984) participants had to detect the onset of a luminance dot presented on the left or right of fixation. A symbolic cue (an arrow) pointed with 80% validity to the location where the dot was most likely to appear. In this extremely simple task (i.e., detecting a luminance onset) the symbolic cue had a clear validity effect: Valid cues gave faster detection times than invalid cues. It is clear that the detection of a luminance onset is very easy and can be done without setting up top-down expectations. Yet in this study participants used the symbolic location cue to improve their performance. Therefore it seems fair to conclude that the simplicity of the task should not prevent participants from setting up top-down expectations. Second, one may argue the opposite, that is, the task used in the present study is not too simple but to complex too show validity effects. For example, cueing in singleton search only may work in simple search and not in compound search because it take much longer to respond in a compound search task than in a simple search task. Indeed, in our Experiment 1 the mean RT was 422 ms and in Experiment 2 it was 586 ms. It is claimed that early cueing effects are obscured by the longer response times associated with the more difficult response requirements of the compound search task. This argument seems to suggest that the more difficult a task the harder it is to obtain cueing effects. Experiments 4 and 5, which also consisted of compound search, provide evidence that cue validity effects can be found even when the response times are high. Indeed, the mean RT in Experiment 4 was 600 ms and a clear validity effect was obtained. Third, the notion that participants simply do not process the cue is invalidated by Experiment 3, which shows that participants knew which cue was presented. Even though this experiment cannot prove that participants actively tried to set up an expectation for the upcoming singleton, the experiment proves that participants processed the cue and knew what the cue entailed.

Our notion that typical cueing effects as reported by Müller et al. (1995, 2003) represent effects that operate on response selection processes is in line with the claims of Cohen and colleagues (Cohen & Feintuch, 2002; Cohen & Magen, 1999; Cohen & Shoup, 1997). Cohen assumes separate response selection mechanism for different visual dimensions. A cross-dimensional task involves multiple response selection mechanisms, whereas an intradimensional task involves just one such mechanism. Similar to our claims, Cohen and Magen (1999) argue that the search processes in simple and compound search are exactly the same (i.e., search for a singleton). In line with Cohen is our argument that the cueing procedure in Experiment 1 did not cue the search process; instead it allowed to activate (feature-specific) response selection processes. Our claim and that of Cohen is that attention is necessary to make an overt response (see also Duncan, 1985). In order to be able to respond to a singleton, attention has to be directed to the location of the singleton. In this sense our view (and that of Cohen) implies that overt responses are postselective, i.e., overt responses can only be made after attention has been focused on the location of the target. Müller et al. (2003) suggest that some responses can be made directly on the detection of activity in the master map. It is assumed that one can respond to the target singleton (i.e., something unique is present) without waiting for complete knowledge to become available through focal attention. Cueing is assumed to affect the preattentive perceptual stage and a response can be given directly on the overall saliency signal.

The current findings suggest that early spatially parallel visual processes cannot be modulated by intentional, top-down processes. The results are consistent with Theeuwes (1991, 1992, 1994), who argued that there is no top-down control at the early preattentive level. Theeuwes concluded this on the basis of studies showing that a top-down attentional set cannot prevent attentional capture by an irrelevant, salient singleton. If there would have been top-down control at the early preattentive level then it should have been possible to increase the top-down "weight" of the relevant dimension thereby eliminating the interference from the irrelevant dimension. The results show that this did not occur, not even after 2000 trials of practice (see Theeuwes, 1992, Exp. 2). The current results suggest that in simple singleton search ("pop-out tasks") the salient element pops out from the background and deliberate top-down operations seem to have no influence on these processes. It should be noted, however, that the present findings suggest that bottom-up priming may play a role at the early preattentive level of processing and it is to be expected that priming will modulate attentional capture.

In conclusion, the simplest search (i.e., search for a pop-out target) appears to be driven in a bottom-up way. There is no evidence for expectancy-based top-down guidance of the search process. Only bottom-up priming affects feature singleton search. Priming occurs independently of top-down processing and its effect cannot even be counteracted by active top-down processing. Therefore, when looking at a cue with a red colour, cells in our brain representing "red" get active causing a selective and automatic enhancement of processing of objects with the colour red. Even though we may know that we do not want to look for red (e.g., our kid was wearing a green sweater that day) by looking at red we cannot avoid red objects receivimg attentional priority.

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