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Attentional guidance in singleton search: An examination of top-down, bottom-up, and intertrial factors

Carly J. Leonard and Howard E. Egeth

Psychological & Brain Sciences, Johns Hopkins University, Baltimore, MD, USA

While it is clear that the goals of an observer change behaviour, their role in the guidance of visual attention has been much debated. In particular, there has been controversy over whether top-down knowledge can influence attentional guidance in search for a singleton item that is already salient by a bottom-up account (Theeuwes, Reimann, & Mortier, 2006). One suggestion is that passive intertrial priming accounts for what has been called top-down guidance (e.g., Maljkovic & Nakayama, 1994). In the present study, participants responded to the shape of a singleton target among homogenous distractors in a trial-by-trial cueing design. We examined the influence of target expectancy, trial history, and target salience (which was manipulated by changing the number of distractors). Top-down influence resulted in fast RTs that were independent of display size, even on trials that received no priming. Our findings show there is a role for top-down guidance, even in singleton search. The designation of intertrial priming as a bottom-up factor, rather than an implicit top-down factor (Wolfe, Butcher, Lee, & Hyle, 2003), is also discussed.

While there is an enormous amount of visual information available, only a small portion of this information ever fully reaches awareness. Attention is highly functional, as the visual system prioritizes what is relevant to current goals as well as that which is salient in the environment. Theories of visual search have often posited how these top-down (i.e., endogenous) and bottom-up (i.e., exogenous) factors influence attentional allocation (e.g., Cave & Wolfe, 1990; Treisman & Gelade, 1980). Importantly, attentional allocation must also be heavily influenced by prior experience, as we often

Please address all correspondence to Carly Leonard, Psychological & Brain Sciences, Johns Hopkins University, 3400 N. Charles St, Baltimore, MD, 21218, USA. E-mail: carly@jhu.edu

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are faced with recurring goals and similar visual scenes (e.g., Chun & Jiang, 1998).

In the visual search literature, the effects of recent experience have been studied by examining how previous trials influence performance on the current trial. Many studies have addressed how a repetition of a target feature from a previous trial leads to a speeded response on the current trial (e.g., Bichot & Schall, 2002; Folk & Remington, *in press*; Goolsby & Suzuki, 2001; Olivers & Humphreys, 2003; Song & Nakayama, 2007). Specifically, these studies have focused on pop-out search paradigms, in which the target (known as a singleton) differs from homogenous distractors on a particular dimension. Some (Kristjansson, Wang, & Nakayama, 2002; Maljkovic & Nakayama, 1994; Theeuwes *et al.*, 2006) have claimed that this type of priming, known as priming of pop-out, may account for findings previously attributed to top-down attentional guidance.

The question at hand regards whether informing participants of an upcoming target feature influences the allocation of attention when the target is a singleton and already the most salient item in the display. This issue has been the subject of much controversy. Bravo and Nakayama (1992) found a distinction between search for a known singleton and search for an unknown singleton. When the specific feature of an upcoming pop-out target varied unpredictably, salience of the target guided search. Reaction times in this condition actually were faster as display size increased, suggesting that the target became more salient due to either an enhancement of local inhibition effects or nontarget grouping as display density increased (see Bacon & Egeth, 1991). However, when the defining target feature was held constant during the entire block, search was faster overall and unaffected by display size. Presumably participants knew the upcoming target feature and could use this information to enact an appropriate attentional set, which would weight the upcoming target feature and facilitate attentional guidance. The benefit for known targets remained even at large display sizes, as top-down knowledge provided a 50 ms benefit even for targets that were highly salient given a purely bottom-up account. Thus, even when bottom-up salience was quite effective at guiding attention to the target rapidly, there was evidence for an additional benefit of top-down prioritization on attentional allocation.

Maljkovic and Nakayama (1994) suggested that this difference in performance between known and unknown targets might instead be due to a disparity in intertrial priming between the blocked and mixed conditions used to manipulate expectancy. Their data showed marked decreases in reaction time when the target feature repeated from one trial to the next. Because the feature of the pop-out target was repeated continuously in the blocked known-target condition, it is possible that the results of Bravo and

Nakayama (1992) were due to a cumulative effect of priming across trials rather than a top-down attentional set for the target feature.

Our experiment addresses the issue of whether top-down modulation of a singleton target is possible, when controlling for intertrial priming effects. A singleton search task, similar to that of Maljkovic and Nakayama (1994), with display sizes of 3, 5, and 7 was used in combination with a trial-by-trial cueing procedure (see Müller, Reimann, & Krummenacher, 2003, for a similar method). On each trial, participants were either given an informative cue that revealed the upcoming target colour or a noninformative cue that forced reliance on bottom-up salience to find the target. The assignment of cue type and defining target colour was random. Reaction times were then analysed as a function of the current cue type and the target colour of previous trials, allowing us to look for possible effects of a feature-based search strategy that cannot be accounted for by intertrial priming.

While it is clear that priming does have some influence on the guidance of attention, there is not a consensus on how this relates to the more traditionally studied bottom-up and top-down factors. Theeuwes et al. (2006) have posited that intertrial priming should be seen as a bottom-up factor that influences the guidance of attention, and more specifically as a factor that accounts for results commonly attributed to top-down influence. Wolfe et al. (2003) have proposed that intertrial priming effects be considered an implicit form of top-down guidance. Olivers and Meeter (2006) propose the idea that intertrial priming can occur at different stages, depending on the level of processing at which there is ambiguity in the stimulus or the task. In addition to addressing whether top-down modulation of a singleton target is possible, we investigate how intertrial priming influences attentional allocation in relation to top-down and bottom-up factors.

METHOD

Participants

Thirty Johns Hopkins students participated in this experiment in exchange for class credit. These observers all reported normal or corrected vision. These participants were randomly assigned to one of six possible order conditions that served to counterbalance the presentation of three different display size conditions.

Stimuli

The experiment was run on a Dell Pentium 1.8 GHz computer with an ATI 128 Ultra screen, using the Matlab 6.1 platform and PsychToolBox software (Brainard, 1997). Observers were seated at a viewing distance of 57 cm from the computer monitor. Similar to those used by Maljkovic and Nakayama (1994), the stimuli consisted of coloured diamonds, each missing a corner. A completed diamond measured 1.3° on its vertical and horizontal axes, but had 0.2° removed from either its left or right side, chosen randomly for each item. In each display, the target was either red or green, with all distractor diamonds the other colour. Displays contained three, five, or seven diamonds, a factor that was manipulated between sessions to minimize differential intertrial effects. On each trial, a diamond was randomly assigned to one of six starting positions in the top-right quadrant of a 6° diameter circle, and then the remaining diamonds (either two, four, or six) were placed equidistant from each other around the circle. One of these diamonds was randomly designated the target item.

Each search display was preceded by one of three possible instructional cues: RED, GREEN, EITHER. The words were drawn in the Courier font using a neutral grey and centred at fixation. Each word extended 0.6° in height, and RED, GREEN, and EITHER extended in the horizontal direction 1.7° , 2.7° , and 3.3° , respectively. The RED and GREEN cues were informative and revealed the colour of the next target with 100% validity. The EITHER cue was noninformative, indicating an equal likelihood of a red or green target next, thus requiring search for the unique item. Participants were instructed to use these cues to help them find the target as quickly as possible, so that they could report which corner of the target diamond was missing (left or right).

Design and procedure

On each trial, a fixation cross appeared, then an instructional cue for 1000 ms, then the fixation returned for 500 ms before the search display was presented. The search display remained on the screen until response. The duration of the fixation display was adjusted on each trial to achieve a constant 2.8 s interval between search displays across conditions. This did not change the duration of the cue or the time between cue offset and display onset. The opportunity for a short break was provided after each 150 trials.

The assignment of expectancy and target colour was randomly chosen for each trial. On each trial, there was an equal likelihood of either target colour (red or green), which was equally likely to be paired with either a noninformative cue (EITHER) or the appropriate informative cue (RED

or GREEN). An example of a single trial and a series of trial displays are shown in Figure 1.

Participants were instructed to identify the chipped side of the target diamond and respond accordingly (“z” key if left, “/” key if right) as quickly as they could. They were told the target diamond would always be the uniquely coloured item (i.e., a green among reds, or a red among greens). In addition, they were instructed to use the cue words before each trial to help them respond as quickly as possible. It was explained that a colour word was always predictive of the upcoming target colour and the word EITHER indicated either target colour was equally likely to occur.

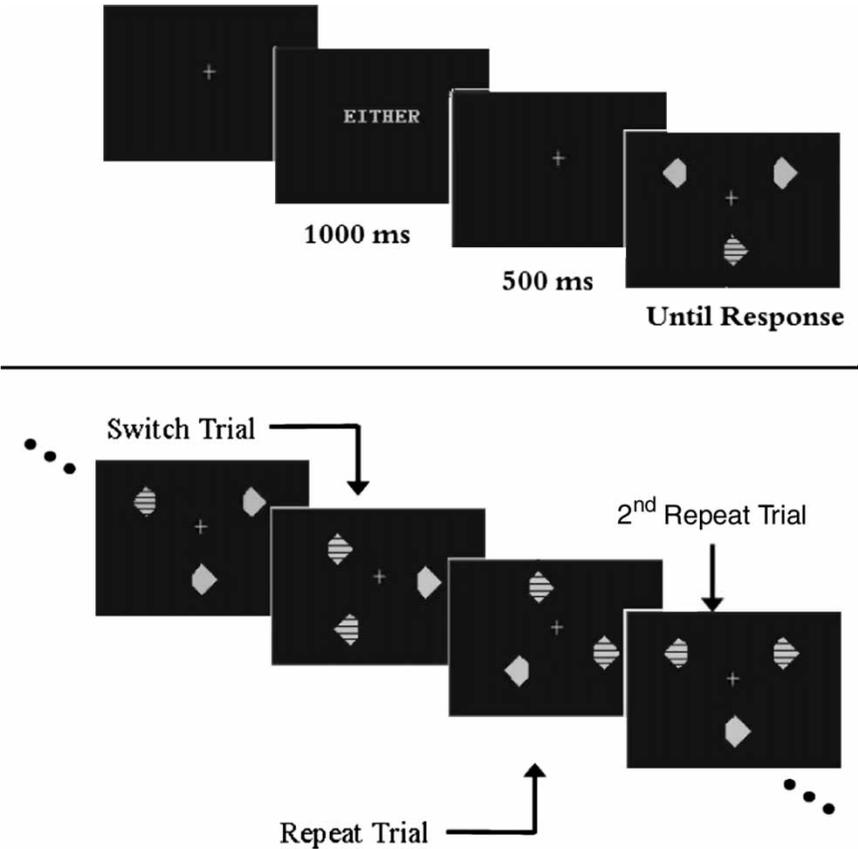


Figure 1. The inset depicts the time course of a single trial from the informative condition. Below are a series of search displays from sequential trials that show the switch, repetition, and second repetition conditions. Solid and striped colorations are used to represent red and green.

To clarify our nomenclature, consider a string of six trials, G-R-G-G-G-G, where the letter represents the target colour (green or red). The first trial, in this case G, of a session (or after a break) was not analysed. The second trial in this example, R, is a switch trial, as the current target colour differs from that of the previous trial. The third trial, G, is another switch trial. The fourth trial is a repeat, as the target colour is the same as the third trial. The fifth trial, G, is a double repeat, as the current target colour is the same as previous trial. Finally, cases such as the sixth trial, where the target colour was repeated more than twice in a row, are considered 2+ repeat trials. The session continued until there were at least 30 trials with informative cues and at least 30 trials with noninformative cues in each of the critical conditions.

A session had on average 517 trials (ranging from 411 to 675 with a standard deviation of 62 trials) and took approximately 40 to 50 minutes to complete. Participants performed three such sessions on three separate days, one for each display size (3, 5, and 7 items). The order of these sessions was counterbalanced, with five unique participants participating in each of the six possible orders. Participants completed the three sessions within an average of 7 days. There were no significant differences in this time to completion ($F < 1$) among the six counterbalanced groups.

RESULTS

Trials with errors (2.6% of all trials) were removed from the reaction time analysis. Average reaction times and standard error are shown in Figure 2. An ANOVA with cue type (informative or noninformative), repetition (switch, single repeat, double repeat, and 2+ repeat), and display size (3, 5, or 7) as within-subject factors and session order as a between-subject factor was conducted on the reaction times for the correct trials. There was no main effect of session order ($F < 1$), but there were several significant interactions. The interaction of cue type and session order, $F(5, 24) = 2.75$,

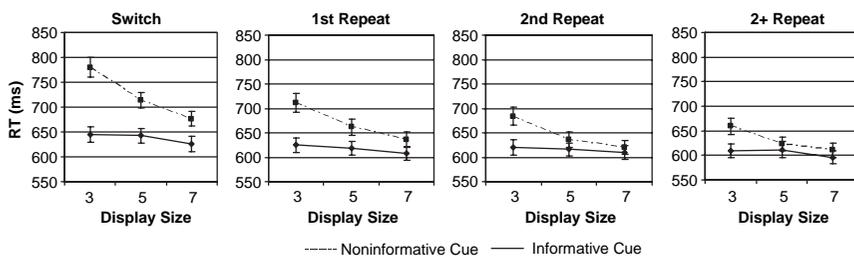


Figure 2. Average reaction time is shown. Previous target colours determined the repetition classification and cue type created disparity in expectancy. Error bars represent standard error.

$p = .04$, and that of display size and session order, $F(10, 48) = 3.22$, $p = .003$, reached significance. Critically, there were no significant interactions involving session order and repetition, the focus of this investigation, and therefore session order was omitted as a factor in subsequent analyses.

In accordance with previous findings, repeating the target colour between trials led to significantly faster RTs, $F(3, 87) = 122.1$, $p < .001$. Reaction times also significantly decreased with an informative cue, $F(1, 29) = 108.8$, $p < .001$. There was a main effect of display size on RTs, $F(2, 58) = 7.5$, $p = .001$. These main effects were qualified by a significant three-way interaction of cue type, display size, and target repetition, $F(6, 174) = 2.778$, $p = .013$. This three-way interaction is described via analysis of the two-way interactions, as well as several simple effects analyses.

The interaction of Display size \times Cue type was significant, $F(2, 58) = 40.4$, $p < .001$. Bravo and Nakayama (1992) had suggested that when search was for a known target mean reaction time should be independent of display size. Consistent with this suggestion, there was no significant effect of display size on reaction time when an informative cue was provided, $F(2, 58) = 1.1$, $p = .341$. Further, as in Bravo and Nakayama, reaction times in the noninformative cue condition decreased significantly with increases in display size, $F(2, 58) = 16.6$, $p < .001$.

The interaction between repetition and cue type was significant, $F(3, 87) = 65.5$, $p < .001$. This can be seen in Figure 2, in that the difference between informative and noninformative RTs tends to decrease across the four panels from switch to 2+ repeats. An ANOVA conducted on the mean reaction times in the informative condition revealed a significant effect of repetition, $F(3, 87) = 20.82$, $p < .001$. For the informative condition, pairwise comparison revealed that the 20 ms difference between reaction times in the switch and repeat conditions was significant, $t(29) = 6.39$, $p < .001$. There was no benefit of additional repetition, as the differences between repeat and double repeat trials, $t(29) = 0.61$, $p = .55$, and between double repeat trials and 2+ repeat trials, $t(29) = 1.85$, $p = .075$, were not significant. In the noninformative cue condition, reaction time was also subjected to an ANOVA and showed significant decreases with repetition, $F(3, 87) = 184.7$, $p < .001$. In this case, the 54 ms difference between switch versus repeat trials was significant, $t(29) = 12.4$, $p < .001$, as was the 23 ms difference between repeat versus double repeat trials, $t(29) = 6.21$, $p < .001$, and the 15 ms difference between double repeat versus 2+ repeat trials, $t(29) = 3.83$, $p = .001$.

The interaction of display size and target repetition was also significant, $F(2, 58) = 4.25$, $p = .001$. This interaction was in turn dependent on expectancy, as indicated by the existence of a significant three-way interaction, $F(6, 174) = 2.778$, $p = .013$. This interaction is depicted graphically in Figure 3, which plots the advantage in RT of each repetition

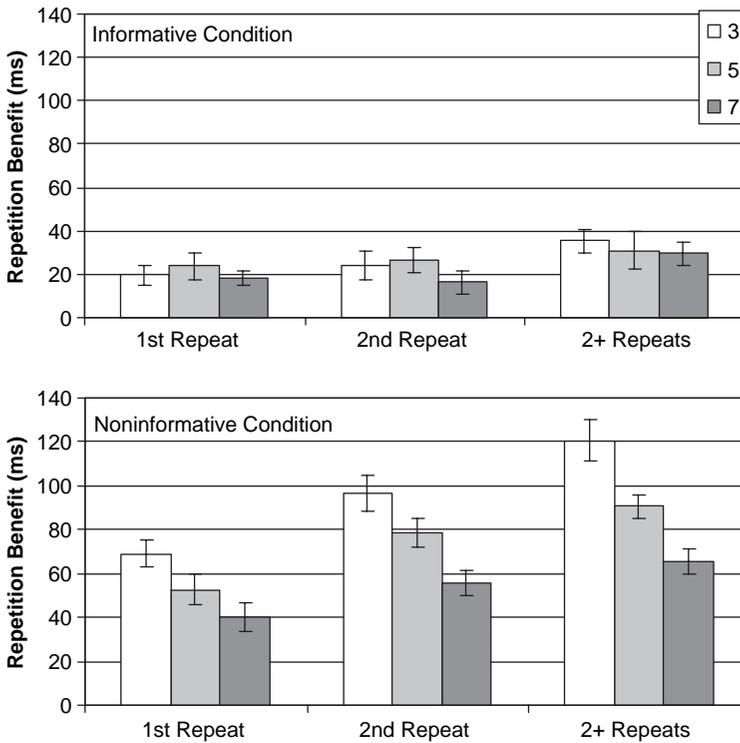


Figure 3. Benefit in reaction time provided by repetition is shown, comparing each of the repetition conditions to performance in the switch condition. Error bars represent standard error.

condition compared to the switch condition as a baseline. Within the informative cue condition, there was no significant interaction between display size and target repetition, $F(6, 174) < 1$. In the noninformative cue condition, this interaction of display size and target repetition was significant, $F(6, 174) = 5.6$, $p < .001$, such that RTs were more speeded by repetition in the small display size conditions.

Pairwise comparisons were done to check for significant differences between the reaction times for noninformative and informative conditions, as after several repetitions these seemed to converge. All 12 comparisons between the noninformative and the informative condition were tested for significance using t -tests with a Bonferroni corrected p -value of .0042. Using this conservative criterion, there were four cases where reaction times between the two expectancy conditions did not differ significantly: The double repeat condition for display size 5, $t(29) = 2.21$, $p = .036$, the 2+ repeat condition for display size 5, $t(29) = 1.71$, $p = .098$, the double repeat

condition for display size 7, $t(29) = 1.955$, $p = .060$, and the 2+ repeat condition for display size 7, $t(29) = 2.33$, $p = .027$.

Error rates were analysed in an ANOVA with cue type, repetition, and display size as well. The effects of the conditions were either insignificant or showed fewer errors for faster responses, inconsistent with a speed–accuracy tradeoff.

DISCUSSION

We found that search speed for an unknown target decreased with increasing display size, while search speed for a known target was faster overall and independent of changes in the number of distractors. These results are consistent with previous research that has shown that top-down influence can modulate attentional access to salient singletons (Bacon & Egeth, 1994; Folk, Remington, Johnston, 1992). Crucially, even on trials in which there has been no repetition of the target feature (i.e., on switch trials), informative cues allowed participants to engage in an efficient feature-based search strategy, as indicated by independence of RT and display size. These results replicate and extend the findings of Bravo and Nakayama (1992), countering the claim of some (e.g., Maljkovic & Nakayama, 1994; Theeuwes et al., 2006) that there can be no top-down modulation in singleton search.

Although our results show that it does not account for top-down modulation, intertrial priming clearly does have an important role in the guidance of attention. Trials on which attentional set can be configured in advance are further speeded if the target feature matches that of the previous trial, although additional repeats provide little further benefit. These results are consistent with Hillstrom (2000, Exp. 2), who showed that that facilitation is maximized after a single repetition in search for a conjunction target that necessitated top-down guidance. When a noninformative cue is given and search depends on bottom-up salience, a repeat in the target feature from the previous trial leads to faster responses that cumulate with consecutive repetitions. Folk and Remington (in press) have found a similar result suggesting such feature-specific priming using a spatial cueing paradigm. For participants searching for a salient target, there was enhanced attentional capture when the colour of a cue singleton on target N matched that of the target singleton on trial $N-1$.

When search cannot be guided explicitly via an informative cue, the salience of the singleton does affect the amount of intertrial priming. We find that there is less intertrial priming as the target becomes increasingly salient (i.e., as display size increases), a result consistent with the findings of Meeter and Olivers (2006). Conversely, we find that the benefit of repetition in the informative condition is not modulated by the salience of the target.

These differences between the repetition effects for known and unknown targets suggest that these types of priming may emerge from different levels of processing (Meeter & Olivers, 2006).

As a caveat, it is worth noting that our experiment has only addressed the influence of salience, top-down guidance, and intertrial priming with regard to two feature values in the colour dimension. All dimensions are not created equal. Several lines of research have shown that colour may be very different from other dimensions, such as location (i.e., Nissen, 1985) or motion and orientation (Nothdurft, 1993). Closer to the current paradigm, Found and Müller (1996) found that intertrial effects for feature values within the colour dimension differed from those in the orientation dimension.

Our conclusion that top-down factors can influence attentional guidance to a salient singleton is in disagreement with that of Theeuwes et al. (2006). In their studies, a similar cueing paradigm was used, such that participants were sometimes informed as to which dimension the singleton would be in. For example, a participant might be told that the singleton will be on the colour dimension (as opposed to the shape dimension).¹ Theeuwes et al. did show benefits of an informative cue when the task involved simple detection of a singleton element (Exp. 1), although these effects were attributed to response selection factors rather than attentional modulation. However, they show no benefit of an informative verbal cue in singleton search (Exps 2 and 3) when the design was changed to a compound search task in which a colour difference defines the target and shape determines the response. This is in contrast to our results, which clearly show an influence of expectancy on search speed using a compound search task. It is not entirely clear what is responsible for this difference in outcomes, but one likely explanation can be found in the display sizes used; 3, 5, and 7 in the present study and 9 in Theeuwes et al. Our reasoning here is similar to that underlying the ambiguity theory of Meeter and Olivers (2006). Basically, as homogeneous distractors are added to a display it becomes less and less ambiguous which element is the target. Meeter and Olivers showed that as the number of homogeneous distractors increased, the effect of intertrial priming decreased. Similarly, we have shown that as the number of homogeneous distractors increased, the benefit of target foreknowledge decreased. This is driven by the fact that although knowing the target in advance lead to constant RTs as display size increased, performance in the noninformative condition became faster as display size increased. One can think of this as a sort of floor effect; with a large number of homogeneous distractors, target

¹ The cues indicated the dimension of the upcoming target singleton, but this was always associated with a particular feature (e.g., a “shape” cue always indicated the target would be a green diamond among the green circle distractors). Because of this, it is not entirely clear whether this should be thought of as feature or dimensional cueing.

salience becomes so high that there is simply no room for improvement from knowing the target identity in advance.²

Notably, our priming results differ from those found by Maljkovic and Nakayama (1994, Exp. 4), who used similar stimuli and found that knowledge of the upcoming target colour did not modulate the strength of intertrial priming. In their experiment, a predictable alternation between two red and two green targets was used in both the known and unknown target condition. In order to manipulate target expectancy, participants either actively tracked this alternating pattern or were encouraged to ignore the repetition by listening to background music or engaging in conversation. Their finding that priming was not modulated by knowledge of the upcoming target (i.e., by the difference between the active tracking and the ignore conditions) may have been because this somewhat unusual manipulation of expectancy was not effective. While our results do show significant priming for both known and unknown targets, we do find modulation: For known targets, the magnitude of this effect is smaller, not cumulative across multiple repetitions, and independent of display size.

Wolfe et al. (2003) suggest that intertrial priming represents information stored in the system that can be considered an implicit form of top-down guidance. In this way, repetitions of a target colour implicitly enhance the visual system's expectations about what colour target is likely to occur next. In accordance with this idea, our data show that reaction times on noninformative cued trials are speeded if the target feature has repeated several times. After several sequential repetitions of a specific target, search using bottom-up salience does begin to approach the efficiency of that using top-down guidance. This would seem to support the idea that intertrial priming alters feature (or dimension) weighting, in the same way as top-down biasing. However, we suggest two reasons why viewing intertrial priming as implicit top-down guidance (i.e., feature weighting) may not be the complete story.

While priming led to reaction times in the noninformative condition that were equivalent to those in the informative condition, this was the case only for display sizes 5 and 7. For display size 3, reaction times were still significantly slower in the noninformative condition. If the noninformative condition reached the level of the informative condition via implicit changes in feature weighting alone, performance should have resembled that of the informative condition, with equivalent performance for all display sizes. Therefore, our results suggest that although priming can lead to perfor-

² In contrast, the results of Bravo and Nakayama (1992) did suggest that even with large display sizes (over 20 items), there was faster performance in the target-known condition. However, since they used consistent versus inconsistent blocks to manipulate target knowledge, it is unclear whether this remaining benefit is attributable to priming differences.

mance equivalent to that of top-down efficiency, it may not be achieved through the same functional changes. Lamy, Carmel, Egeth, and Leber (2006) have also questioned whether the speeded performance caused by priming results from alterations of attentional weighting or implicit top-down guidance. In particular, their experiments examined the influence of an irrelevant distractor singleton. When participants relied on bottom-up salience to guide search, this irrelevant singleton caused interference. This interference was drastically reduced when participants knew the upcoming target feature and could engage in feature search. If feature weighting increases with priming, a reduction in singleton interference when the target feature has repeated between trials would be expected, even when there was no explicit top-down cue. However, no such reduction was found.³ In conjunction with our own findings, Lamy et al. provide further evidence that intertrial priming is not equivalent to changes in feature weighting.

A more likely alternative posits that priming effects are largely due to the efficacy of feedforward (i.e., bottom-up) processes, such as the speed at which feature differences accumulate (for a similar theory in relation to a dimensional account of guidance, see Müller, Krummenacher, & Heller, 2004). According to this account, changes in the RT for pop-out displays can be explained by a facilitation of the speed at which information from the salient location propagates throughout the visual system. Increases in this processing speed can be driven by either salience or priming effects. Neural evidence also supports this model, as target-specific responses in frontal eye fields, an area often thought to represent the locus of attention, occur more quickly if the target has repeated from a previous trial (Bichot & Schall, 2002).

When the singleton is not very salient (e.g., at a small display size), propagation is slow and intertrial priming leads to a large benefit in RT. With a highly salient singleton target (i.e., at a large display size), propagation speed is already fast and intertrial priming has an underadditive effect. When given an informative cue, top-down attention can bias neuronal responses in advance of the stimulus via feedback signals, such that the speed of propagation matters very little.

Like Theeuwes et al. (2006), we feel that intertrial priming should be considered a bottom-up influence on the guidance of attention, rather than an implicit top-down influence. We provide further evidence suggesting that intertrial priming should be considered an influence on the efficacy of bottom-up processing rather than modulation of top-down feature

³ Pinto, Olivers, and Theeuwes (2005) found that distractor interference was reduced on repeat trials, a seemingly contradictory result. However, this discrepancy may be due to their design, in which the distractor and no distractor conditions were blocked, rather than intertrial effects (see Lamy et al., 2006, p. 929 for a more detailed discussion).

weighting itself. We also show evidence that intertrial priming does not account for some effects previously attributed to top-down guidance in singleton search. In conclusion, our study confirms a role for top-down guidance in singleton search, and also explores further the nature of intertrial priming.

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