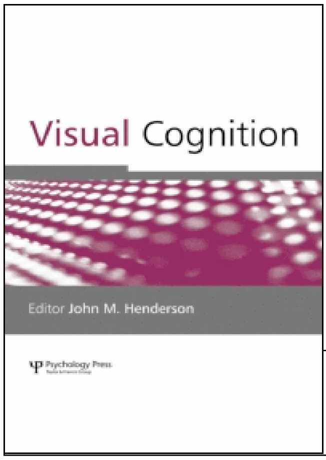

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Repetition streaks increase perceptual sensitivity in visual search of brief displays

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Studies examining possible priming effects on visual search have generally shown that repeating the same type of search facilitates or speeds performance. But such studies typically assess any priming via measuring response latency, in tasks where accuracy is at or near ceiling. This leaves open the possibility that criterion shifts alone might produce the apparent improvements, and such shifts could plausibly arise when, say, a particular type of repeated search display becomes predictable. Here we assessed criterion-free perceptual sensitivity (d') for visual search, in two experiments that used brief masked displays to bring performance off ceiling. In Experiment 1, sensitivity for a relatively difficult search task improved with successive repetitions of the same type of search, with sensitivity enhanced for both target-present and target-absent trials. In Experiment 2, sensitivity for a search task requiring discrimination on a colour-singleton target likewise showed enhancement with repetition. Experiment 2 also showed that the priming effects seem to influence the speed of attention shifts towards the target rather than influencing visual acuity directly. We conclude that priming in visual search, arising due to repetition streaks, is characterized by genuine improvements in perceptual sensitivity, not just criterion shifts.

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Visual search tasks involve searching for target visual items among nontargets, or distractors, which are currently irrelevant to the goal at hand. Such tasks have been widely used to study visual processing as they both can be carefully controlled and are relevant in daily life.

The original focus in visual search studies was upon what properties made targets pop out or be instantly noticed (Cavanagh & Chase, 1971; Egeth, Virzi, & Garbart, 1984; Julesz, 1984; Smith, 1962; Treisman & Gelade, 1980; see, e.g., Wolfe, 1998, for a comprehensive review). Over the last decade or so, however, a large number of researchers have switched their focus to possible learning or priming effects on visual search. By priming we here mean enhanced performance on a particular task because of previous exposure to that same task. This body of research has shown that when subjects search for a target in a visual array, performance is typically faster than otherwise if the same target or target feature is repeated across search trials (e.g., Goolsby & Suzuki, 2001; Hillstrom, 2000; Kristjánsson, 2006b, Kristjánsson, Wang, & Nakayama, 2002; Maljkovic & Nakayama, 1994, 1996; Olivers & Meeter, 2006; Theeuwes, Riemann, & Mortier, 2006; Treisman, 1992; Wang, Kristjánsson, & Nakayama, 2005).

For instance, in Maljkovic and Nakayama's (1994, 1996) pioneering experiments, observers had to find a uniquely coloured diamond (the singleton target) among two diamonds of a different colour. The observers then judged whether the target diamond had a notch cut off at its left or right. Maljkovic and Nakayama (1994) found that performance on this task was faster if the same target colour was repeated across successive trials, and/or if the target appeared in the same location as on preceding trials (see also Geng et al., 2006; Kristjánsson, Vuilleumier, Malhotra, Husain, & Driver, 2005; Kristjánsson, Vuilleumier, Schwartz, Macaluso, & Driver, 2006). Kristjánsson et al. (2002) subsequently found a similar priming effect in a more difficult search task where the target was not defined by a singleton feature but a combination of features, i.e., a conjunction search. The results of these studies indicate that search performance is influenced by repetition of target properties, and has been taken by some as evidence for the operation of an implicit memory system that can modulate search (Kristjánsson & Nakayama, 2003; Nakayama, Maljkovic, & Kristjánsson, 2004; see also Chun & Jiang, 1998; Kristjánsson, 2006a).

Priming in visual search (see Kristjánsson, 2006a, for a review) has usually been interpreted as reflecting perceptual facilitation for the target. However, an unanswered question is whether many—or even all—of these putative effects on search might be accounted for in terms of shifts in response criteria. For instance, repeating the same search type could change not perception as such, but search strategies, such that observers start to respond faster but with less accuracy. Such speed–accuracy tradeoffs have never been definitively ruled out, and could thus complicate interpretation of existing findings. In general, one would expect such shifts to go along with substantial changes in error rates (Green & Swets, 1966; Norton, Corliss, & Bailey, 2002; Wickens, 2002). In reaction time studies of priming in visual search, however, assessing this in detail can be problematic, especially when the error rates are low or near floor (see e.g., Palmer, Huk, & Shadlen, 2005; Palmer, Verghese, & Pavel, 2000).

For instance, in the studies of Kristjánsson et al. (2002), and Maljkovic and Nakayama (1994, 1996), the error rates were very low, typically lower than 5%, which does not allow for a detailed assessment of any speed–accuracy tradeoffs. It is conceivable that the speeded responses reflect changes in thresholds for deciding target presence, or target identity rather than changes in perception. Accordingly, in the two new experiments presented here, we directly assessed whether priming effects in visual search (arising due to repetition streaks, as in the recent studies of Kristjánsson et al., 2002, and Wang et al., 2005) can reflect genuine changes in perceptual sensitivity rather than mere criteria shifts.

In our first experiment, a visual array requiring a relatively difficult search was presented for a short time and followed by a mask. In the second experiment, we similarly used brief displays, but now the target was defined by a singleton colour feature. In both experiments, the probability of repeating the same kind of search was high, leading to repetition streaks. We used brief masked search displays to bring accuracy off ceiling, and separated sensitivity from criterion with the help of signal detection theory analysis (Gescheider, 1997; Green & Swets, 1966; Norton et al., 2002; Wickens, 2002). The goal was to assess whether repetition increased sensitivity or merely led to shifts in response criteria.

EXPERIMENT 1: REPETITION STREAKS INCREASE PERCEPTUAL SENSITIVITY IN A DIFFICULT SEARCH TASK

In Kristjánsson et al. (2002) priming patterns in a variant of a "conjunction" search task were investigated, using response time as the dependent measure. In that study, observers had to determine whether an oddly oriented (vertical or horizontal) red bar was present or absent in an array of red bars of the orthogonal orientation and green bars of the same orientation as the target. Using a repetition streak design, where the probability of search repetition was high, Kristjánsson et al. found large decreases in response times as the same search was repeated. On the basis of those results, one cannot, however, rule out that the observed pattern simply reflected changes in response criteria. For example, observers could have reverted to a more liberal criterion for deciding target presence following the repetition of the same target and distractors for a few trials in a row, which might then lead to faster responses. In principle, such a criterion strategy might also lead to false alarms (i.e., deciding that a target is present when it is actually not; see, for example, Di Pace, Marangolo, & Pizzamiglio, 1997; Simon & Small, 1969), but when accuracy is already at or close to ceiling, false alarms can be few even with a liberal search strategy. Here we addressed the issue of whether priming effects in visual search can reflect real changes in perception instead of just changes in response criteria. We used a task similar to Kristjánsson et al., but now used brief masked displays to bring performance off ceiling, and applied formal signal detection theory measures of sensitivity and criterion.

We assessed sensitivity (*d′*) and criterion (*c*) as a function of the repetition of the same search type. By search type repetition, we mean identical kinds of distractors on adjacent trials; the distractors defined the target, so repetitions could occur regardless of whether the target was actually present or not. We have previously shown that considerable priming effects, as measured by changes in response latency, can be seen when distractors are repeated, both for successive target-present and target-absent trials (Kristjánsson & Driver, 2005; Kristjánsson et al., 2002; Wang et al., 2005). But as outlined above, these effects are potentially contaminated by the confound of speed–accuracy tradeoffs.

Methods

Observers. Ten observers (aged 20–52, five females) each participated in 3000 trials spread over two sessions. They completed at least 300 practice trials before actual data collection. All had normal or corrected visual acuity.

Stimuli. Figure 1 shows a representative set of stimuli from the experiment. The display was prepared in the C programming language using the VisionShell function library (see www.visionshell.com) and presented on a 75 Hz cathode ray tube (CRT) screen controlled by a 7500 Power Macintosh computer.

A central light-grey (56.6 cd/m^2) fixation cross appeared at the start of each trial and was present until the onset of a brief 200 ms display of coloured bars. Each bar was either horizontal or vertical, and its colour could be red (14.8 cd/m^2) or green (13.9 cd/m^2). The size of individual bars was 54×18 arc min. The bars appeared on a black (0.5 cd/m^2) background. Stimuli were presented within an invisible 8×8 matrix subtending $14.4^\circ \times 14.4^\circ$ at a viewing distance of 60 cm. Within each square of the matrix, a bar could be centred in one of nine random positions. This resulted in a slight irregularity in the spatial layout of the array.

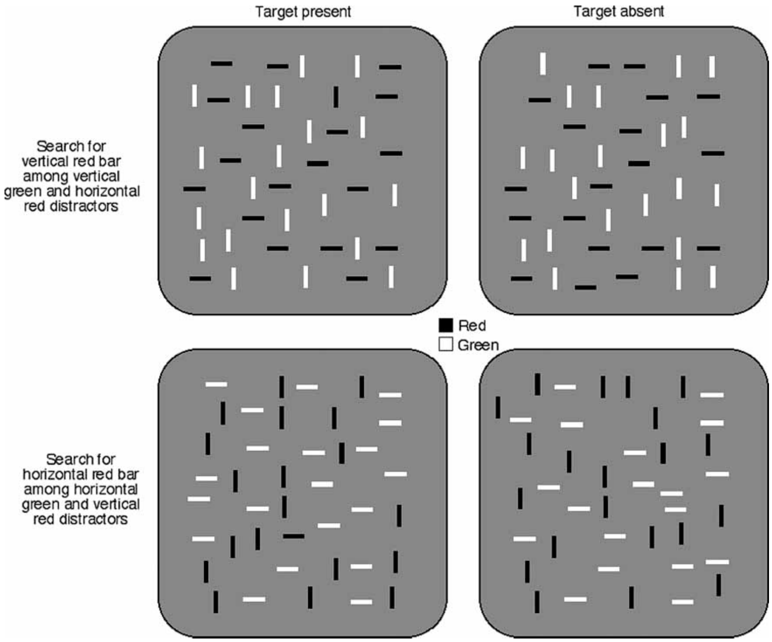

Figure 1. Four displays (set size = 40) illustrating the possible search tasks from Experiment 1. The observer was always required to indicate whether a uniquely oriented red item was present or absent in the display.

Procedure. Target presence or absence was unpredictable on any given trial. The target was always red when present, but its orientation (horizontal or vertical) varied between trials. The distractors defined the target identity, such that if the distractors were green verticals and red horizontals, the target was a red vertical, and if the distractors were red verticals and green horizontals, the target was a red horizontal. Likewise, on target-absent trials the distractors were red verticals and green horizontals, or vice versa.

The search type for the first trial within a block of trials was decided randomly with a probability of .5 for each type. By search type we mean search for either a horizontal or vertical red target. We refer to search types, rather than simply the two different targets, since the target was only present on half of the trials.

To maximize possible priming effects, a number of similar adjacent trials was needed. Therefore, the two different search types were not always equally likely to occur. Instead, we used an approach introduced in Kristjánsson, Mackeben, and Nakayama (2001) to increase the probability of repeating a particular search type. The probability that the search type from the previous trial would be repeated on any one trial was equal to

$1-m(0.1-(0.01m))$, where m is the streak length, i.e., the current number of subsequent presentations of this search type.

Thus, if the search was for a horizontal red target on trial $n-2$ but a vertical red target on trial $n-1$, m was 1 and the probability that a vertical red target would have to be searched for on trial n was .91; if the target searched for was indeed a vertical red bar on trial n, the probability that it would also have to be searched for on trial $n+1$ was .84 ($m = 2$), and so on. The probability function was set to asymptote at .75, so that when m was 5, 6, or 7, the probability of search type repetition remained at .75. However, if m reached 8, the probability was set to 0 and the search type was switched. Therefore, 8 was the maximum length of a streak of similar searches. The streak length was therefore never fixed, but a search type similar to the previous one was, on the whole, more likely than the other.

Observers were told to press one of two keys to indicate whether an oddly oriented bar was present or absent in a search array (see Figure 1). The array consisted of 8, 16, 24, 32, 40, or 48 display items; each possible set size was equiprobable and determined randomly from trial to trial.

The display items were visible for 200 ms, after which a random dot mask appeared, covering the whole 14.4° × 14.4° grid. The size of each dot in the mask array was 13 arc min, and its colour was selected randomly from the same red and green colours as were used for the visual search stimuli. If the observer's response was correct, then "-OK-" appeared on the screen for 1500 ms; if the response was incorrect, "!!X!!" appeared for the same duration.

Results and discussion

Figure 2 shows the mean d' scores (black disks) for the 10 observers as a function of repetition streak length (0 to 7) of a particular search type. It is clear that d' increases with successive repetitions, indicating heightened sensitivity for detecting target presence or absence in the briefly presented display. The figure also shows how c, the criterion measure, was affected by repetition (white disks). A repeated measures ANOVA on d' scores for each observer confirmed that the effect of search type repetition was highly significant, $F(7, 63) = 8.18$, $p < .001$. A similar ANOVA on the c scores also revealed a main effect of repetition of search type, $F(7, 63) = 7.36$, $p = .002$.[1] But the key point for present purposes is that even when effects of criterion shifts had been accounted for, a genuine effect on perceptual sensitivity was found. Even though accuracy was the main dependent variable of interest,

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[1] Mauchly's test of sphericity was significantly different from zero so the degrees of freedom were adjusted using a Greenhouse-Geisser correction.

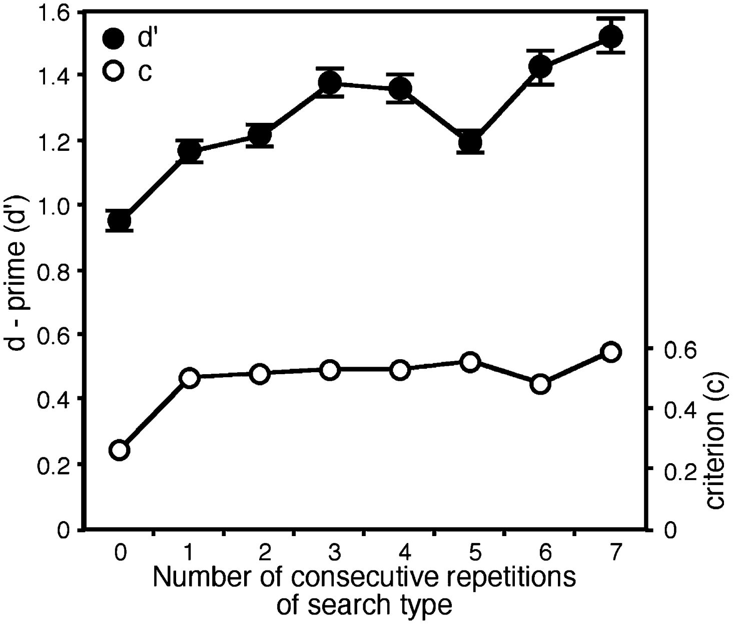

Figure 2. The mean *d′* and *c* scores for the 10 observers from Experiment 1, as a function of the number of successive presentations of similar search type trials. The error bars show the standard deviations of the means. For *c*, the error bars are either similar in size or smaller than the symbols for each mean, and therefore are not shown.

we also measured response times. Response times decreased significantly with repetition of search type (mean slope = − 12.7 ms for each repetition), $F(7, 63) = 3.38$, $p < .005$, in agreement with prior studies of priming in search. Accuracy decreased linearly with increased set size (by 0.675% for each added distractor, from 87% correct for set size = 8, to 60% correct for set size = 48) indicating that the search task became more difficult with increased set size.

Since *d′* generally increased with repetition of search type this indicates that observers became more sensitive to whether the target was present or not as the same search was repeated. They were not merely adjusting their response criterion (measured with *c*), although some criterion shifts were found. The increase in *c* was by far the largest when search types were switched, but *c* changed very little with further repetitions of the new search type. On the other hand, *d′* continued to improve.[2]

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[2] Note that even though *c* would increase to the same degree as *d′*, the latter is a criterion free measure of sensitivity; increased *d′* therefore indicates increased sensitivity, regardless of any changes in *c*.

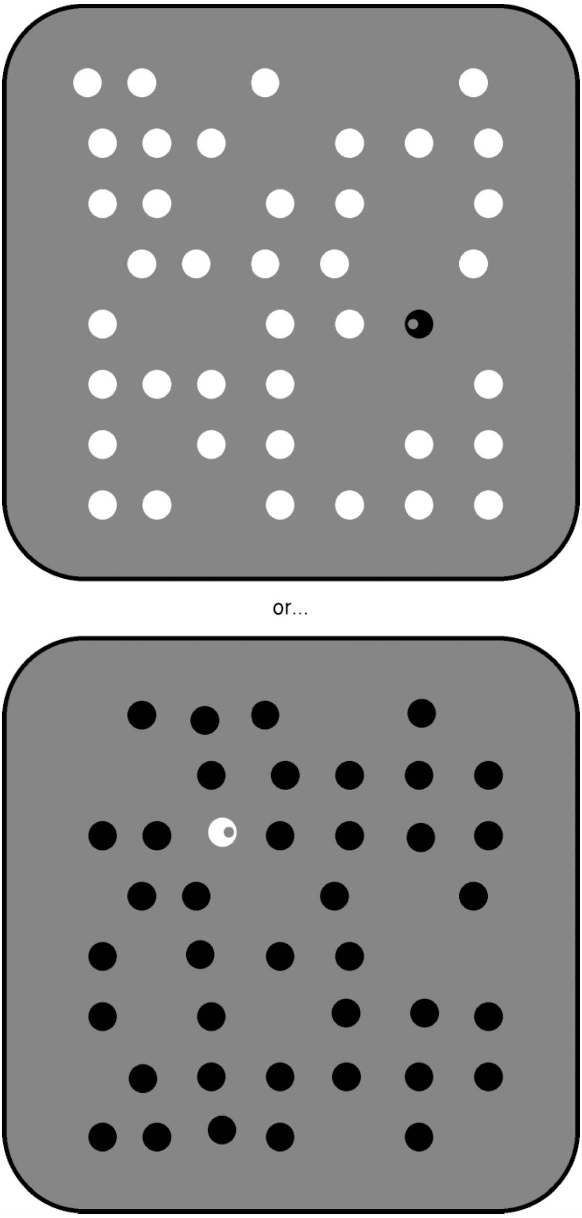

Figure 3. The two possible search types from the second experiment. The task was to find the oddly coloured singleton target (either red among green distractors, denoted with black and white, respectively, or green among red distractors), and then indicate whether the small hole in it was slightly displaced to the left or right of the target's centre. A singleton target was present on every trial.

EXPERIMENT 2: REPETITION STREAKS ENHANCE SENSITIVITY IN VISUAL SEARCH FOR SINGLETON TARGETS

The results from Experiment 1 show that sensitivity in a variant of a conjunction search task can increase with repetition of search type. In Experiment 2, we sought to test whether repetition can also enhance sensitivity when the target has a unique singleton feature, namely colour. A singleton target was now present on each trial defined by its unique colour. The task was not only to find this singleton target, but to make a certain judgement about its attributes, for which we could calculate *d′*. Specifically, observers had to find an oddly coloured disk (red among green, or vice versa), and then judge whether a small "hole" in this disk was slightly displaced to the left or right from the disk's centre (see Figure 3).

Methods

Participants. Eight observers participated, all with normal or corrected visual acuity. Two of the authors participated; the rest were unaware of the purpose of the experiment. Results were comparable between naïve and non-naïve observers. Data was collected from 3000 trials for each observer, in blocks of 100 over two experimental sessions. Each observer also completed at least 300 practice trials before data collection.

Stimuli and apparatus. The same equipment was used for presentation and data collection as in Experiment 1. Figure 3 illustrates the stimuli from the experiment. The task was to find the oddly coloured disk on each trial, and indicate by pressing the appropriate key whether the small hole within this target disk was horizontally offset to the left or right. A target was now present on *all* trials.

The diameter of each disk was 2.1° and the diameter of the small hole within the target was 0.7°. This hole was displaced on each trial by 0.05°, 0.1°, 0.15°, or 0.2° to the left or right of the disk's centre. The target was either red (14.8 cd/m^2) among green (13.9 cd/m^2) distractors, or green among red distractors. Each array of disks was presented for 200 ms on a light grey background. A random dot mask identical to the one in Experiment 1 followed the presentation of the stimuli and remained visible until the subject responded.

The likelihood that the target colour was repeated from the previous trial was determined by the same algorithm as in Experiment 1. The probability of the repetition of target colour was therefore .75 or higher until after the eighth presentation of the colour; then the probability of repetition was set

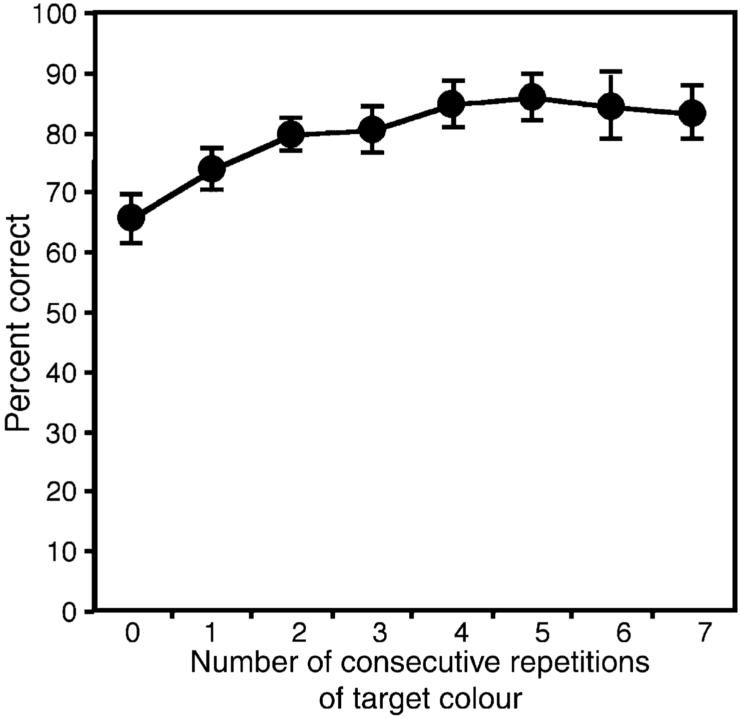

Figure 4. The mean percentage correct scores for the eight observers from Experiment 2. The error bars show the standard deviations of the means.

to zero and the target colour was bound to change (see Method section of Experiment 1 for details of this procedure).

Results

Figure 4 presents the overall percentage correct on the acuity "hole" task, as a function of how often the same target colour was successively repeated. Performance on the acuity task improved quite significantly as search colour was repeated, $F(7, 49) = 62{,}761$, $p < .001$. Response times decreased slightly (but significantly) with search type repetition (slope $= -7.32$ ms for each repetition), $F(7, 49) = 2.53$, $p < .05$.

Figure 5 shows the d' scores (extracted through a conversion of two-alternative forced-choice results into d'; see Gescheider, 1997; Hacker & Ratcliffe, 1979[3]) for each of the four possible horizontal offsets of the hole

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[3] The formula $d' = (\sqrt{2})(z[\rho])$, where ρ is the proportion correct, yielded similar results (see Wickens, 2002).

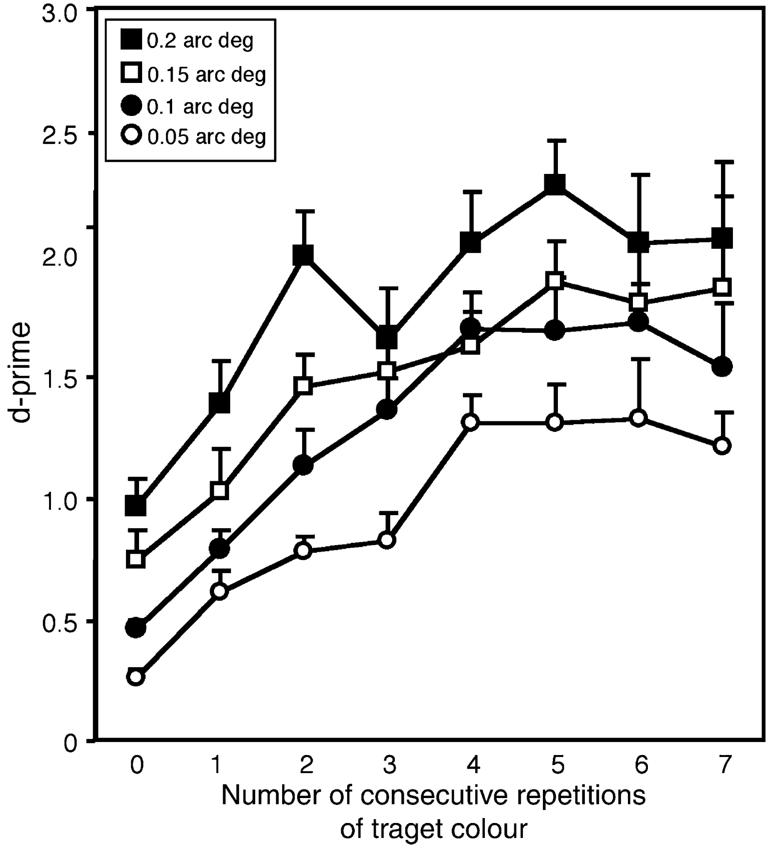

Figure 5. The average *d′* scores as a function of repetition of search type. The *d′* scores are shown as a function of the displacement size of the smaller disk within the larger disk. The error bars are only shown for the "upwards" error to avoid cluttering the graph. The "downwards" errors are identical to

within the target. These results clearly show that sensitivity increased systematically with search repetition. A repeated-measures ANOVA revealed a main effect of repetition of search task on *d′*, $F(7, 49) = 9.38$, $p < .001$, as well as a main effect of displacement of the small hole, $F(3, 21) = 16.02$, $p < .001$, but no significant interaction, $F(21, 147) = 1.13$, $p > .05$.

The data in Figure 5 can also help to address whether search repetition increased acuity for the hole-offset judgement, or simply facilitated the process of finding the target. Nakayama et al. (2004) and Kristjánsson (2006a) have argued that priming has a direct effect upon attentional allocation. It is possible that acuity is influenced directly with the priming, especially in light of the demonstrated beneficial effects of attention on discrimination performance (e.g., with spatial cues, Carrasco, Pencepi-Talgar, & Eckstein, 2000; Carrasco, Williams, & Yeshurun, 2002; Eriksen & Hoffman, 1973; Shiu & Pashler, 1995; Solomon, Lavie, & Morgan, 1997).

It is to be expected that increased acuity has the most beneficial effects on performance for small offsets of the hole in the target. If repeated search enhances acuity, then the differences between small and large offsets might be reduced. Conversely, if search repetition makes the target easier to find, but has no effect upon acuity itself, then effects of search repetition and hole-offset might be expected to be additive and no statistical interaction between the two factors should be seen (cf. Sternberg, 1969).

In fact, the statistics from the repeated measures ANOVA mentioned above suggest that the processes are independent, because while there was a main effect of both displacement and search task repetition, there was no significant interaction between the two variables. This suggests that the repetition had no effect upon visual acuity but instead allowed for faster attending to the target and thus more time for its analysis. Post hoc *t*-tests between each individual also revealed no significant difference between any of the effects even at uncorrected *p*-values (all ts < 1.2; p-values $> .2$), which further cements our conclusions of independence of the effects of displacement size and search type repetition.

GENERAL DISCUSSION

Many recent studies (see introduction for a review) have reported priming effects on visual search, in the sense that responses are faster when some aspect of a search task is repeated. However, most such studies have not been able to conclusively rule out criterion shifts or potential speed–accuracy tradeoffs, because they have used reaction time measures, with accuracy typically at or close to ceiling. While a separate and extensive literature has applied formal signal detection theory analyses to visual search data (Palmer et al., 2000, 2005), most such studies have not been concerned with priming in particular, as the case was here. We tested for the first time whether repetition streaks during visual search tasks can genuinely affect perceptual sensitivity (d'), as separated formally from criterion (c), in brief masked displays.

Experiment 1 involved a variant of a conjunction search task, where the presence or absence of a uniquely oriented red bar had to be detected among green bars with the same orientation, and red bars of the orthogonal orientation. We found that sensitivity to target presence or absence generally increased with repetition of the search type (i.e., searching repeatedly among red verticals and green horizontals, or vice versa). To our knowledge, this provides the first unequivocal demonstration that search repetition can truly enhance perceptual sensitivity.

Experiment 2 extended this new result to a situation where the target was a colour singleton, with an "acuity" offset judgement being made on this target. Once again, successive repetitions of the search type (now, the colour of the singleton target) led to progressive increases in perceptual sensitivity (*d*′). The result is also important in light of claims that brief displays where accuracy is measured, and longer displays present until response do not, in all cases measure the same facets of performance (Mordkoff & Egeth, 1993). For example Santee and Egeth (1982) contrasted letter recognition performance with brief versus long duration displays and argued that the two types of task do not always reflect the same type of process.

Overall, these results indicate that repeating a search task, even over just a few successive trials within a "repetition streak" (Kristjánsson et al., 2001, 2002), can enhance perceptual sensitivity. The present results add to the growing literature showing how consistencies over time can improve perceptual performance (e.g., Chun & Jiang, 2003; Geng & Behrmann, 2005; Kristjánsson & Nakayama, 2003; Maljkovic & Nakayama, 1994, 1996; Miller, 1988).

In Kristjánsson and Nakayama (2003) we argued for the existence of a memory system not under voluntary control that allows for fast reorientation to previously viewed, behaviourally important items. This memory system has a strong influence on the operation of attentional mechanisms. In Kristjánsson et al. (2002) we reported that search priming results in changes in the allocation of attention. We argued then that those results indicated that an extensive part of performance in visual search tasks that has often been attributed to top-down factors (see, e.g., Treisman, 1988; Wolfe, 1994) might be explained by priming via target repetition instead. But prior to the present experiments, those previous priming effects on latencies might have been attributed solely to criterion shifts. Here we were able to demonstrate unequivocally that genuine improvements in perceptual sensitivity can be induced with repetition of search type.

One interesting aspect of Experiment 2 here was that while perceptual sensitivity was enhanced with successive repetitions of the singleton feature, this effect was simply added to (cf. Sternberg, 1969), but did not interact with, the distinct effect of the extent of the horizontal offset to be judged in the acuity task. This may indicate that the main benefit from search repetition lay in finding the target, rather than performing the acuity judgement task once the target was found.

In conclusion, our two experiments add to the growing literature on priming effects in visual search, by showing for the first time that successive streak repetitions of a search task can enhance perceptual sensitivity, rather than merely shift response criteria, thus indicating that repetitions have a genuine effect upon visual perception.

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