Journal of Experimental Psychology: Human Perception and Performance

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An extensive amount of research indicates that repeating target and distractor features facilitates pop-out search while switching these features slows the search. Following the seminal study by Maljkovic and Nakayama (1994), this "priming of pop-out" effect (PoP) has been widely described as an automatic bottom-up process that is independent of the observers' expectations. At the same time, numerous studies highlight the crucial role of expectations in visual attention deployment. Our experiment shows that in contrast to previous claims, PoP in a classic color singleton search task is a mix of automatic processing and expectations. Participants searched for a uniquely colored diamond among 2 same-colored distractors. Target color sequences were either predictable (e.g., 2 red-target-green-distractors trials, followed by 2 green-target-red-distractors trials, and so on) or random. Responses were faster in predictable color sequences than randomly changing ones with equal number of repetitions of target colors on preceding trials. Analyses of observers' eye movements showed that predictability of target color affected both latency and accuracy of the first saccade during a search trial. Our results support the idea that PoP is governed not only by automatic effects from previous target or distractor features but also by top-down expectations.

Public Significance Statement
People respond faster if they have to search for a target of the same color as on the previous trial, and they slow down if target color changes. Such priming of attention shifts from previous trials is very strong and influential accounts claim that they are fully automatic and do not depend on observers' expectations. We measured the effects of repetition and expectations on response times and saccadic eye movements during visual search, finding that expected feature repetitions lead to faster response times than unexpected ones, and reduce switch costs. Similar effects were found for eye movements. While priming effects are strong they do not completely overshadow top-down effects of expectation.

Research over the past 20 years or so has shown that visual attention is necessary for accurate visual perception (Mack & Rock, 1998; Most, Scholl, Clifford, & Simons, 2005; Rensink, 2000) Attention, in turn, is strongly influenced by what we have recently viewed and interacted with (Kristjánsson, 2006). It is automatically drawn to objects of interest that may, for example,

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contain a critical feature (Campana, Pavan, & Casco, 2008; Kristjánsson, 2006; Lamy, Carmel, Egeth, & Leber, 2006; Maljkovic & Nakayama, 1994), combinations of features (Ásgeirsson & Kristjánsson, 2011; Becker & Horstmann, 2009; Geyer, Müller, & Krummenacher, 2006; Kristjánsson & Driver, 2008; Kristjánsson, Wang, & Nakayama, 2002) or spatial relations (Fuggetta, Campana, & Casco, 2007; Fuggetta, Campana, & Lanfranchi, 2009) that were important during preceding attention deployments. For example, after watching a TV show about snakes one could be prone to attend to branches on the ground during a walk in the park. Such priming is adaptive and can help us keep track of objects important for behavior as these objects move around in the world, and as we move around the world. Consistent with this, priming in visual search task been found to determine where we choose to orient our attention (Brascamp, Blake, & Kristjánsson, 2011; Chetverikov & Kristjansson, 2015). However, it is not clear to what extent such effects reflect short-lasting automatic "bottom-up" influences or some form of learning, resulting in conscious, top-down expectations.

Automatic Influences in Priming of Pop-Out

According to well-known theories of visual search, two basic processes drive visual attention, "top-down" and "bottom-up" processes. Kristjánsson et al. (2002) argued that priming from previous trials could account for most, if not all, effects of top-down knowledge of target identity on visual search (see also Belopolsky, Schreij, & Theeuwes, 2010 and Wolfe, Butcher, Lee, & Hyle, 2003, for some related findings). These findings show how powerful priming can be. At the extreme, single-feature search has been assumed to reflect only priming (Leonard & Egeth, 2008; Theeuwes, Reimann, & Mortier, 2006). Consistent with this, priming is often thought to occur automatically, and is assumed to be under only limited top-down control.

The strongest evidence for the claim that priming is not influenced by top-down control comes from the work of Maljkovic and Nakayama (1994, Experiment 2). Maljkovic and Nakayama pitted expectancy and perceptual priming against one another by varying how regular switches between target types were, during a feature search task for a red target among green distractors (or vice versa). A key to understanding this is shown in their Figure 3, reproduced here in Figure 1. If predictability or expectancy explains the data, they should follow the inverted U-shaped function shown in Figure 1, which peaks at 50% probability of a switch between target and distractors. The upcoming target is completely predictable both when the probability of a switch is 0 and when it is 1. Maljkovic and Nakayama manipulated the transition probability of color switches. If expectations play a dominant role in the search, then there should be no difference in performance between blocks where the transition probability is 0 (resulting in no changes of target color), and blocks where the transition probability is 1 (resulting in constant alternation of target colors), because in both cases the participant can form completely reliable expectations about what the target color will be on the next trial. However, if perceptual priming determines search, performance during blocks with constantly alternating colors should be worse because then there would be no benefit from repeating the same target.

The results were surprising. Response times (RTs) increased roughly linearly with increased switch probability, being highest
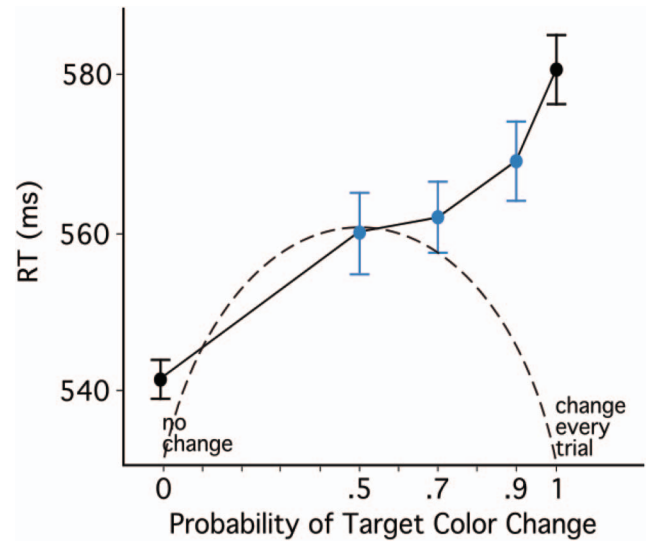

Figure 1. Repetition rather than expectancy determines perceptual priming. The dashed line shows expected performance if predictability of the target identity from one trial to the next (on the *x*-axis) determined performance. The solid line shows performance as a function of the likelihood of target change. Blue points represent conditions with unpredictable target color change, while black points indicate conditions with 100% predictability of upcoming target color (replotted from Figure 3, Maljkovic & Nakayama, 1994). See the online article for the color version of this figure.

when the probability of switch was 1, even though target color was completely predictable (as shown in Figure 1). Additionally, Maljkovic and Nakayama tested performance when observers always knew that there would be two red targets followed by two green targets and that this alternation would continue throughout the block. Even though in this case, target color was completely predictable, responses were much longer than when target color changed unpredictably, and these high RTs were mostly because of trials where target identity switched, even though it was entirely predictable. Perceptual priming, therefore, almost completely determined performance, while expectancy had little or no effect.

This finding contradicts a large body of research showing the influence of top-down processes on feature-based attention. There are many examples of how observers are sensitive to statistical regularities in the environment (Chetverikov, Campana, & Kristjánsson, 2016, 2017a; Fiser & Aslin, 2001; Geng & Behrmann, 2005; Kristjánsson, Mackeben, & Nakayama, 2001; Sigurdardottir et al., 2017). Other findings also indicate that priming is probably not entirely perceptual as it can, for example, be influenced by financial reward (Kristjánsson, Sigurjónsdóttir, & Driver, 2010), or by intertrial precuing of the singleton target (Fecteau, 2007; Wolfe, Horowitz, Kenner, Hyle, & Vasan, 2004). Wolfe et al. (2004) showed that even word cues produced a faciliatory effect that mimicked repetition priming (but to a lesser extent than picture cues). Furthermore, Cochrane, Nwabuike, Thomson, and Milliken (2018) recently reported that imagining a target color opposite to the preceding target color can reverse priming of pop-out effects (although this only occurred if observers had enough time to generate the template, otherwise priming determined the pattern).

Taking into account that different top-down factors can modulate repetition effects it seems unlikely that observers' expectancies do not affect the results obtained with repeated patterns and switches in visual search. We attempted to understand the contribution of these two potential influences on search performance as targets are repeated or switch identity with distractors.

Here, we should note a critical detail in the Maljkovic and Nakayama analyses: they analyzed average responses times for the whole block of trials. However, during the same block of trials in all conditions (except when the target always has the same identity) there are trials where target and distractors stay the same while on others they switch so that the target from the previous trial becomes the distractor or vice versa. These two types of trials create *repetition benefits* (decreased RTs, increased accuracy with increased number of repetitions of the target's and distractors' features) and *switch costs* (increased RT, decreased accuracy after the increased number of interchanges between target's and distractor's features). There is ample evidence that these two effects can be dissociated with experimental manipulations (Chetverikov et al., 2016; Chetverikov, Campana, & Kristjánsson, 2017b; Kristjánsson & Driver, 2008; Lamy, Yashar, & Ruderman, 2013). More important, because of random selection of target and distractors on trials with unpredictable changes, it is impossible to completely disentangle effects of predictability and bottom-up effects without analyzing these two effect types separately. For example, with a 50% probability of change there are streaks of trials with the same target color repeated once ($p = .5$), twice ($p = .25$), thrice ($p = .125$), and so on. Longer streaks will create larger repetition benefits but also larger switch costs making interpretation of the average search times problematic. Note that while the RTs on each trial are a combination of both switch costs and repetition benefits, the effects themselves can be dissociated even in the traditional PoP study design used by Maljkovic and Nakayama. The former depend by definition on the number of repetitions of the same color while the latter depend on the number of preceding repetitions of a different color.

Moreover, observers' expectations are likely to be nonlinear when sequences are random (e.g., Jarvik, 1951). With streaks shorter than average they might expect a target of the same color, while with more repetitions they might start expecting a switch (the "gambler's fallacy"), even though the trials are independent. Analyses of average RTs in blocks with different change probabilities conflate the effects of different streak lengths and different expectations, undermining conclusions about how automatic or "bottom-up" the repetition effects are and how they might be affected by expectations.

Using Saccade Characteristics to Assess Salience

Priming effects are usually measured with response times, but importantly saccade characteristics can also be used to assess attentional orienting and, therefore, also priming. For example, saccade deviations can be used to measure the salience of nontargets. Saccade trajectories tend to deviate from targets if there is competition for attention from different items in the visual field, and the location of the saccade endpoint is thought to reflect the outcome of this competition between potential targets (Godijn & Theeuwes, 2002; Mulckhuyse, Van der Stigchel, & Theeuwes, 2009; Sheliga, Riggio, Craighero, & Rizzolatti, 1995); see Van der

Stigchel, 2010, for review). Models of saccade deviation assume that population coding determines saccade vectors such that eye movements are initiated in the average direction of the possible saccade vectors (McPeek, Han, & Keller, 2003; McSorley, Haggard, & Walker, 2004). This vector sum is influenced by the salience (or priority) of the items in the visual field in priority maps (Zelinsky & Bisley, 2015). Saccade deviations may, therefore, be an index of their salience. If intertrial repetition affects the salience of the items, the influence of a distractor on the saccade vector should vary according to the strength of priming. This was demonstrated by McPeek, Skavenski, and Nakayama (2000), who found that when the target had been a distractor on a previous trial during a single-feature search task (a "switch") the saccades deviated in the direction of a distractor, and were corrected "in–flight," toward the actual target. This suggests that two saccades can be programmed simultaneously (McPeek et al., 2000), and that the result of such competition will affect the saccade vector, and in-flight compensations can be applied. McPeek, Maljkovic, and Nakayama (1999) then showed that saccades are made more quickly and are more accurate when the target was the same as on previous trials than when it switched, and importantly that this benefit accumulated across trials, so that the more often the same target was repeated, the faster and more accurate the saccades—just as with the response time effect.

Such findings are important because eye movements may then yield a more precise measure of priming effects than the more typically studied response time effects. Response times are ambiguous, because in the current context, they cannot, on their own, separate whether intertrial speeding of repeated search is determined by increased salience or by other nonperceptual processes, such as response facilitation (Palmer, Huk, & Shadlen, 2005) or episodic memory (Hillstrom, 2000; Huang, Holcombe, & Pashler, 2004; Thomson & Milliken, 2011).

Current Experiment

We revisit the classic finding of Maljkovic and Nakayama and test whether collapsing responses from different types of trials, may mask the crucial distinction between two types of effects during priming of pop-out, namely, repetition benefits and switch costs. We modified Experiment 2 in Maljkovic and Nakayama (1994) that served as the main ground for the claim that expectations do not play a role in attentional priming, to dissociate these two types of effects. We expected to obtain the same results as Maljkovic and Nakayama when we did the same analyses as they did. However, we show that expectations both increase the repetition benefits and decrease the switch costs, contributing to attentional priming even though bottom-up effects are controlled for. Furthermore, we use eye movement data to assess whether expectations affect attentional selection rather than response selection or other postperceptual processes.

Both long and short sequences of trials with the same target color were either predictable or not. This manipulation allowed us to analyze effects of expectation independently of the effects of feature repetition. We contrasted four different scenarios, where in three conditions the switches and repetitions were 100% predictable, but critically occurring at different rates: where the target color (red or green) always switched from one trial to the next (R1G1), where there were always two adjacent trials with the same

target color followed by two trials with the other target color (R2G2), or where there were five trials of each color before a switch to the other (R5G5). We contrasted this with a "Random" condition where the switch randomly occurred after 1, 2, 5, or 7 trials, in addition to two baseline conditions (see Method).

We used two measures of priming, the traditional response time measure, but also characteristics of saccadic eye movements to the targets, to assess the salience of the items as a function of repetition of target properties. We mainly focused on saccade deviations, as we assumed, in light of previous literature, that the salience of a distractor can be assessed by the saccade deviation it causes, but we also measured saccadic latencies and landing point accuracy.

Method

Participants

Thirteen healthy adults took part in the experiment (10 women; mean age 24 years, $SD = 8$, range 18–46). The experiment was approved by the ethics committee (Ethikkomission) of the Institut für Psychologie at the Humboldt-Universität zu Berlin. All participants were recruited at the Institute of Psychology at the Humboldt Universität zu Berlin. As compensation for participation they received points counting toward the completion of their psychology program. Information about the details of the experiment was provided to the participants at the beginning of the procedure and all of them gave informed consent. For the eye-tracking data analysis, three of the participants were excluded because of technical problems.

Stimuli

The stimuli for the visual search task were red and green diamonds. One corner of the diamonds (at left or right) was cut off. The length of each side of a diamond was 0.707° (1° diagonal). The size of the cut-off was 0.14°. The diamonds were located equidistant from the center of the screen (the distance from the center of the screen to the center of a diamond was 10° to force participants to execute the eye movements).

Each trial started with a fixation cross at screen center for 1,000 ms followed by the three diamonds. The target diamond was always of an odd color (red or green) and two diamonds of the other color were distractors (e.g., one green diamond was a target while two red ones were distractors). The task was to decide which side of the target diamond was cut off (left or right) and to press the corresponding key as soon as possible (left arrow key for the left side and right arrow for the right side). During the trial, participants could move their eyes freely and were only instructed to fixate on a central cross before the stimuli appeared.

The four repetition conditions were:

1. *R1G1 condition*: Constant alternation (e.g., red-green-red-green . . .; average transition probability—ATP, the probability of color change—was 1.0); 80 trials.

2. *R2G2 condition*: Two red targets followed by two green targets (red-red-green-green . . .; ATP = 0.5) 160 trials. This condition replicates Experiment 4 in Maljkovic and Nakayama (1994).

3. *R5G5 condition*: Five red targets followed by five green targets (5 times red – 5 times green . . .; ATP = 0.2); 400 trials.

4. *Random condition*: Sequences of 1, 2, 5, or 7 trials of the same color mixed randomly (ATP = 0.27); 300 trials.

The number of trials was chosen so that there were 40 switches from red to green and vice versa in each condition. Additionally, there were two control conditions:

5. *R40G40 condition*: Target color was the same for 40 trials in a row (40 red targets followed by 40 green targets or vice versa); 80 trials.

6. *No distractor condition*: We measured saccade latency, accuracy, and curvature when a target was presented alone without any distractors, to obtain baseline values of eye movement parameters; 80 trials.

Trials from control conditions are not included in further analyses, as we used them for a sanity check in RT comparisons and analysis of eye movements. The first block was always R40G40. The order of the other blocks was randomized.

Before starting each block, participants read the task instructions along with the description of the current condition. Therefore, participants were aware, at the beginning of each block, of the pattern of between-trial color changes. This was done to provide the same task knowledge in each condition (the patterns of trials in Conditions 1 to 3 are obvious). In Conditions 1 to 3 and 5, the conditional probability of change on a given trial given all previous trials was always either 0 or 1 and observers could potentially utilize this pattern during their search.

Participants took a self-paced break after every 80 trials and between the blocks with different conditions. At the beginning of each block a 9-point calibration of the eye-tracker was performed followed by a validation, and if the validation failed, the calibration was repeated. All in all, the experiment took about an hour.

Apparatus

The task was programmed with MATLAB R2014b and Psychtoolbox-3. The stimuli were presented on a Samsung Sync Master 2233 monitor, diagonal size 21.5 in., 1920 × 1080 pix resolution, with a refresh rate of 60 Hz. The experiment was run in a dark room with dim diffuse lighting. Viewing distance was 70 cm and the participants head was stabilized with a chin rest. We recorded the eye movements from the left eye only, with an SMI iView X Hi-Speed system at a 1250 Hz sampling rate.

Data Analysis

Preprocessing of RT data. Of the 14,300 trials performed by the 13 participants, we excluded trials with incorrect responses (958 trials), trials with response times that were too fast (less than 200 ms), or too long (longer than 2500 ms)—42 trials. We also eliminated the first trials after each break—163 trials. In total, 13,137 trials remained for analyses. We analyzed log-transformed RTs but to aid understanding, the plots and tables show untransformed values.

Preprocessing of eye movement data. To extract the first saccade on each trial we used the "velocity peak method." "The first velocity peak was identified as the first set of contiguous samples with a velocity greater than 100°/s The start and end points of the saccade were identified by searching from this peak backward and forward in time, respectively, until a sample with velocity below 35°/s and acceleration below 0°/s² (Tudge & Schubert, 2016). For eye movement measurements we used saccade latencies and overall direction (the angle between a straight line from saccade start to saccade landing position and saccade start and the target).

In total, we analyzed 7,503 trials out of 11,000 trials. After excluding trials with incorrect responses (383 trials), trials with manual response times longer than 2,500 ms (38 trials) and shorter than 200 ms (0 trials), we excluded first trials after the breaks (129 trials). Then we excluded missing values for latencies (185), missing values for saccade deviation (50), and trials in which the distance from fixation cross to saccade starting point was higher than 2° (2,592). This yielded a total of 7,740 trials. After excluding trials with too short (less than 80 ms) latencies (78) and trials with latencies longer than 400 ms (42), 7,503 trials remained. As distractors were located equidistant in both directions away from the target, we measured the absolute value of overall saccade direction independently of whether it was clockwise or counterclockwise from target position. To analyze all varieties of saccade trajectories we did not exclude "wrong" saccades with overall direction away from target position or landing position far away from the target. This allowed us to examine a wide spectrum of saccade directions.

However, to analyze saccade latencies in the same way as we analyzed RTs we decided to include only "correct" saccades, in other words saccades toward the target (overall direction <60 degrees), providing us with 5,197 trials.

Results

Behavioral Effects

Average performance. Overall accuracy was high and did not differ between conditions (see Table 1). The overall average RT pattern is consistent with the original results of Maljkovic and Nakayama (1994; see Figure 1 for replotted data from Participant KN in Experiment 2 in the Maljkovic & Nakayama study and Figure 2A for averaged data in our study). On average, RTs increase with the average transition probability (ATP) from 0.2 (in the R5G5 condition) to 1 (in the R1G1 condition). To account for individual differences, we used a mixed-effects regression with random intercepts for each participant[1] using the *lme4* library in R (Bates, Maechler, Bolker, & Walker, 2014). A model with successive difference contrasts (comparing the differences between the conditions ordered in one-way layout, ATP = 0.2 vs. 0.27, ATP = 0.27 vs. ATP = 0.5, ATP = 0.5 vs. ATP = 1.0) demonstrated that RTs in the condition with ATP = 0.2 (R5G5) were significantly lower than with ATP = 0.27 (Random, $B = 0.03$ (0.005),[2] $t = 6.83$, $p < .001$). RTs in the R1G1 condition (ATP = 1) were also higher than in the R2G2 condition (ATP = 0.5, $B = 0.021$ (0.008), $t = 2.58$, $p = .010$). However, an almost twofold increase of ATP from 0.27 (Random) to 0.5 (R2G2) did not affect RTs ($B = -0.006$ (0.006), $t = -1.02$, $p = .308$).

Repetition benefits. The results clearly demonstrate the priming of pop-out effect. Figure 2B shows repetition benefits: RTs decreased when target color was repeated. Within longer streaks, RTs decreased from the first trial to the third one. A linear mixed-effects regression with Helmert contrasts (comparing each level of the trial number with the average of the following levels) on RTs supported these observations indicating that the first and second trials of each streak in the R5G5 and the first to third trials in the Random condition were slower than later trials. Figure 2B also shows an increase in RT on the 5th repetition for the R5G5 condition, which suggests that observers anticipated the switch (all $p < .01$, see details in online supplemental material Table 1).

To investigate the role of expectations we then analyzed the effects of condition for each repetition in the streak separately, using a linear mixed-effects model with condition as a fixed effect and participant as a random effect. We reasoned that if expectations play no role in determining repetition benefits, RT should be the same in the different conditions on trials after the first one as they had the same number of target color repetitions.

Our results, however, clearly show that this was not the case. Responses were faster in the R2G2 and R5G5 conditions than in the Random condition even though the number of repetitions was the same. For the second trial in a streak the largest response times were seen for the Random condition compared with the R5G5 ($B = -0.035$ (0.01), $t = -3.54$, $p < .001$) and R2G2 ($B = -0.052$ (0.01), $t = -5.17$, $p < .001$) conditions, respectively. For the third trial in a streak, RTs for the R5G5 condition were lower than for the Random condition ($B = -0.043$ (0.01) $t = -4.14$, $p < .001$). For the fourth trial in a streak, RTs in the R5G5 condition were also lower than in the Random one ($B = -0.042$ (0.01), $t = -4.09$, $p < .001$).

Switch costs. We next analyzed the first trials within a streak, which reveal the switch costs. In agreement with the previous literature, we found that the number of repetitions before the switch affected RTs: the longer the sequence of the same target

Table 1
Average Accuracy and RT by Condition

Conditions	Accuracy (%)			RT (ms)		
	M	95% CI		M	95% CI	
R40G40	.94	.92	.95	747	740	754
No distractors	.94	.93	.96	612	606	617
Random	.93	.92	.94	794	790	798
R1G1	.93	.91	.94	808	801	815
R2G2	.93	.92	.94	793	788	798
R5G5	.93	.93	.94	773	770	776

Note. CI = confidence interval.

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[1] Note that for this analysis, additional inclusion of random slopes for each participant makes the differences between conditions not significant (R5G5 vs. Random: $B = 0.03$ (0.02), $t = 1.67$, $p = 0.120$; Random vs. R2G2: $B = -0.005$ (0.02), $t = -0.32$, $p = 0.755$, R2G2 vs. R1G1: $B = 0.02$ (0.02), $t = 1.32$, $p = 0.213$). The conclusions from the mixed-effects regression models reported later in the text are the same irrespective of whether the random slopes are included in the models.

[2] Here and later when reporting mixed-effects regression results we provide *SE* of the regression coefficients *B* in parentheses.
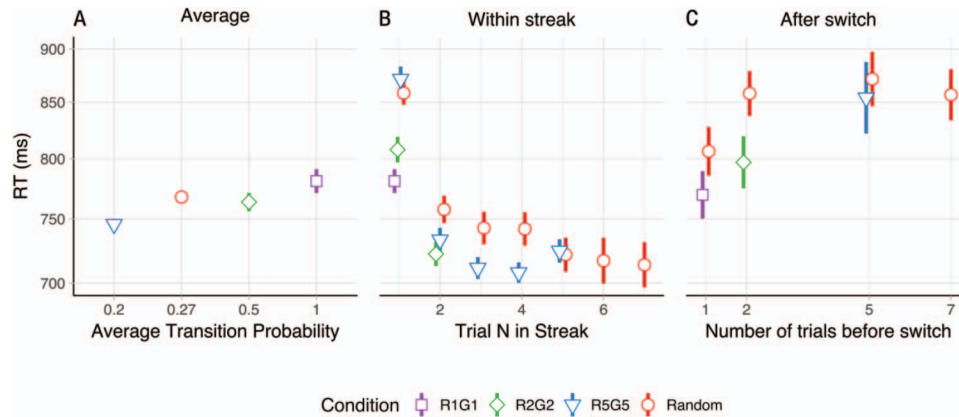
Figure 2. Response times. RTs increase on average as a function of the average transition probability (panel A). However, both within the streak (panel B) and after the switch (panel C) RTs for predictable conditions (R1G1, R2G2, and R5G5) are lower than for the Random condition showing the beneficial effect of expectations on performance. Bars represent 95% confidence interval. See the online article for the color version of this figure.

color before the switch the longer the response times in the first trial of a new streak (Figure 2C; see online supplemental material Table 2 for comparisons between different trial numbers within the Random condition).

If observers' expectations have no effect, the switch costs should be similar between conditions where the number of trials with the same target color, preceding the switch is the same. This was not the case, however. For Conditions R1G1 and R2G2, the predictability of target color led to faster response times after the switch, compared with the Random condition ($B = -0.049$ (0.02), $t = -3.45$, $p < .001$ and $B = -0.074$ (0.02), $t = -4.82$, $p < .001$ for R1G1 and R2G2 against Random, respectively).

However, for longer sequences (R5G5) we did not find any benefits or costs of predictability ($B = -0.021$ (0.02), $t = -1.43$, $p = .153$).

Eye Movement Results

In general, there was large variability in saccade trajectories. Participants were only instructed to perform the task as quickly and accurately as possible and to fixate on the central cross at the beginning of the trial. There was no feedback on how accurate the saccades were. Participants nevertheless made saccades on the vast majority of trials (70% of trials that measured eye movements contained information on first saccades suitable for analyses).

Average latencies. On average, the results pattern for saccade latencies was similar to the RT data, where latencies increased with increased average transition probability (Figure 3A). We performed the same kind of analysis as for RT data. Mean latency in the Random condition (ATP = 0.27) was significantly higher than in the R5G5 condition (ATP = 0.2 $B = 10.25$ (1.42), $t = 7.20$, $p < .001$). As was seen for the RT data, there was no significant difference in latencies in the R2G2 (ATP = 0.5) and Random conditions (ATP = 0.27, $B = 1.34$ (1.86), $t = 0.72$, $p = .471$). Average latency was higher in the R1G1 (ATP = 1) than the R2G2 condition ($B = 9.97$ (2.75), $t = 3.63$, $p < .001$).

Repetition benefits. Within streaks (Figure 3B) we found facilitation from the first to the second trial in the R2G2, R5G5,

and Random conditions. After the second trial latencies were constant for further repetitions (for detailed analysis see online supplemental material Table 3). Crucially, latencies on predictable trials were shorter than on unpredictable ones for the 1st, 2nd, 3rd or 4th trial in a streak. As for within-streak analysis of RT, we used a linear mixed-effects model with condition as a fixed effect and participant as a random effect for each trial in a streak. On the second trial in the streak, latencies for the R5G5 and R2G2 conditions were shorter than for the Random condition ($B = -13.57$ (2.97), $t = -4.58$, $p < .001$; $B = -10.17$ (2.93), $t = -3.47$, $p < .001$, respectively). Saccades in the R5G5 condition also had shorter latencies than in the Random condition on the 3rd ($B = -9.601$ (2.97), $t = -3.23$, $p = .001$), 4th ($B = -7.07$ (3.08), $t = -2.29$, $p = .022$), and 5th ($B = -9.36$ (2.77), $t = -3.38$, $p < .001$) trials.

Switch costs. As we did for RTs, to analyze switch costs, we divided trials with different streak lengths before the switch into separate groups (Figure 3C). The only significant difference was found between latencies after a streak of five trials, where for R5G5 they were faster than for the Random condition ($B = -21.539$ (9.66), $t = -3.45$, $p = .027$). In other comparisons, saccade latencies were numerically lower for the predictable than the unpredictable condition, but these differences were not significant because of high noise in the data from the Random condition (potentially, resulting from the fact that many of the saccades in the Random conditions were excluded because they were not directed to the target).

Eye Movement Trajectories

We analyzed distances between saccadic landing position and target location coupled with absolute values of overall direction of saccade as a measurement of eye movement accuracy. We calculated overall direction as the angle between the straight line from saccade start to saccade endpoint and a straight line from saccade start to the target location (Tudge, McSorley, Brandt, & Schubert, 2017). We found that distances and overall direction were tightly coupled and we will, therefore, describe data for overall direction. Plots with measurements of distance from target to saccade land-
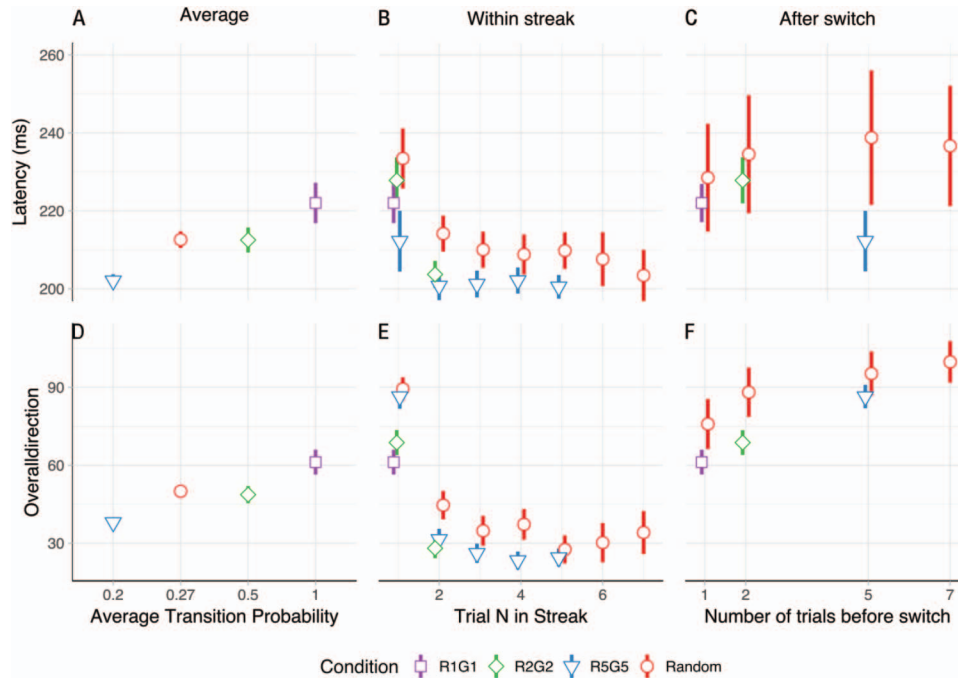
Figure 3. Eye movement data. Panels A, B, and C: Saccade latencies for trials with overall direction toward the target. D, E, and F: Saccade overall direction measured for all trials with analyzable eye movement data. Bars show 95% confidence intervals. See the online article for the color version of this figure.

ing position are presented in the supplementary materials (Figures 1 and 2).

Average saccade direction. Generally, overall direction demonstrated that increased average switch probability was accompanied by higher probability of inaccurate eye movements. Density plots of overall saccade direction demonstrate the difference in the proportions of saccades toward the target and toward the distractors in the different conditions (see Figure 4). As the stimuli were equidistant on the invisible circle, the angle between central fixation, target and distractor was always 120°. In general, the density plots, therefore, demonstrate that most of the saccades that participants made were either toward the target or toward a distractor.

Figure 4 shows that while in the R1G1 condition the probability of saccade direction toward the target is almost the same as toward one of the distractors, the R5G5 condition has the highest probability of correct saccades. At the same time, the probability of correct saccades in the Random condition was lower than in the R5G5 condition. Figure 3D shows the average overall direction for different transition probabilities. In general, the increase of ATP was accompanied by the larger average overall direction. We compared the differences in overall direction in different conditions depending on ATP in the same way as for the analyses of latencies and RT. R5G5 versus Random ($B = 12.52$ (1.60), $t = 7.84$, $p < .001$; R2G2 vs. Random $B = -1.60$ (2.03), $t = -0.79$, $p = .430$; R1G1 versus R2G2 $B = 13.00$ (2.83), $t = 4.6$, $p < .001$).

Repetition benefits. Figure 3E shows overall direction within a streak. As with the other measures, we found a strong effect for the first and second trials in a streak (both have a larger overall

direction than averaged subsequent trials) for the Random and R5G5 conditions (online supplemental material Table 5). To demonstrate the difference in overall direction in predictable and random conditions for separate trials within streaks we separately analyzed the 2nd, 3rd, and 4th trials in a streak. For all these trials the Random condition was on average characterized by less accurate first saccades. For the second trial in a streak the overall direction was closer to the target in both the R5G5 and R2G2 trials relative to the Random condition ($B = -13.24$ (3.24) $t = -4.08$, $p < .001$ and $B = -16.81$ (3.23) $t = -5.21$, $p < .001$ for the R5G5 and R2G2 conditions, respectively). On the third and fourth trials in a streak, participants were also more accurate in the R5G5 than in the Random condition ($B = -8.38$ (3.33) $t = -2.51$, $p = .012$ and $B = -14.33$ (3.25) $t = -4.41$, $p < .001$, for the 3rd and the 4th trials in a streak, respectively).

Switch costs. Overall direction on trials after a color switch is shown in Figure 3F. For the first trial after a target color switch we performed the same kind of analysis of overall saccade direction as for the RT and latency results. In general, the more trials of the same color preceded the switch the more the saccade direction deviated from target direction in the first trial with the new target color (see online supplemental material Table 6 for contrasts within the Random condition).

To assess whether expectations play a role in overall saccade direction we compared the first trials in a streak for Random and predictable trials. On the first trials after the switch for the R1G1 and R2G2 conditions, the first saccades were more accurate than in the Random condition with the same streak length before the switch. ($B = -14.77$ (5.33) $t = -2.77$, $p = .006$ for R1G1 relative
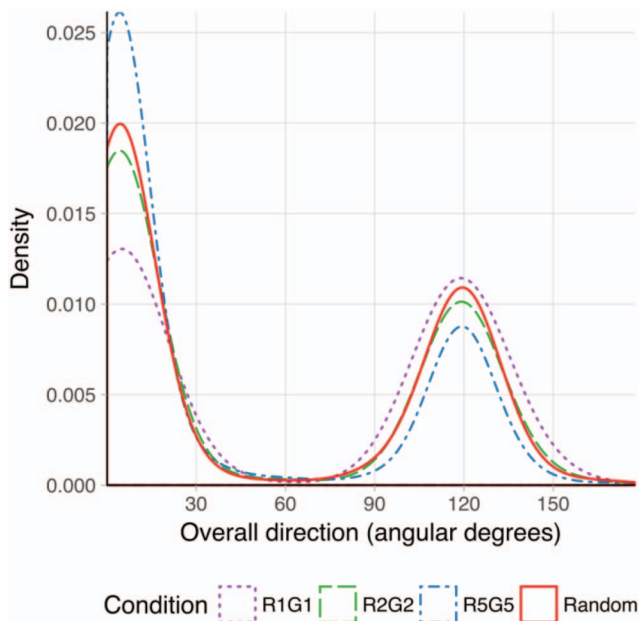
Figure 4. Probability density for the overall directions of the first saccades on each trial. The peak at 120 degrees reflects saccades toward one of the distractors. See the online article for the color version of this figure.

to Random; $B = -19.62$ (5.46) $t = -3.60$, $p < .001$ for R2G2 relative Random). Longer streaks before the switch also demonstrated the effect of predictability on saccade accuracy: saccades on the first trial after the switch in the R5G5 condition were more accurate than in the Random condition ($B = -9.79$ (4.96) $t = -1.98$, $p = .048$).

In many ways the saccade deviation results mimic the response time patterns. They suggest, as with response times, that both expectations because of predictability and perceptual priming influence intertrial facilitation after repetition or inhibition after a switch.

General Discussion

Maljkovic and Nakayama (1994) found strong evidence for the automaticity of attentional priming using odd-one-out visual search. When looking for a red target among green distractors, focal attention was applied more quickly and accurately to a repeated target color than if the target color changed. Most surprisingly, even when the color changes of the target were completely predictable (alternating periodically between red and green) observers demonstrated very poor search performance when these changes occurred. Nakayama, Maljkovic, and Kristjánsson (2004) proposed that such intertrial speeding because of repeating targets, or slowing when targets change, reflects the operation of a primitive memory system for attention deployments.

However, here we argue that the original analyses of Maljkovic and Nakayama confounded different types of trials (repeated colors and switching colors) and different streak lengths. We measured the effects of these variables by comparing predictable and unpredictable switches and repetitions with an equal number of repetitions on preceding trials. Our results reveal that the influence

of expectancy because of predictability is considerable. What this means is that when the sequences of target types on adjacent trials were completely predictable, observers were able to utilize this information to improve their performance, which shows that the priming effect is not entirely bottom-up and impenetrable to top-down influences as some have claimed (e.g., Theeuwes, 2013). However, it is also notable that the effect of bottom-up processing is nevertheless quite strong, because expectancies are far from accounting for the whole pattern of results. For example, in line with the mechanisms proposed by Maljkovic and Nakayama (1994), RTs after a switch to a new color were longer following longer repetition streaks even when the switch was fully predictable. Both implicit and explicit sources, therefore, have an influence on observed history effects in visual search tasks.

In the beginning of the article we mentioned that there are many demonstrations that observers can learn detailed statistical patterns in visual displays (Chetverikov et al., 2016, 2017a; Fiser & Aslin, 2001; Geng & Behrmann, 2005; Kristjánsson, 2009; Kristjánsson et al., 2001; Sigurdardottir et al., 2017). Perhaps the finding that statistical properties can influence history effects, as we show here, is not surprising in light of these demonstrated statistical learning effects.

A fascinating analogy with our results can be found in the patterns of RT in task switching studies. For instance, Monsell, Sumner, and Waters (2003) used predictable and unpredictable switches between two types of the tasks (participants had to classify the digit as either odd/even or high/low). Task type was cued either by background shape or by background color. Participants were faster and more accurate in subsequent trials of the same task after the switch. Both repetition benefits and switch costs for accuracy and RT were affected by predictability of the task switch (the switch costs were higher in the unpredictable sequences and the effect of repetition was more prominent in predictable ones). However, it is not clear yet whether the parallels between the effect of expectations in priming of pop-out and task-switching literature are because of similarity in underlying mechanisms.

Sequence effects similar to the repetition benefits and switch costs in this study have been found for two-choice manual RT tasks (Bertelson, 1961; Kirby, 1972; Williams, 1966). Responses were faster when the signals were the same as in previous trials. Longer streaks of the same signals led to faster response times. This repetition effect was in the opposite direction with increased time between subject's response and the onset of the next stimulus. With longer RSIs (response stimuli interval) RT was faster after the alternation of the stimulus that was attributed to the Gambler's Fallacy (Gao, Wong-Lin, Holmes, Simen, & Cohen, 2009). Currently, we are not aware of any studies that compare sequence effects and choice RT tasks in visual search.

An important addition in the current project involves the analysis of eye movement data during the search. Priming effects are typically studied with response times. Fewer studies have analyzed the effects on visibility or saliency. Sigurdardottir, Kristjánsson, and Driver (2008) assessed priming in brief masked displays, finding that sensitivity for a relatively difficult search task improved with successive repetitions of the same type of search. Yashar and Lamy (2010) then reported similar findings. Using briefly presented stimuli followed by a mask, Ásgeirsson, Kristjánsson, and Bundesen (2014, 2015) concluded that perceptual mecha-

nisms are sufficient to produce priming in visual search. However, these questions have not often been addressed with eye movement measurements. Our results indicate that the salience of targets increases the more often the target and distractor identity remains the same, because saccades deviated in the direction of previous targets when they switched to becoming distractors.

The question of the contribution of expectancy and priming to visibility has previously been addressed by Pascucci, Mastropasqua, and Turatto (2012). They assessed whether expectations changed visibility by assessing the efficacy of a metacontrast mask (see also Kristjánsson, 2015). In agreement with our results, they found that both expectations and priming affect target visibility. Combined with the eye movement and RT analyses reported here, it is likely that all stages of the perceptual process that are affected by priming of pop-out are also affected by expectations, and the two may also interact.

Another highly interesting aspect of priming effects that is often overlooked is their time course. The priming effects as measured by RT, build up and add cumulatively over a number of trials (Brascamp et al., 2011; Kruijne, Brascamp, Kristjánsson, & Meeter, 2015; Maljkovic & Nakayama, 1994; Martini, 2010). Our results show how expectation affects the response time priming pattern in the long-term. An interesting find was that the same pattern is also seen in saccade latencies and deviations.

Our results also underscore the importance of separating switch costs and repetition benefits and controlling the number of previous repetitions in analyses of other factors within the context of priming of pop-out. Otherwise, average performance estimates might lead to erroneous conclusions.

Conclusions

Overall, our results show that although priming effects are hard to overcome volitionally, they are nevertheless strongly influenced by expectancy. We show not only that these expectancies have an influence on how quickly observers respond during the visual task, but also that the expectancies have an influence on overall saccade direction, which suggests that the expectancies have an actual effect on the salience of the items, not just on decision factors or more global episodic traces of previous trials.

From a broader perspective, our results demonstrate how higher-level influences, such as the expectations based on the knowledge of switch regularities in visual search trials, can add to lower-level automatic effects to optimize behavior. This behavior remains nonoptimal: after all, the average response times and overall saccade direction were still higher when target colors changed from green to red and red to green with full predictability on each trial. This might, however, reflect the rarity of both completely predictable patterns and constantly changing patterns in nature.

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