



# Selection history influences an attentional decision bias toward singleton targets

Bryan R. Burnham<sup>1</sup>

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## Abstract

Selection history effects are ubiquitous findings that show how implicitly encoding a target's feature or location on a trial can facilitate target activation on the following trial. Although the target-defining feature (e.g., color) is usually unpredictable, it is often relevant to determining the target on a given trial. The present study used a feature priming task, like the three-item oddball search task, but varied the target-defining feature (shape) orthogonal to the priming feature (color) that could influence target activation. On any trial the target could be a color singleton or not, and the target's feature could repeat or switch between trials. Larger priming effects were seen when the current target was a color singleton than a nonsingleton. Importantly, diffusion analyses showed that pretrial selection bias contributed to these larger priming effects. The results suggest selection history facilitates target activation through an attentional decision bias to select the object with the most recently attended color, and this attentional decision is easier when the current target is also distinct.

**Keywords** Feature priming · Selection history · Target activation · Diffusion model

Some primary functions of attention include selection of relevant information and suppression of irrelevant and potentially distracting information, which can occur in bottom-up and top-down manners. Additionally, an abundance of research indicates that *selection history* influences target and distractor activation/processing (e.g., Awh et al., 2012; Kristjánsson & Campana, 2010; Maljkovic & Nakayama 1994, 1996, 2000). The present study used diffusion modelling to examine how selection history via feature priming influences target activation.

One of the earliest studies to demonstrate selection history effects on visual search was Maljkovic and Nakayama's (1994) classic *priming of popout* (PoP) effect. PoP is the finding that responding to a feature singleton target is facilitated when its identifying feature (e.g., color) on Trial N – 1 is repeated on Trial N, even though the specific color (e.g., red, green) of the target is irrelevant on a given trial and unpredictable across trials. Importantly, it is repetition of the selected feature of the target that produces such priming, and

this can occur whether the target is a singleton or a nonsingleton.

Several mechanisms have been proposed for selection history effects. According to preattentive or salience-based accounts (Becker, 2008; Bichot & Schall, 2002; Maljkovic & Nakayama, 1994, 1996, 2000), implicitly encoding the target's feature on Trial N – 1 boosts the gain of that feature on Trial N; that is, selection history effects arise through an increase in signal strength of the primed feature. In contrast, biased decision accounts suggest selection history biases attention toward features associated with the most recent target (Amunts et al., 2014; Lleras et al., 2008; Tseng et al., 2014; Yashar & Lamy, 2010; Yashar et al., 2017). That is, feature salience is unaffected by priming, but the attentional decision for which item to select is biased by a preceding target's feature. Other accounts suggest selection history influences response selection and only after a target is selected (Hillstrom, 2000; Huang et al., 2004; Huang & Pashler, 2005; Thomson & Milliken, 2011, 2013). In this account, there is no influence on priming on feature salience or decision bias; rather, response retrieval is facilitated when the current target's feature matches a preceding target. Despite evidence for each account, many agree that selection history effects arise due to several mechanisms (e.g., Ásgeirsson & Kristjánsson, 2011; Ásgeirsson et al., 2015; Kristjánsson & Campana, 2010; Lamy, Yashar & Ruderman, 2010; Yashar et al., 2013).

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✉ Bryan R. Burnham  
bryan.burnham@scranton.edu

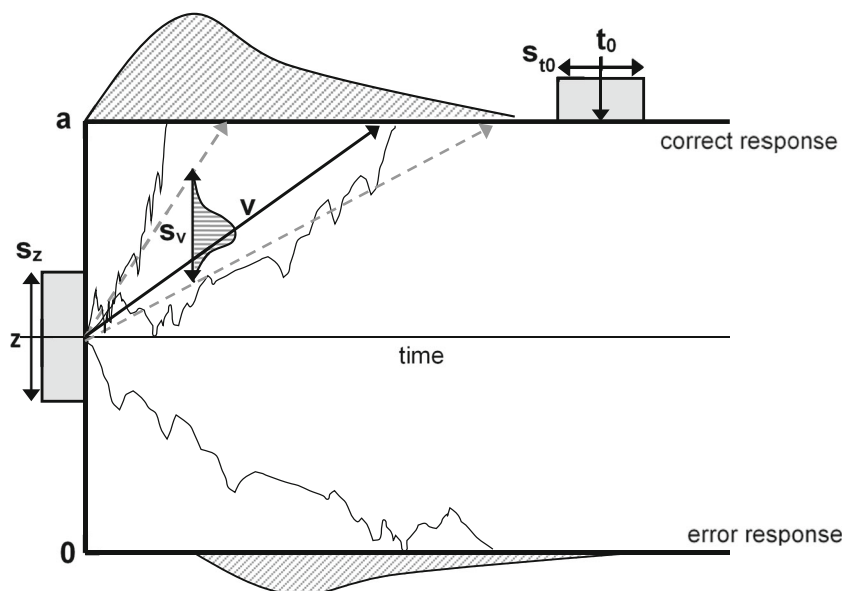
<sup>1</sup> Department of Psychology, University of Scranton, Scranton, PA 18510, USA

One means of examining the mechanisms behind selection history's influence on target activation is to apply *Ratcliff diffusion modelling* (RDM; Ratcliff, 1978, 1981, 2002; Ratcliff & McKoon, 2008; Ratcliff & Rouder, 1998; Ratcliff & Smith, 2010; Ratcliff et al., 1999) to data from PoP tasks. These models assume that evidence accumulates over time until a decision is made, and they can use RT distributions for correct and error responses to estimate parameters that relate to different, ongoing cognitive processes presumed to be involved with a decision. Importantly, these models have been adapted to make specific predictions about the cognitive processes operating during attentive decisions and priming tasks (e.g., Voss et al., 2013; Voss et al., 2004; Voss et al., 2015), which are the focus of the present study.

Figure 1 illustrates the typical RDM: On any trial, a decision process begins at point  $z$  ( $z_r$ ) and continues until the lower or upper decision boundary ( $a$ ) is reached and a response is made. The model is defined by several parameters, which are indicators of different cognitive processes: The *threshold parameter* ( $a$ ) is the distance between response (evidence) thresholds and corresponds to liberal-conservative response criteria or decision strategies. *Starting point* ( $z$ ) or *relative starting point* ( $z_r$ ; Voss et al., 2015) is the pretrial, a priori bias toward one of the response thresholds. In the present study,  $z_r$  was the bias toward selecting the correct target. *Drift rate* ( $v$ ) is the mean rate of evidence accumulation toward a response and reflects the speed of information accumulation during the decision process (Voss, et al., 2013). Lastly, a *nondecision constant* ( $t_0$ ) is the duration of nondecision processes including response retrieval or other response-related processes. Additionally, variability for each of the parameters can be estimated (i.e.,  $s_z$ ,  $s_v$ ,  $s_{t_0}$ ).

The present study used diffusion modelling to examine the influence of selection history on processes involved with feature priming. If priming engages a pretrial attentional decision bias (biased selection), this should be reflected in the  $z_r$  parameter; that is, a target's feature on Trial  $N - 1$  should bias selection of the same feature on Trial  $N$ . On the other hand, if priming leads to enhanced pre-activation of a previously selected target's features and speeds processing of that feature, this should be reflected by priming effects in the  $v$  parameter. Lastly, if priming activates a motor response system associated with the preceding target, this should be seen in the  $t_0$  parameter.

Several studies have used diffusion modeling to examine the processes involved with selection history. Tseng et al. (2014) examined the mechanisms underlying PoP by applying RDM to saccadic RTs in a popout search task. Subjects made a saccade toward a color singleton target and withheld saccades if no singleton was present, and they found that only the bias parameter ( $z$ ) predicted PoP on target processing. This bias parameter reflected a pretrial tendency to make saccades toward the item with the preceding target's color; that is, priming biased the attentional decision over which item to select. Additionally, Burnham (2018) applied RDM to a standard (manual response) PoP task that included a speed-accuracy manipulation. Results showed several parameters (i.e.,  $z$ ,  $v$ ,  $t_0$ ) predicted overall PoP effects, but importantly, only specific parameters predicted the speed-accuracy manipulation on PoP. Specifically, decision bias ( $z$ ) was associated with priming effects under accuracy instructions, whereas drift rate ( $v$ ) was associated with priming for speed instructions. Hence, RDM logic can be applied to examine how selection history manifests its influence on feature priming.



**Fig. 1** The Ratcliff diffusion model. Evidence accumulation begins from a starting point ( $z$ ) within interval ( $s_z$ ). Evidence accumulates in a noisy manner with a drift rate ( $v$ ) and intertrial variation ( $s_v$ ) until one of two

decision thresholds is reached, which are separated by boundaries ( $0$ ,  $a$ ). The response (correct or error) is based on whichever boundary is reached first. A nondecision time  $t_0$  with variation  $s_{t_0}$  is added to the RT

Although PoP and selection history effects are useful for examining target activation, one issue in previous studies is that although a specific color does not per se define the target on any trial (target color is random), color *is* relevant to identifying and selecting the target, and observers have incentive to attend to color. To examine implicit encoding and priming of target features without top-down incentive, the target-relevant feature can be made orthogonal to the feature that is used to assess selection history effects on target activation. In the present study, observers viewed displays containing three diamonds that included a color singleton and two homogenous nonsingletons, with the colors (red and green) chosen randomly (Fig. 2). On each trial, the target was defined as the diamond missing its left or right corner, whereas the two nontargets were diamonds missing the top or bottom corners. Hence, the target was always defined by its shape, but was unpredictably a color singleton or nonsingleton. This orthogonal relationship between target-relevant feature (shape) and priming feature (color) allows examination of selection history effects on target activation that are uncontaminated by the target-relevant feature being correlated with the priming feature. Indeed, this setup should eliminate top-down selection strategies based on color, and allows examination of priming when the target is a singleton or not on Trial  $N - 1$  and on Trial  $N$ .

## Methods

### Subjects

Previous research from my lab has observed PoP effects with effect sizes in excess of  $d = 1.50$ , and a power analysis indicated that six subjects were needed to detect priming effects of that size to achieve power = .80 ( $\alpha = .05$ ). A total of nine University of Scranton undergraduates participated (six females; all subjects right-handed). Subjects ranged from 18 to 19 years old ( $M = 18.56$  years,  $SD = 0.53$ ) and reported normal or corrected-to-normal vision. All subjects passed an Ishihra colorblindness test.

### Apparatus

The experiment was programmed and presented using E-Prime software (Version 3.0.3.82) on a Dell OptiPlex 3050 x64 computer. Subjects sat 60 cm from a Dell E178Fpv monitor (1,024 × 768; 60 Hz). A five-button response box was used for responding.

### Stimuli

A white cross (25.77 cd/m<sup>2</sup>, RGB: 255, 255, 255) appeared throughout each trial to maintain fixation. Search

displays (Fig. 2) contained three diamonds (1.1° × 1.1°) on a black background (0.16 cd/m<sup>2</sup>, RGB: 0, 0, 0). Each diamond was missing one corner (0.14°). The target was missing the left or right corner, and the two nontargets were missing the top or bottom corner. One diamond was a color singleton, and the other diamonds were homogeneously colored nonsingletons. The colors of the singleton and nonsingletons were chosen randomly on each trial to be red (20.44 cd/m<sup>2</sup>, RGB: 255, 0, 0) or green (20.62 cd/m<sup>2</sup>, RGB: 10, 177, 31). The target was unpredictably the singleton. Each diamond appeared at a different one of 12 randomly chosen locations on the circumference of an imaginary ellipse (10° wide × 8° high), with no constraints on where the diamonds appeared.

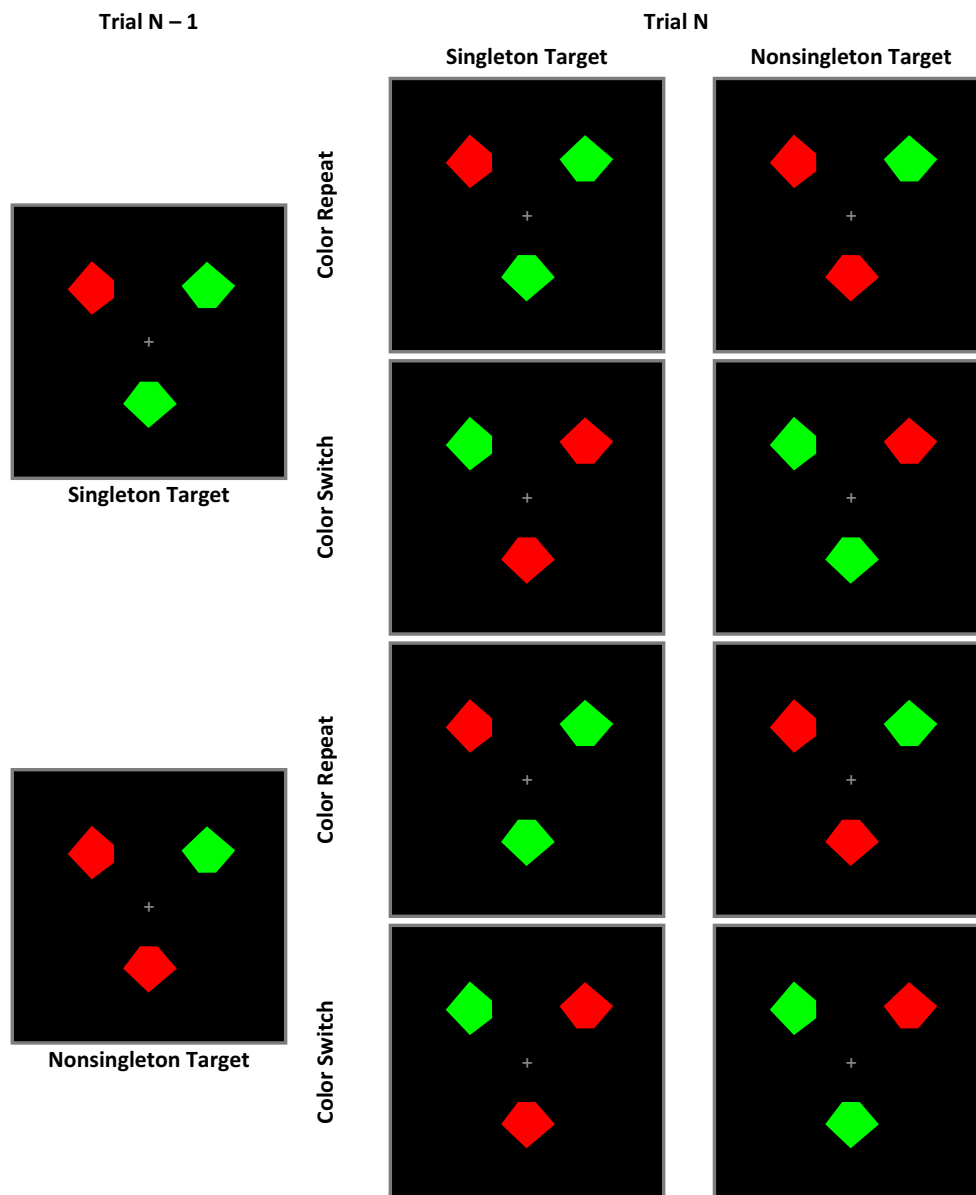
## Procedures

As data collection occurred during the Covid-19 pandemic, subjects wore mouth and nose-covering masks throughout the study. Subjects were informed they would see displays containing three diamonds, one of which (target) was missing the left or right corner and the other two (nontargets) were missing the top or bottom corners. Subjects were told their task was to indicate whether the target was missing its left or right corner as quickly and accurately as possible by pressing a corresponding key on the response box. Subjects were informed that one diamond would be colored differently from the other two (one red among two green diamonds or vice versa). Importantly, subjects were told (a) color would not help identify the target, as the colors were chosen randomly, and (b) the target would unpredictably appear as a color singleton or nonsingleton; hence, features of the target were completely unpredictable.

Each subject completed a practice block of 48 trials followed by 10 blocks of 120 trials each with a self-paced break after each block, for a total of 1,248 trials. Each trial began with a fixation display containing a grey '+' for 500 ms. Next the target display appeared for 2,000 ms or until the subject responded. The next trial began after a 100-ms delay. If a subject responded incorrectly or took longer than 2,000 ms, a 500-Hz tone played in the 100-ms delay.

## Design

The target was unpredictably a singleton or nonsingleton and was unpredictably colored green or red on each trial. Considering the target's color and singleton/nonsingleton status on both Trial  $N - 1$  and Trial  $N$ , eight conditions emerged (Fig. 2) in a 2 (Trial  $N - 1$  Target: Singleton vs. Nonsingleton) by 2 (Trial  $N$  Target: Singleton vs. Nonsingleton) by 2



**Fig. 2** Example of the eight between-trial transitions created by the factors Trial N – 1 Target (Singleton vs. Nonsingleton), Trial N Target (Singleton vs. Nonsingleton), and Transition (Repeat vs. Switch). The

target appears in the upper left in each panel, but the target and nontarget locations and orientations (left/right for the target and up/down for the nontargets) were randomized across trials. (Color figure online)

(Transition: Target Color Repeat vs. Target Color Switch) fully within-subjects design.

averaged over all nine subjects appear in Table 1 and results are plotted in Fig. 3A.

## Results

For RT analyses, only trials with a correct response on the current trial and preceding trial were used, which resulted in the removal of 5.4% of trials. For error analyses, only trials with a correct response on the preceding trial were used. Each subject's mean RT ( $M_{RT}$ ) and percent error was calculated for each of the eight conditions. The  $M_{RT}$  and percent errors

## RTs

A 2 (Trial N – 1 Target: Singleton vs. Nonsingleton) by 2 (Trial N Target: Singleton vs. Nonsingleton) by 2 (Transition: Repeat vs. Switch) repeated-measures analysis of variance (ANOVA) was conducted on the  $M_{RTs}$ . The main effect of Trial N Target was significant,  $F(1, 8) = 13.23$ ,  $MSE = 1,581$ ,  $p = .007$ ,  $\eta_p^2 = .62$ , due to responses being faster when the current target was the color singleton ( $M_{RT} = 838$

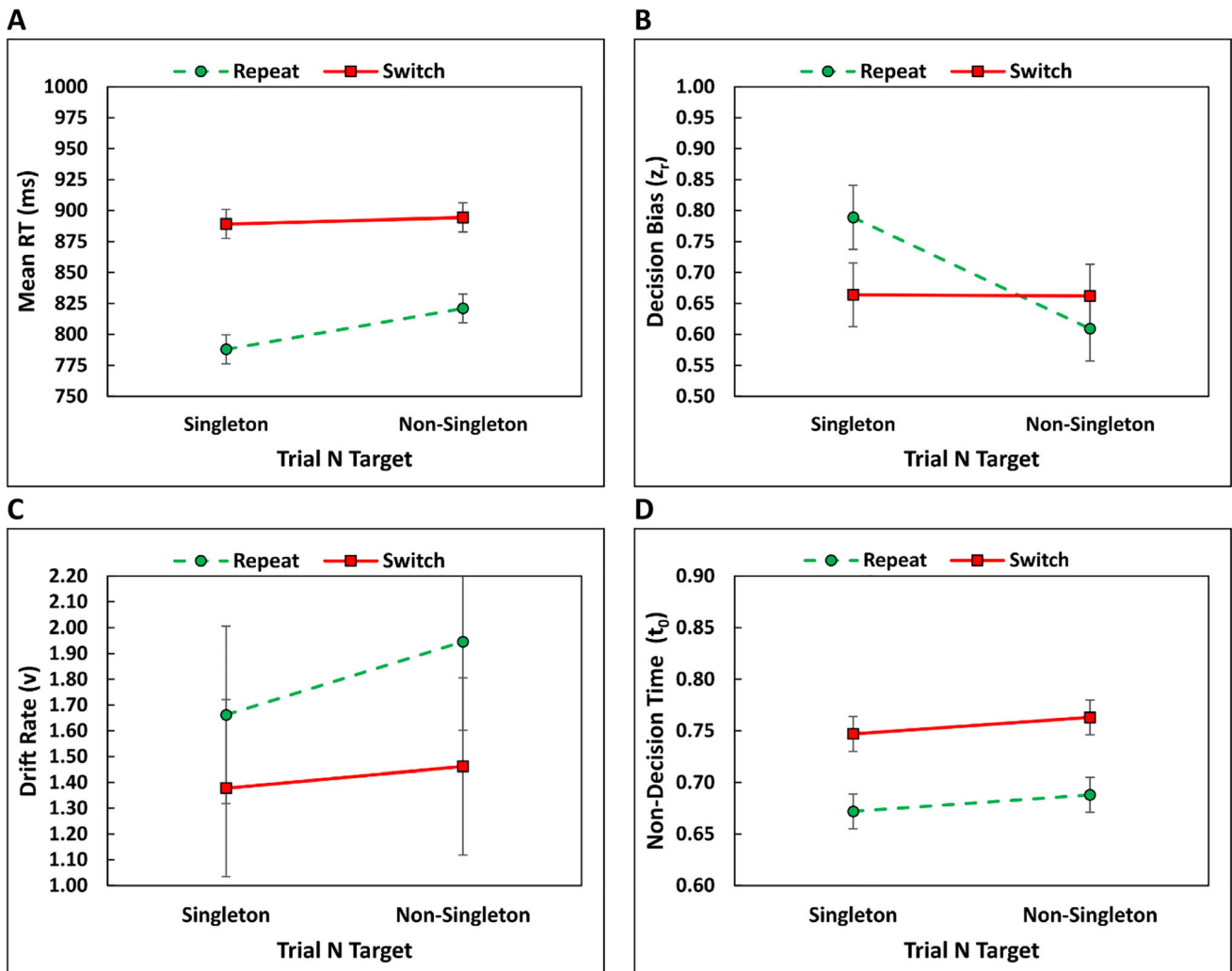
**Table 1** Mean response times (RTs), percent errors, and standard deviations in the Trial N – 1 Target by Trial N Target by Transition design

Trial N – 1 Target	Trial N Target	Transition	RTs		Percent Errors	
			M	SD	M	SD
Singleton	Singleton	Switch	887	174	2.3	1.2
		Repeat	779	144	2.6	1.9
	Nonsingleton	Switch	904	184	2.7	1.3
		Repeat	844	167	2.7	2.5
Nonsingleton	Singleton	Switch	892	171	3.5	2.9
		Repeat	796	135	2.6	2.5
	Nonsingleton	Switch	897	176	3.3	2.8
		Repeat	845	175	2.5	2.2

Mean RTs are rounded to the nearest millisecond and percentage errors to the nearest tenth.

ms; 95% CI [712, 965]) than a nonsingleton (873 ms; [746, 999]). The main effect of Transition was significant,  $F(1, 8) = 41.32$ ,  $MSE = 2700$ ,  $p < .0001$ ,  $\eta_p^2 = .84$ , due to responses

being faster when the target color repeated (816 ms; [690, 943]) than switched (895 ms; [768, 1022]): a *priming effect* of 79 ms [50, 107]. The only interaction was between Trial N



**Fig. 3** Mean response times (RTs), decision bias ( $z_r$ ), drift rate ( $v$ ), and nondecision times ( $t_0$ ) in the Trial N Target by Transition interaction. Error bars are the 95% confidence intervals. (Color figure online)

**Table 2** Means and standard deviations of the estimates for the diffusion model parameters in the Trial N – 1 Target by Trial N Target by Transition design

Trial N – 1 Target	Trial N Target	Transition	$z_r$		$\nu$		$t_0$	
			<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Singleton	Singleton	Switch	0.654	0.108	1.441	0.563	0.745	0.222
		Repeat	0.794	0.116	1.898	1.043	0.666	0.165
	Nonsingleton	Switch	0.657	0.114	1.466	0.735	0.768	0.230
		Repeat	0.581	0.066	2.005	0.427	0.681	0.184
Nonsingleton	Singleton	Switch	0.674	0.097	1.316	0.473	0.749	0.191
		Repeat	0.783	0.114	1.426	0.936	0.677	0.166
	Nonsingleton	Switch	0.667	0.137	1.458	0.670	0.758	0.207
		Repeat	0.637	0.083	1.886	0.545	0.696	0.190

For estimation,  $a = 1$ .

Target and Transition,  $F(1, 8) = 20.25$ ,  $MSE = 459$ ,  $p = .002$ ,  $\eta_p^2 = .72$ . No other effects were significant ( $F_s < 2.1$ ,  $ps > .18$ ). As seen in Fig. 3A, the interaction resulted from a larger priming effect when the Trial N target was the color singleton, 101 ms;  $t(8) = 6.9$ ,  $SE = 14.70$ ,  $p < .0001$ ;  $d = 2.3$ , than a nonsingleton, 56 ms;  $t(8) = 4.82$ ,  $SE = 11.61$ ,  $p = .001$ ;  $d = 1.6$ .

### Percent errors

A similar repeated-measures ANOVA on percent errors did not yield any effects ( $F_s < 1.02$ ,  $ps > .341$ ).

### Diffusion model analysis

Correct responses were assigned to the upper boundary and errors to the lower boundary of the model (Fig. 1). RT distributions for correct and error responses were entered into a diffusion-model analysis using *fast-dm* (Voss & Voss, 2007; Voss et al., 2015), with parameters estimated separately for each subject. Drift rate ( $\nu$ ), nondecision constant ( $t_0$ ), and starting point ( $z_r$ ) were estimated in each of the eight conditions, whereas intertrial variability parameters ( $s_v$ ,  $s_{zr}$ ,  $s_{t_0}$ ) were estimated over all conditions and the threshold parameter was constant ( $a = 1$ ). Kolmogorov–Smirnov optimization was used to estimate the parameters due to moderate number of trials per condition (~125 trials/condition). Table 2 provides parameter estimates averaged over the nine subjects. The intertrial variability estimates were:  $s_{zr}$  ( $M = 0.154$ ;  $SD = 0.116$ ),  $s_v$  ( $M = 0.222$ ;  $SD = 0.149$ ),  $s_{t_0}$  ( $M = 0.569$ ;  $SD = 0.245$ ).

A 2 (Trial N – 1 Target) by 2 (Trial N Target) by 2 (Transition) repeated-measures ANOVA was conducted on the  $z_r$  estimates. The main effect of Trial N Target was significant,  $F(1, 8) = 25.65$ ,  $MSE = .006$ ,  $p < .0001$ ,  $\eta_p^2 = .76$ , due to a larger bias estimate toward correct responding when the target was a singleton (.73; [.66, .76]) than a nonsingleton

(.64; [.57, .70]). The only other reliable effect was the interaction between Trial N Target and Transition,  $F(1, 8) = 15.90$ ,  $MSE = .009$ ,  $p = .004$ ,  $\eta_p^2 = .66$ , which is congruent with the interaction in the RT analysis. No other effects were significant ( $F_s < 3.0$ ,  $ps > .109$ ). As seen in Fig. 3B, a priming effect emerged when the Trial N Target was a singleton, priming = .13;  $t(8) = 5.36$ ,  $SE = .023$ ,  $p < .0001$ ,  $d = 1.79$ , which was nonsignificant and reversed when the target was a nonsingleton,  $-.05$ ;  $t(8) = -1.49$ ,  $SE = .035$ ,  $p = .174$ ,  $d = -.50$ .

A similar ANOVA was conducted on drift rate ( $\nu$ ) estimates. Only the effect of Transition was significant,  $F(1, 8) = 7.32$ ,  $MSE = .361$ ,  $p = .027$ ,  $\eta_p^2 = .48$ , due to greater drift toward correct responding when the target color repeated (1.80; [1.45, 2.16]) than switched (1.42; [1.07, 1.78]). No other effects approached statistical significance ( $F_s < 2.78$ ,  $ps > .134$ ).

Lastly, an ANOVA was conducted on the nondecision ( $t_0$ ) estimates. The only effect that arose was Transition,  $F(1, 8) = 23.85$ ,  $MSE = .004$ ,  $p = .001$ ,  $\eta_p^2 = .75$ , due to greater nondecision time when the target color switched (.76; [.61, .90]) than repeated (.68; [.53, .83]). (All other  $F_s < 2.77$ ,  $ps > .135$ .)

### Model fit

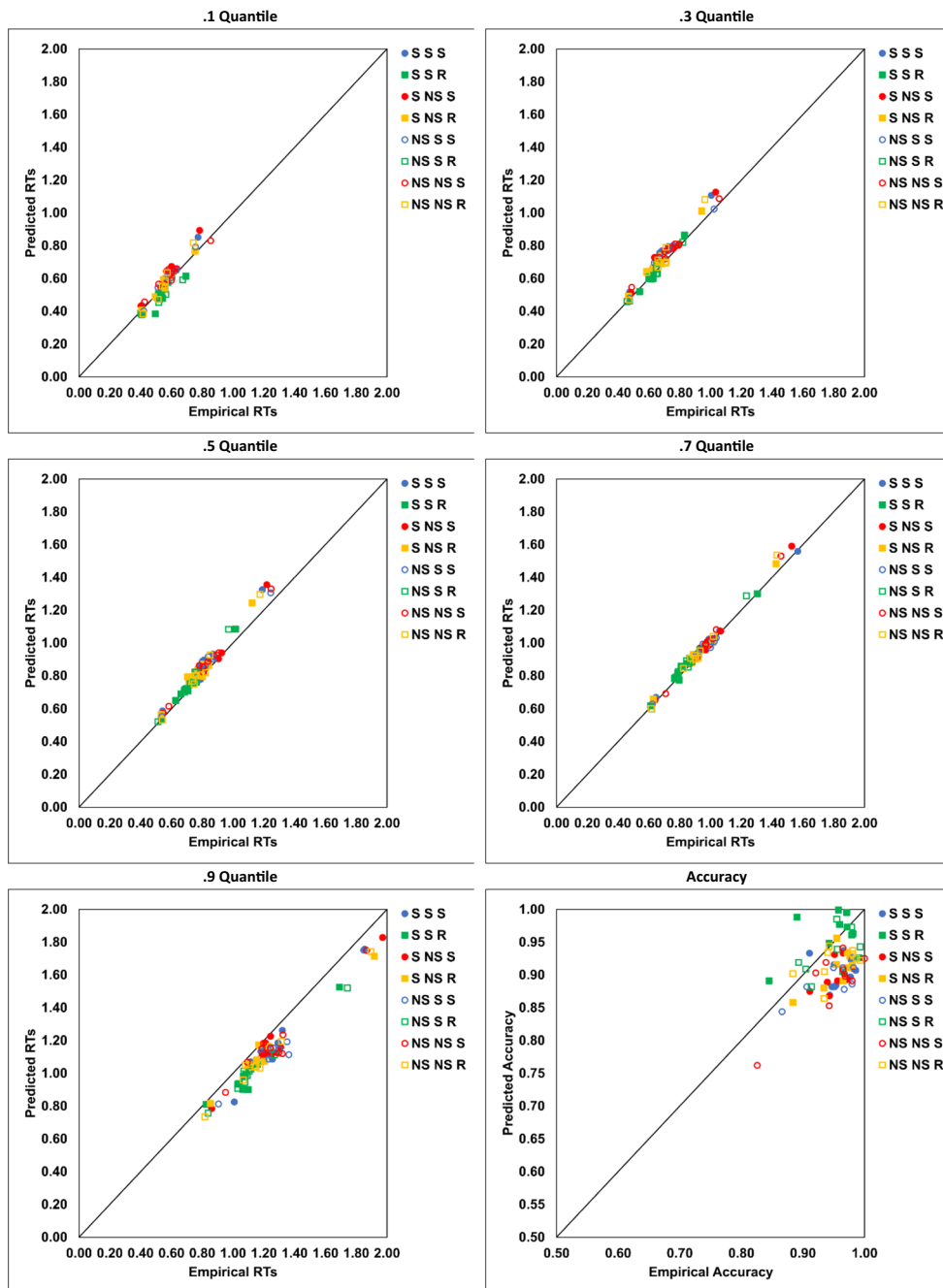
Fit was examined graphically by comparing the empirical RTs and accuracies to a distributions of predicted RTs and accuracies. Predicted response time and error distributions were generated for each condition for each subject using the construct-samples routine from *fast-dm* (Voss & Voss, 2007). Using the parameter values obtained from each subject separate data sets of  $N = 1,000$  trials each were generated, for a total of 9 (subjects)  $\times$  8 (conditions) 72,000 trials.<sup>1</sup> Parameters were

<sup>1</sup> The number of trials (1,000) generated is based on previous work (Burnham, 2018; Voss et al., 2013).

then re-estimated, from the predicted data, for each subject using *fast-dm*. The predicted accuracies and  $M_{RT}$  in each of the conditions were compared against the empirical accuracies and  $M_{RT}$  for the 10<sup>th</sup>, 30<sup>th</sup>, 50<sup>th</sup>, 70<sup>th</sup>, and 90<sup>th</sup> quantiles (Voss et al., 2004, 2008, 2013, 2015). As seen in Fig. 4, the points lie close to the line of perfect congruency, suggesting a good fit of the model and no bias in the predicted data.

### Discussion

This study used a variant of the three-item oddball search task by orthogonally manipulating the target feature (shape) and priming feature (color), to examine how decoupling these features, which negated top-down selection, influenced selection history on target activation. The results showed that feature



**Fig. 4** The figures display the relationship between the empirical versus predicted RTs based on fits to the diffusion model. Each symbol represents the mean of a single subject in a single experimental condition. In the legend, the first and second letter refer to the target on

Trial N – 1 and Trial N, respectively (S = singleton; NS = nonsingleton), and the third letter refers to the between-trial transition (S = switch colors; R = repeat colors). (Color figure online)

priming occurred whether the current target was a color singleton or nonsingleton (Fig. 3B), but the priming effect was larger when the current target was the singleton. Thus, irrelevant features of a selected target were implicitly encoded and facilitated selection on the following trial when the target appeared with the same feature. Importantly, the priming effect was *greater* when the current target was the color singleton, revealing the influence of bottom-up activation.

The diffusion analysis showed that feature priming influenced attentional selection (decision) bias ( $z_r$ ), target processing time ( $v$ ), and post-selection processes ( $t_0$ ). That is, priming influenced pretrial selection bias, information accumulation, and response execution. More importantly, the interaction in RTs between transition and target status on Trial N was driven by an influence of pretrial selection bias ( $z_r$ ). Thus, the larger feature priming effect when the current target was a color singleton was driven completely by a larger influence of pretrial bias ( $z_r$ ) and not facilitated processing time ( $v$ ) or post-selection response processes ( $t_0$ ; see Fig. 3). The results suggest selection history induced a bias to select the most likely target—the item or items with the repeated target color—and when that item was the color singleton, the attentional decision was facilitated by bottom-up salience.

However, because the target was the color singleton on half the trials, it may have been rational for observers to select the singleton in a top-down manner. That is, to observers, it may have seemed easier to select the singleton rather than the nonsingletons as a potential target. If so, the larger priming effect when the Trial N target was the color singleton may have been driven by a strategy to select the singleton, rather than bottom-up activation, as noted above. Such a singleton selection strategy predicts carryover when the Trial N – 1 target was the singleton, in the form of a Trial N – 1 Target by Transition interaction and a three-way Trial N – 1 by Trial N by Transition interaction. If observers adopted a singleton selection strategy, larger priming should have been observed when the Trial N – 1 target was the singleton, and when both the Trial N – 1 and Trial N targets were singletons, but neither interaction was statistically reliable. Although null interactions are difficult to interpret, such a singleton selection strategy is plausible.

Nonetheless, it is noteworthy that the singleton status of the target on Trial N – 1 had no influence on priming. Specifically, whether the target was the color singleton or a nonsingleton on Trial N – 1 had no influence on RTs, accuracy, or the diffusion parameters. This suggests a target's features are implicitly encoded only after it has been selected. Or, more specifically, it is the features of the selected target, whether salient or not, that are encoded and lead to priming. Also, interestingly is that 'inhibitory tagging' did not occur when the target was a nonsingleton on Trial N – 1, which is somewhat unlike the *distractor preview effect* (e.g., Ariga & Kawahara, 2004; Goolsby & Suzuki, 2001).

In conclusion, the results of the present study add to other studies that suggest several mechanisms are involved in selection history (priming) effects on target activation and selection (PoP). The unique outcome from this study is showing that selection history influenced target selection primarily through a pretrial attentional decision bias to select the most likely target in the current display. That is, implicitly encoding a target's features biased the attentional decision on the following trial to select the item (or items) with that same feature. Critically, this decision was made easier when the current target was distinct and displayed as a singleton, suggesting bottom-up attention (or possibly top-down strategies) of current displays may be a critical factor in selection history.

**Open practices statement** None of the experiments reported in this study was preregistered; however, data or materials used to run the experiments will be made available upon request.

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