

Optimal Task-Sets Override Attentional Capture by Rare Cues

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Many studies converge on the conclusion that spatially irrelevant precues do not capture attention when cue and target features do not match. However, a recent study reported that rare onset cues captured attention even though observers searched for a nonmatching color target. Hence, attentional capture by rare onsets cues might be cognitively impenetrable (Folk & Remington, 2015). Although we replicated these findings (Experiment 1), we hypothesized that capture by rare onset cues can be prevented when the target display promotes a stronger task-set for the target or suppression of the cue features (i.e., a white onset). Therefore, we presented the color target together with a single white nontarget, and indeed found that the rare onset cues failed to capture (Experiment 2). Moreover, we examined the previous suggestion that frequency effects are limited to onset cues by presenting rare color cues with nonmatching color targets (Experiment 3). We observed capture by rare color cues, but again, capture could be prevented when a nontarget in the cue color was added to the target display (Experiment 4). Overall, these findings suggest that capture by rare cues can be prevented when the suppressive bias against nontarget features is optimally directed against the cue properties.

Public Significance Statement

This study suggests that rare visual distractors can capture attention against the intentions of the observer. However, observers can prevent (or at least attenuate) attentional capture by rare distractors when the search task promotes the suppression of features similar to those of the distractors.

Keywords: visual attention, attentional capture, contingent attentional capture, spatial cueing, visual search

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When do visual stimuli capture attention? When they have particular physical properties or when they have the featural properties observers wish to find? In other words, how does attentional capture depend on bottom-up and top-down control signals? Many studies suggested that top-down signals override the influence of bottom-up signals on attentional allocation (e.g., McDonald, Green, Jannati, & Di Lollo, 2013; Sawaki & Luck, 2013), especially when spatial cueing tasks were used (e.g., Anderson & Folk, 2010, 2012; Folk & Remington, 1998, 2006, 1999; Folk, Remington, & Johnston, 1992; Folk, Remington, & Wright, 1994). In these tasks, a cue array is presented before the target array. Critically, the cue location is not predictive of the target location, so that observers can “ignore” the cue and effects of cue presentation on performance are attributable to bottom-up signals elicited by the cue (e.g., Jonides, 1981; Posner & Cohen, 1984).

The Influence of the Stimulus Class and the Task-Set on Attentional Capture

Early studies indicated that onset cues, which are defined as the only new elements in an array (e.g., a set of white dots; see Figure 1), capture attention even though observers should ignore them. This suggested that bottom-up signals from that particular stimulus class are top-down impenetrable (e.g., Jonides, 1981; Yantis & Jonides, 1984). However, Folk et al. (1992) found that onset cues do not always capture attention. Specifically, onset cues only captured attention in combination with onset targets, but not in search for red color singleton targets. Color singleton targets are uniquely colored items presented among homogeneously colored nontargets (e.g., a red target among white nontargets). Why did the cues only capture attention when the stimulus class of cue and target were matching, but not when they were nonmatching? Folk et al. (1992) proposed that attentional capture is contingent on a top-down task-set for the stimulus class of the sought-for target. The task-set facilitates attentional capture by all matching stimuli, whether relevant or irrelevant for the task. When a stimulus does not match the task-set, its bottom-up signal is excluded from attentional processing. In Folk, et al.’s. (1992) study, attentional capture was assessed by spatial cue validity effects on target identification; that is, faster response times (RTs) in trials in which cue and target appeared at the same stimulus position (valid trials) than in trials in which they were presented at different positions (invalid trials). Other studies replicated these findings using optimized designs and/or different measures (Chen & Mordkoff, 2007;

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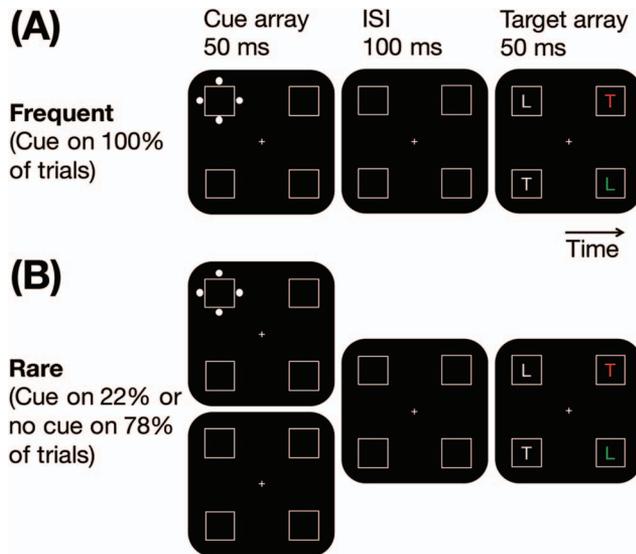


Figure 1. Stimulus displays in Experiment 1. White onset singleton cues were presented in combination with red feature targets. (A) In the frequent cue condition, the cue appeared on each trial. (B) In the rare cue condition, the cue appeared on 22% of the trials. See the online article for the color version of this figure.

Folk & Remington, 1999; Lien, Ruthruff, Goodin, & Remington, 2008; but see Belopolsky, Schreij, & Theeuwes, 2010; Lamy & Egeth, 2003, for findings of attentional capture by onset cues against the task-set).

The Influence of Cue Frequency on Attentional Capture

Given the long series of studies in which nonmatching cues did not capture attention, the discrepant results from a recent study are surprising. Folk and Remington (2015) investigated how the frequency of the irrelevant cues influenced attentional capture. In their Experiment 1, white onset cues were presented in combination with red color singleton targets. Typically, this combination does not result in attentional capture (e.g., Folk et al., 1992). However, when the cues appeared on only 20% of the trials and no cue was presented on the remaining 80% of trials, validity effects were observed, indicating that rare onset cues captured attention, even though they did not match the target. In a second group of observers, the same onset cues appeared on each trial, but consistent with previous findings (e.g., Folk et al., 1992), no validity effects were observed.

Why did the rare onset cues, but not frequent cues, capture attention? Folk and Remington (2015) offered two accounts for the effect of cue frequency. First, rare cues might violate an internal expectation about a typical trial, which triggers an automatic attentional orienting response. Following the ideas of Sokolov (1975), observers might form an internal model of the visual world. Stimuli that are inconsistent with this model (i.e., novel stimuli) elicit an automatic orienting response, whereas consistent stimuli do not trigger an orienting signal. Accordingly, frequent cues might have been part of an internal trial model, and therefore did not elicit an automatic orientation response. Conversely, rare

cues might not have been incorporated in the trial model, and therefore caused attentional capture. Because the rare cues captured attention even though they did not match the task-set, this orienting response might be top-down impenetrable.

Second, rare cues might change the task-set. There are various ways of how rare cues may influence the task-set differently from frequent cues. One possibility is based on the premise that observers use the task-set that is most efficient for performing the task and the least effortful to establish. Hence, when the cues were rare, observers might have established a task-set for singletons (*singleton search mode*) because rare attentional capture was not sufficiently detrimental to task performance and because a task-set for singletons required less cognitive effort than a set for a specific feature (*feature search mode*; Bacon & Egeth, 1994).

To test these accounts, Folk and Remington (2015) presented rare or frequent onset cues in combination with red feature targets. That is, red targets were presented among two white and one green nontarget (see Figure 1). Hence, observers could not use a task-set for singletons, but must have established a task-set for red. Nevertheless, the rare cues still captured attention, and the frequent ones did not. This finding supported the hypothesis that rare onsets captured attention because of expectancy violation.

However, post hoc analyses of the rare onset cue conditions in those two experiments led to a more complex picture. The analyses examined whether validity effects depended on the *lag*, that is, the number of trials between two subsequent trials that contained onset cues. Cue validity effects did not depend on the lag when the targets were red singletons (Folk & Remington, 2015, Experiment 1), which is rather consistent with a singleton search account, according to which participants form a task-set for singletons on the first few trials and keep that task-set for all remaining trials, so that the cues always capture attention to the same extent. Conversely, when the targets were feature-defined, validity effects were larger for long than short lags (Folk & Remington, 2015, Experiment 3). This finding is more in line with an expectancy violation account because after short lags the internal trial model might expect cues and prevent capture, whereas after long lags the trial model might not contain cues, leading to attentional capture. In sum, rare onset cues seem to capture attention in combination with color singleton targets because of a singleton search strategy, and in combination with feature targets because of expectancy violation.

The Present Study: The Influence of the Task-Set on Attentional Capture by Rare Cues

The main question in the current study was whether attentional capture by rare cues is impenetrable by the task-set. There is evidence that task-sets are more complex than previously assumed (Folk & Remington, 2015). Hence, attentional capture by rare cues might be overridden by the task-set when not only target, but also cue and nontarget features are considered.

If task-sets were exclusively determined by the sought-for target property, color singleton targets should have led to a task-set for color singletons, regardless of cue frequency. However, because rare, but not frequent, onset cues resulted in attentional capture with the same color singleton targets, the task-set is shaped not only by the target features, but also by cue frequency (Folk & Remington, 2015, Experiment 1). One account for this finding is

that frequent cues enforce the enhancement of the target property through an improved task-set. Another possibility is that task-sets comprise one component that enhances attentional processing of the target property, and a further component that suppresses the cue properties (Folk & Remington, 2015).

In the present study, we hypothesized that task-sets might be influenced not only by properties of irrelevant cues, but also by the properties of salient but irrelevant nontargets (e.g., Müller, Geyer, Zehetleitner, & Krummenacher, 2009; Zehetleitner, Goschy, & Müller, 2012). Imagine a target display with a red target, one green and two white nontargets (see Figure 1), and a second target display with a red target and three white nontargets. The green nontarget in the first display is probably more salient than any of the three white nontargets in the second display, as predicted by many saliency models (e.g., Itti & Koch, 2001; Navalpakkam & Itti, 2007; Wolfe, 2007). To prevent capture by the salient nontarget, observers might suppress its specific feature (Burra & Kerzel, 2013; Gaspar & McDonald, 2014; Vecera, Cosman, Vatterott, & Roper, 2014; Zehetleitner et al., 2012). Hence, we suggest that the salient green nontarget in the target display might lead to the suppression of green, which attenuates capture from cues sharing this feature, whether they are rare or frequent.

To test whether salient nontargets affect the task-set, we applied the following strategy. In each experiment, we presented rare or frequent cues, and measured whether the rare cues captured attention more than frequent ones. When an experiment showed that the rare cues captured attention more than did the frequent ones, we ran a second experiment in which a salient nontarget with a feature similar to the cue was added to the target display (see Table 1). If salient nontargets lead to a task-set that comprises the suppression of the nontarget features, the same suppressive component might attenuate the attention-driving signal from rare cues with similar features.

Experiment 1

In Experiment 1, rare or frequent onset cues were presented in combination with red feature targets (a red target together with one green and two white nontargets). The goal was to replicate Folk and Remington's Experiment 3. To measure attentional capture by the cues, we analyzed validity effects on RTs. In accordance with Folk and Remington's (2015, Experiment 3) results, we expected that the rare, but not the frequent onset cues would elicit a validity

effect. We refer to this result, that is, a larger validity effect for rare than frequent cues, as *frequency effect*. This finding would suggest that rare onsets elicit an attention-driving signal that can override the task-set.

Additionally, for the rare cue condition, we analyzed whether validity effects depended on the *lag*, that is, the number of trials between two subsequent trials that contained onset cues. We expected that validity effects would be larger for long than short lags (Folk & Remington, 2015, Experiment 3). Such a finding would indicate that rare cues capture attention because of expectancy violation.

Method

Participants. In all experiments, students from the University of Geneva, Switzerland, took part for course credit. Informed consent was given before an experimental session started. All participants reported normal or corrected to normal visual acuity, and normal color vision. Forty-two students participated in Experiment 1 (32 female, mean age of 23 years).¹

Apparatus. Participants were seated in a dimly lit room, and placed their heads on a chin rest to view the stimulus monitor (24-in. LCD, 144 Hz, 1,920 × 1,080 pixels) from a distance of 57 cm. Observers pressed one of two designated response keys on a USB keyboard using the index and middle finger of their preferred hand. Colors were measured with a Cambridge Research Systems ColorCAL MKII colorimeter and are specified in CIE 1976 L , u' , v' triplets.

Stimuli. Stimuli were generated using the Psychophysics Toolbox (Kleiner et al., 2007) and were presented on a black background (0.30 cd/m²). Three types of displays were presented: fixation, cue, and target display (see Figure 1). The fixation display consisted of four peripheral gray squares (2.00° × 2.00°; line width: 0.03° or 1 pixel; $L = 30.01$ cd/m², $u' = 0.20$, $v' = 0.46$) and a central gray fixation cross (0.35° × 0.35°, line width: 0.03°). The squares' centers had a distance of 6.00° from the center of the fixation cross and were arranged on the vertices of an imaginary square.

When a cue was presented in a trial, the cue display consisted of the fixation display and an additional set of four filled white circles (0.40° × 0.40°, $L = 40.00$ cd/m², $u' = 0.20$, $v' = 0.46$), around one of the peripheral squares. The circles had a distance of 1.30° from the center of the peripheral square and were centered on the vertices of an imaginary diamond. When no cue was presented, the cue display consisted only of the fixation display.

The target display consisted of the fixation display and an L or T (1.00° × 1.40°, 0.2° line-width) inside each peripheral square. The target letter was red ($L = 29.90$ cd/m², $u' = 0.46$, $y = 0.51$), one randomly (equal probability for each stimulus position) chosen nontarget letter was green ($L = 30.09$ cd/m², $u' = 0.13$, $v' = 0.56$) and the remaining two letters were white.

Design. The target was always red. Cue frequency (22%, 100%) varied between participants. Within participants, the variables cue position (placeholder 1 to 4), target position (placeholder 1 to 4), target identity (L, T), and the identity of the uniquely colored nontarget (L, T) were fully counterbalanced across trials,

Table 1

Colors of the Items in the Cue and Target Arrays

| Experiment | Cue array | | Target array | | Frequency effect |
|------------|-----------|-----------------|--------------|------------|--------------------|
| | Cue | Context cues | Target | Nontargets | |
| 1 | w | No context cues | r | g, w, w | 21 ms ^a |
| 2 | w | No context cues | r | w | -2 ms |
| 3 | g | w, w, w | r | w, w, w | 19 ms ^a |
| | r | w, w, w | r | w, w, w | 21 ms ^a |
| 4 | g | w, w, w | r | g, w, w | -13 ms |
| | r | w, w, w | r | g, w, w | 18 ms ^a |

Note. Colors were white (w), red (r) and green (g). Frequency effect refers to the difference between the cue validity effect in the rare and the frequent condition.

^a Indicates that frequency effect is significant.

¹ We used twice as many participants and trials as Folk and Remington (2015, Experiment 3) to ensure replication.

resulting in 64 combinations. The combinations appeared in random order. The positions of the single colored green nontarget and the two white nontargets varied randomly. The identity of the two white nontarget letters were chosen so that a target display always contained two Ls and two Ts.

Each participant worked through 576 trials, separated by pauses after 144 trials. In the 22% cue frequency condition, the 576 trials consisted of two sets of 64 trials in which the cue singleton was present, and 7 sets in which a cue singleton was not present. Cue presence varied randomly. In the 100% cue frequency condition, the cue singleton was always present.

Procedure. Participants were informed about the spatial relationship between cue and target, and consequently, asked to ignore the cue. They were instructed to report the identity of the red target letter (L or T) by pressing the corresponding left or right response key with their middle or index finger, respectively. The key-to-response assignment was counterbalanced across participants. Moreover, they were instructed to maintain central fixation throughout each experimental block and to respond as fast and accurately as possible.

Each trial started with the presentation of the fixation display (500 ms). Then, the central square blinked off (100 ms) to remind participants to fixate for the upcoming trial. The full fixation display was shown again for a randomly chosen foreperiod (1,000 ms to 1,400 ms). Next, cue (50 ms), fixation (100 ms), and target display (50 ms) were sequentially presented. Finally, the fixation display appeared until response.

If a response was correct, the next trial started. If a response was too early (RT < 100 ms), incorrect, or late (RT > 1,500 ms), participants received feedback by a written word, signaling the type of error, and a brief tone (750 Hz, 100 ms).

Results

An alpha level of .05 (two-sided) was used to determine statistical significance. The p values were adjusted using the Greenhouse-Geisser epsilon correction for nonsphericity when necessary.

Exclusions. Early (0.2% of all data), late (1.5%), and responses on other than the designated keys (0.7%) were removed before further analysis. RTs exceeding the mean of a cell by more than three standard deviations were trimmed (1.0%).

RTs. The average mean RTs on correct trials are shown in Figure 2A. Analyses by a 2 (cue validity: valid, invalid) \times 2 (cue frequency: rare, frequent) mixed analysis of variance (ANOVA) revealed a significant main effect of validity, $F(1, 40) = 12.69, p = .001, \eta_p^2 = 0.24$, showing that responses were overall faster on valid than invalid trials. However, this effect was qualified by a reliable Validity \times Frequency interaction, $F(1, 40) = 11.21, p = .002, \eta_p^2 = 0.22$, indicating that validity effects differed depending on the factor levels of frequency. Pairwise comparisons showed that this interaction reflects a reliable validity effect of 22 ms when onset cues were rare, $t(20) = 3.701, p = .001, d = .80$, but no reliable validity effect (1 ms) when onset cues were frequent, $t(20) = 0.30, p = .770, d = .06$.

For the 22% cue frequency condition, we examined whether cueing effects by singleton cues on the current trial depended on the lag (Figure 2B). For this purpose, we pooled trials with a lag of one or two trials, of three or four trials, and of more than four

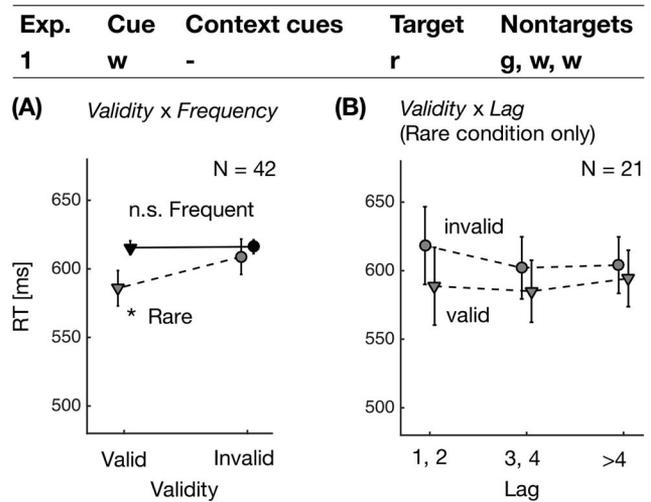


Figure 2. In Experiment 1, white onset singleton cues were presented in combination with red feature targets. The graphs show average mean response times (RTs) on valid and invalid trials, as a function of cue frequency (A) and cue lag (B, rare condition only). The error bars indicate the 95% confidence intervals for the difference between invalid and valid cue trials for each level of the respective variable (Franz & Loftus, 2012). * $p < .05$.

trials. We subjected the data to a 2 (validity) \times 3 (lag) repeated-measures ANOVA. We obtained a reliable main effect of validity, $F(1, 20) = 6.82, p = .017, \eta_p^2 = 0.25$. The main effect of lag, $F(2, 40) = 0.53, p = .592, \eta_p^2 = 0.02$, and the Validity \times Lag interaction, $F(2, 40) = 0.72, p = .495, \eta_p^2 = 0.04$, were not significant. These results differ from Folk and Remington's (2015) findings (Experiment 3), who found larger validity effects for long than short lags.

Errors. The mean error rates for Experiment 1 (and all following Experiments) are shown in Table 2. Error rates were subjected to the same ANOVAs as RTs. Neither the Validity \times Frequency mixed ANOVA ($F_s < 1$) nor the Validity \times Lag repeated-measures ANOVA ($F_s < 1$) showed significant results.

Discussion

Experiment 1 replicated Folk and Remington's (2015) Experiment 3 in that rare onset cues elicited validity effects, even though the target was a red feature target. Hence, the attention-driving signal elicited by rare onset cues outweighed the task-set for red color, and the cues consequently captured attention against observers' goals.

In Folk and Remington's (2015) Experiment 3, rare onset cues elicited larger validity effects for long than short lags, suggesting that rare onset cues captured attention because of expectancy violation. In the present Experiment 1, validity effects did not depend on the trial-lag. To accommodate these findings, one may assume that expectancies are not continuously updated after recent encounters with a cue, but are set at the beginning of a block of trials and remain unchanged thereafter (e.g., Müller et al., 2009).

Alternatively, rare cues might have led to an adaption of the task-set. However, this adaption cannot have resulted in a task-set for singletons in general, because the target was not a singleton

Table 2
Mean Error Proportions (in %, on Valid and Invalid Trials as a Function of Cue Frequency and Lag)

| Experiment | Validity | Frequency | | Lag | | |
|----------------|----------|-----------|----------|------|------|-----|
| | | Rare | Frequent | 1, 2 | 3, 4 | >4 |
| 1 | Valid | 5.1 | 5.4 | 4.7 | 5.5 | 5.1 |
| | Invalid | 5.0 | 6.1 | 5.3 | 5.1 | 5.1 |
| 2 | Valid | 7.7 | 3.9 | 6.7 | 4.2 | 8.0 |
| | Invalid | 6.6 | 3.9 | 7.1 | 7.7 | 8.4 |
| 3 (Green cues) | Valid | 2.1 | 2.8 | 1.9 | 3.8 | 1.8 |
| | Invalid | 3.4 | 3.4 | 3.7 | 2.6 | 3.8 |
| 3 (Red cues) | Valid | 1.4 | 2.1 | 1.4 | 0 | 2.5 |
| | Invalid | 4.4 | 3.1 | 4.7 | 3.7 | 4.5 |
| 4 (Green cues) | Valid | 2.1 | 2.7 | 3.0 | 1.0 | 2.0 |
| | Invalid | 2.3 | 2.8 | 3.1 | 2.1 | 1.3 |
| 4 (Red cues) | Valid | 3.3 | 2.5 | 5.2 | 1.4 | 1.1 |
| | Invalid | 6.3 | 4.7 | 7.0 | 1.5 | 4.6 |

Note. For the analyses of Lag \times Validity, only the data for rare cue frequency conditions are shown.

and, consequently, required feature search (Bacon & Egeth, 1994). Rather, we pursue the idea that rare cues resulted in a task-set with reduced inhibition of the attention-driving signal from onset cues (Folk & Remington, 2015, Experiment 1; Müller et al., 2009).

Experiment 2

In Experiment 1, rare onset cues captured attention despite a task-set for red color, suggesting that the attention-driving signal from the rare onsets outweighed the top-down signal. However, does this finding imply that rare onset cues always override the task-set and always capture attention?

Instead, the target display might not have been optimal to prevent attentional capture by rare cues. If task-sets involve a suppressive component to deal with features of salient nontargets, the green nontarget might have led to the suppression of green. However, the properties of the white onset cues might not have been optimally suppressed because it was only rarely present in the cue display and never part of the target display. In Experiment 2, we changed the target display to contain only one white nontarget (and no other nontargets). Hence, the nontarget properties were as similar to the properties of the onset cue as possible, creating a strong incentive to suppress unique or white elements. Thus, in Experiment 2, we predicted that white onset cues elicit no validity effects on RTs, regardless of cue frequency.

Method

Participants. Forty-two new participants took part in Experiment 2 (32 female, mean age of 22 years).

Apparatus, stimuli, design, and procedure. Instead of the single green and two white nontargets in Experiment 1, only a single white nontarget was presented. The nontarget letter was chosen randomly with the constraint that it was equally often an L or a T. Otherwise the methods were identical to Experiment 1.

Results

Exclusions. Early (<0.1% of all data), late (1.0%) and responses on other than the designated keys (0.6%) were removed

before further analysis. RTs were trimmed if they exceeded the individual condition mean by more than three standard deviations (1.0%).

RTs. The average mean RTs on correct trials are shown in Figure 3A. All analyses were the same as for Experiment 1. However, neither the Validity \times Frequency mixed ANOVA ($F_s < 1$) nor the two Validity \times Lag repeated-measures ANOVA ($F_s < 1$) revealed reliable effects.

Finally, we examined whether cue validity effects in the rare cue conditions of Experiment 1 and 2 differed by using a 2 (validity) \times 2 (target: feature target in Experiment 1, singleton target in Experiment 2) mixed ANOVA. The main effect of validity, $F(1, 40) = 5.65$, $p = .022$, $\eta_p^2 = 0.12$, and the Validity \times Target interaction were reliable, $F(1, 40) = 5.45$, $p = .025$, $\eta_p^2 = 0.12$, showing that the rare cues elicited a significantly larger validity effect in Experiment 1 than in Experiment 2. The target main effect was not significant ($F < 1$).

Errors. Error rates were subjected to the same ANOVAs as RTs. Again, neither the Validity \times Frequency mixed ANOVA ($F_s < 2.03$) nor the Validity \times Lag repeated-measures ANOVA ($F_s < 1.71$) showed reliable results. Finally, the Validity \times Target mixed ANOVA did not return reliable results ($F_s < 1$).

Discussion

When the target array contained a red target and a single white nontarget, neither rare nor frequent onset cues captured attention. The task-set probably contained a suppressive component against the features of the onset-like nontarget, which overrode or down-modulated the attention-driving signal elicited by the rare onset cues.

Experiment 3

Folk and Remington (2015) suggested that frequency effects are specific to onsets and do not generalize to other feature dimensions

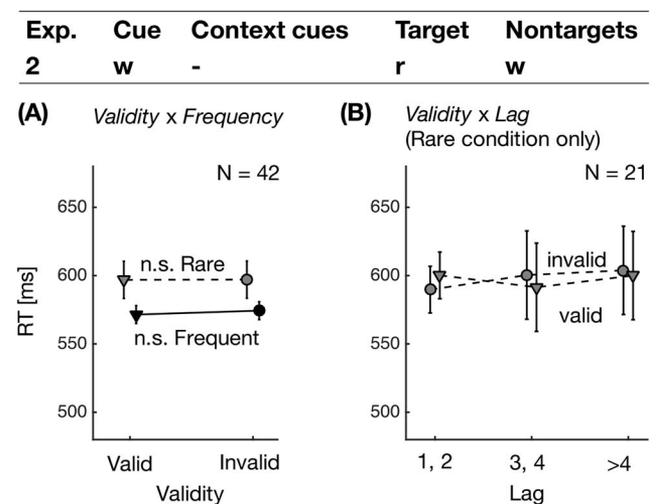


Figure 3. In Experiment 2, the same white onset singleton cues were presented as in Experiment 1. The target, however, was a red singleton presented among a single white nontarget. The graphs show average mean response times (RTs) on valid and invalid trials, as a function of cue frequency (A) and cue lag (B, rare cue condition only).

such as color because rare onset cues in their study captured attention in combination with color targets, whereas rare color singleton cues did not capture attention in search for onset targets. We reexamined this claim using stimulus parameters from studies in which nonmatching color-cues had captured attention (Belopolsky et al., 2010; Noesen, Lien, & Ruthruff, 2014) to maximize possible effects of cue frequency. Hence, in the nonmatching cue condition of Experiment 3, green color singleton cues were presented in combination with red color singleton targets. These stimuli had larger surface area and larger eccentricity than those in Experiments 1 and 2.

Moreover, trials without color singleton cue contained white cue elements around each of the four placeholder squares, and were chosen instead of displays without any cue elements (Folk & Remington, 2015) to ensure that the rare event was a color singleton and not the entire cue display.

Finally, we also included a condition with matching color cues to assess whether the cue frequency manipulation changes the task-set to a singleton-search. With rare cues, it might be that observers employ a search mode for all color singletons, irrespectively of their specific color, resulting in similar attentional capture by matching and nonmatching cues (Folk & Remington, 2008). If observers establish a task-set for red targets instead, matching red cues should capture attention more than mismatching green cues.

Method

Participants. Sixty-five students participated in Experiment 3 (55 female, mean age of 22 years).²

Apparatus, stimuli, design, and procedure. Apparatus, stimuli, design, and procedure were as in Experiment 1, with the following exceptions: The stimulus monitor was a 21-in. CRT screen (100 Hz, 1,280 × 1,024 pixels).

In the fixation display, the peripheral squares were larger (2.4° × 2.4°; line width: 0.03°; $L = 23.01$ cd/m², $u' = 0.19$, $v' = 0.43$) and were presented 8° from the screen center. Instead of the fixation cross a fixation square was used with the same size and color as the peripheral ones (Noesen et al., 2014). In the cue display, a set of four circles (1° × 1°; line width: 0.2°) was presented around each of the peripheral squares. The circles had a distance of 2° from the center of a peripheral square. In the neutral cue condition, all circles were white. In the singleton cue displays, the circles around one peripheral box were red ($L = 22.49$, $u' = 0.43$, $v' = 0.53$) or green ($L = 22.43$, $u' = 0.12$, $v' = 0.56$). In the target display, the target letter (1.6° × 1.2°; line-width: 0.2°) was red and the remaining letters were white.

Cue color (red, green) and cue frequency (25%, 100%) varied between participants. Within participants, the variables cue position (placeholder 1 to 4), target position (placeholder 1 to 4), and target identity (L, T) were fully counterbalanced across trials, resulting in 32 trials. Each participant completed 512 trials, separated by pauses after 128 trials. In the 25% cue frequency condition, the 512 trials consisted of four sets of 32 trials in which the cue singleton was present and 12 sets in which a cue singleton was not present. Cue presence varied randomly. In the 100% cue frequency condition, the cue singleton was always present.

Results

Exclusions. Early (<0.1% of all data), late (<0.1%) and responses on other than the designated keys (0.5%) were removed before further analysis. RTs exceeding the mean of a cell by more than 3 standard deviations were trimmed (1.8%).

RTs. The average mean RTs on correct trials are shown in Figure 4A and 4C. Mean RTs were subject to a 2 (validity) × 2 (frequency) × 2 (color match: matching, nonmatching) mixed ANOVA. The main effect of validity was significant, $F(1, 61) = 156.43$, $p < .001$, $\eta_p^2 = 0.72$, indicating overall faster responses on valid cue trials (valid: 535 ms, invalid: 587 ms). The interaction between validity and color match was significant, $F(1, 61) = 28.35$, $p < .001$, $\eta_p^2 = 0.32$, reflecting that cueing effects were overall larger when cue and target color matched (same color: 75 ms, different colors: 30 ms). Importantly, the Validity × Frequency interaction was significant, $F(1, 61) = 6.21$, $p = .015$, $\eta_p^2 = 0.09$, showing that cueing effects were larger in the 25% cue-frequency condition (25%: 62 ms, 100%: 42 ms). Notably, the three-way interaction between validity, frequency and color match was not significant ($F < 1$), showing that the frequency effect was of comparable size for matching and nonmatching cues. Other main effects or interactions involving the between-subjects factors (frequency and color match) did not reach significance ($F_s < 2.07$).

Pairwise comparisons of RTs on valid and invalid trials showed that the nonmatching green cues elicited a cueing effect in both cue-frequency conditions (25%: 39 ms), $t(15) = 4.80$, $p < .001$, $d = 1.20$; (100%: 20 ms), $t(16) = 5.40$, $p < .001$, $d = 1.35$, but the cueing effect in the 25% condition was significantly larger, $F(1, 31) = 4.88$, $p = .035$, $\eta_p^2 = 0.14$. Also, the matching red cue elicited cueing effects in each cue-frequency condition (25%: 85 ms), $t(15) = 6.21$, $p < .001$, $d = 1.55$; (100%: 64 ms), $t(15) = 17.00$, $p < .001$, $d = 4.25$, and again the validity effect in the 25% condition was larger, $F(1, 30) = 5.64$, $p = .024$, $\eta_p^2 = 0.16$.

Figure 4B and 4D show the validity effects as a function of lag, for the 25% cue frequency conditions. The statistical analyses, however, are not reported for brevity because the analyses showed no interactions between validity and the other factors.

Errors. The 2 (validity) × 2 (frequency) × 2 (color match) mixed ANOVA on errors showed a main effect of validity, $F(1, 61) = 20.72$, $p < .001$, $\eta_p^2 = 0.25$. The Validity × Color Match approached significance, $F(1, 61) = 2.71$, $p = .105$, $\eta_p^2 = 0.04$, and the Validity × Frequency interaction reached significance, $F(1, 61) = 4.88$, $p = .031$, $\eta_p^2 = 0.07$. All other main effects and interactions were not reliable ($F_s < 1$).

Pairwise comparisons of errors on valid and invalid trials showed that errors reflected the tendencies of the RT results. The nonmatching green cues elicited a cueing effect in the 25% condition (1.3%), $t(15) = 2.54$, $p = .023$, $d = 0.64$, but not in the 100% condition (0.5%), $t(16) = 1.21$, $p = .242$, $d = 0.29$. Those

² In the current study, the critical effect was a larger validity effect for rare than frequent cues. In Experiment 1, the corresponding Validity × Frequency interaction showed an effect size of $\eta_p^2 = 0.22$. This interaction requires 16 participants for the rare and 16 participants for the frequent cue condition, aiming for a power of .80 (Faul, Erdfelder, Lang, & Buchner, 2007). Experiment 3 involved matching and nonmatching cues, and consequently required 64 participants.

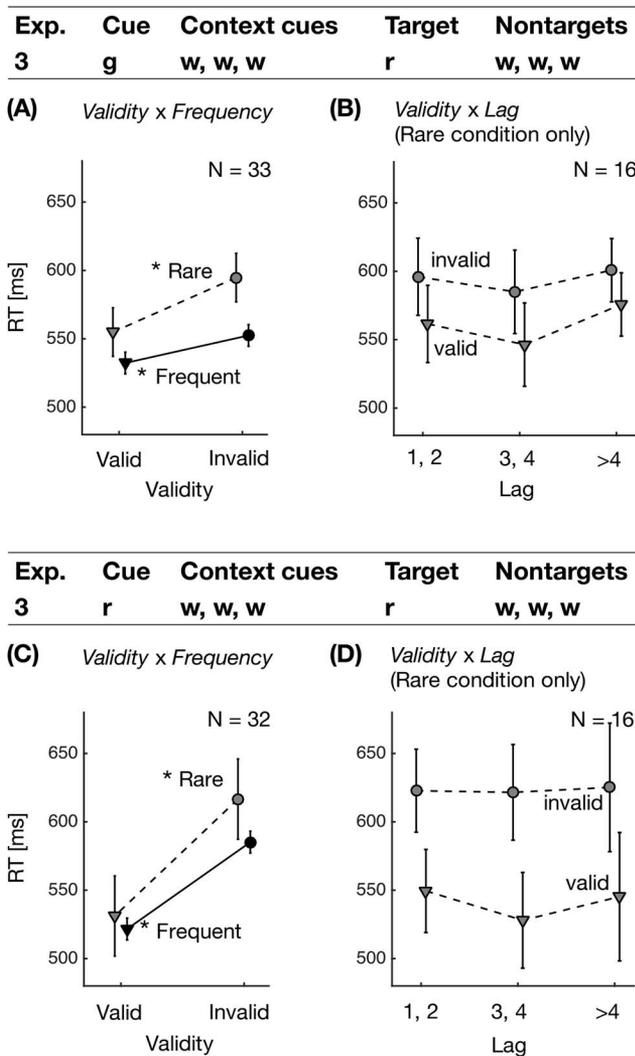


Figure 4. In Experiment 3, green or red color singleton cues were presented in combination with red color singleton targets. The graphs A and B show average mean reaction times (RTs) for green cues, and graphs C and D show the results for red cues. * $p < .05$.

cueing effects did not differ significantly ($F = 1.15$). The matching red cues elicited a cueing effect on errors when cues were rare (3.0%), $t(15) = 3.07$, $p = .008$, $d = 0.79$, but not when cues were frequent (1%), $t(15) = 2.02$, $p = .062$, $d = 0.50$. The difference between those cueing effects approached significance, $F(1, 30) = 3.68$, $p = .064$, $\eta_p^2 = 0.11$.

Discussion

Somewhat surprisingly, nonmatching green cues elicited a validity effect in combination with red color singleton targets. The validity effect by nonmatching cues was larger for rare than for frequent cues, undermining the assertion that only rare onset cues produce frequency effects. Moreover, rare matching red cues elicited larger cueing effects than rare nonmatching green cues, showing that participants had not established a task-set for color sin-

gletons in general, but a task-set for red that increased the attention-driving capacity of matching compared to nonmatching cues.

Further, even the frequent green cues elicited validity effects in combination with red color singleton targets. This suggests that the bottom-up salience signal overrode the task-set for red color singletons. The finding replicates previous studies, in which target-nonmatching cues captured attention (Belopolsky et al., 2010; Noesen et al., 2014). The stimuli in previous and the present study had larger surface area than in other studies. Hence, they might have been relatively more salient because the cue elements appeared denser (Rangelov, Müller, & Zehetleitner, 2017) or because the stimuli had a higher luminance contrast relative to the black background.

Another explanation for the unexpected validity effect with frequent green cues may be that the larger stimuli resulted in a weaker task-set than the smaller stimuli used in other studies. Hence, even though the bottom-up salience of the cues might have been the same as with smaller stimuli, larger stimuli were able to override the task-set.

A further possibility is that the red color singleton targets resulted in a combined task-set for red color and singletons in general (e.g., Carmel & Lamy, 2015). Thus, because the green cues were singletons (similar to the target) they might have captured attention, but less so compared to red cues, which were singletons and additionally matched the target color.³

Experiment 4

In Experiment 3, rare green cues captured attention, despite a task-set for red targets, suggesting that the attention-driving signals from rare nonmatching cues overrode the task-set. However, as Experiments 1 and 2 showed, this might not necessarily imply that the task-set cannot override attentional capture by rare items at all. In Experiment 3, the task-set's suppressive component against the cue properties might not have been optimal. The target display only contained three white nontargets, which might not have afforded a strong negative bias against green. Following our main hypothesis, we argued that when a salient nontarget has similar features as the cue, the resulting task-set includes a negative bias against those nontarget properties, which might attenuate the attention-driving signals by the rare color cues. In Experiment 3, the cue arrays contained a green item among several white items. Hence, to optimize a suppressive bias against those features, the nontargets in the target display of Experiment 4 contained one

³ Carmel and Lamy (2015, Experiment 3) presented matching and non-matching color singleton cues with color singleton and color feature targets. The matching cues elicited larger cueing effects with the singleton than with the feature targets. Therefore, they speculated that, while feature targets only result in a task-set for color, color singleton targets can evoke a combined task-set for features and singletons. In the current study, matching cues did not elicit larger validity effects with color singleton than color feature targets. We examined this possibility with a 2 (validity) \times 2 (frequency) \times 2 (target: singleton target; feature target) mixed ANOVA. It showed a significant main effect of validity, $F(1, 61) = 234.70$, $p < .001$, $\eta_p^2 = 0.79$, and a significant Validity \times Frequency interaction, $F(1, 61) = 6.16$, $p = .016$, $\eta_p^2 = 0.92$. However, the interactions involving the target factor were not reliable ($F_s < 1$). Because the cueing effects were rather large (on the order of 80 ms), it is possible that a ceiling effect concealed differences between feature and singleton targets.

green and two white nontargets in addition to the red target. We expected that attentional capture by rare green cues would be reduced compared to Experiment 3.

Method

Participants. Sixty-five new participants took part Experiment 4 (56 female, mean age of 20 years).

Apparatus, stimuli, design, and procedure. Apparatus, stimuli, design, and procedure were as in Experiment 3, except that a randomly chosen nontarget letter was green.

Results

Exclusions. Early (<0.1% of all data), late (<0.1), and responses on other than the designated keys (<0.1%) were removed before further analysis. RTs exceeding the mean of a cell by more than 3 standard deviations were trimmed (1.7%).

RTs. The average mean RTs on correct trials are shown in Figures 5A and 5C. Mean RTs were subject to a 2 (validity) \times 2 (frequency) \times 2 (color match) mixed ANOVA. The main effect of validity was significant, $F(1, 61) = 89.64, p < .001, \eta_p^2 = 0.60$, indicating overall faster responses on valid cue trials (valid: 551 ms, invalid: 587 ms). Also the main effect of color match was reliable, $F(1, 61) = 5.29, p = .025, \eta_p^2 = 0.08$, reflecting that, overall, RTs were faster when cue and target color matched than when they were nonmatching (matching: 547 ms, nonmatching: 592 ms). Moreover, the Validity \times Color Match interaction was significant, $F(1, 61) = 92.52, p < .001, \eta_p^2 = 0.60$, reflecting that cueing effects were overall larger when cue and target color matched (same color: 73 ms, different colors: -1 ms). Critically, unlike in Experiment 3, the three-way interaction between validity, frequency and color match was significant, $F(1, 61) = 6.48, p = .013, \eta_p^2 = 0.10$, showing that there was a frequency effect with matching, but not with nonmatching cues. Other main effects or interactions did not reach significance ($F_s < 2.38$).

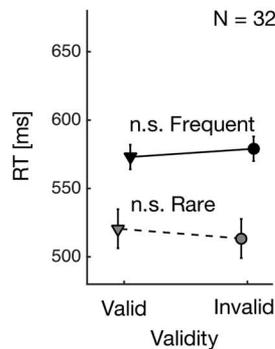
Pairwise comparisons between invalid and valid cue trials, showed that the nonmatching green cues did not elicit a validity effect in either frequency condition (25%: -7 ms, $t(15) = -1.07, p = .302, d = 0.27$; (100%: 6 ms), $t(15) = 1.43, p = .175, d = 0.17$). These validity effects did not differ significantly, $F(1, 30) = 2.56, p = .120, \eta_p^2 = 0.08$. The matching red cues showed cueing effects in both frequency conditions (25%: 88 ms), $t(16) = 10.01, p < .001, d = 1.99$; (100%: 60 ms), $t(15) = 7.86, p < .001, d = 2.00$. These validity effects were significantly larger in the 25% cue frequency condition, $F(1, 31) = 5.75, p = .023, \eta_p^2 = 0.16$.

Figures 5B and 5D show the validity effects as a function of lag, for the 25% cue frequency conditions. Again, the statistical analyses are not reported, since the analyses showed no interactions between validity and the other factors.

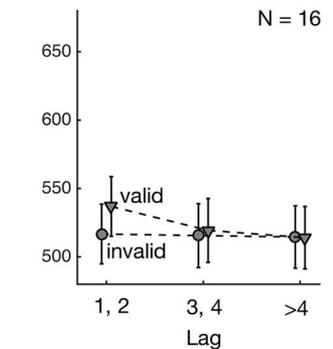
Finally, we examined whether validity effects by the rare, non-matching green cues in Experiment 3 and 4 differed, by employing a 2 (validity) \times 2 (target: singleton target in Experiment 3, feature target in Experiment 4) mixed ANOVA. The main effect of validity, $F(1, 30) = 9.37, p = .005, \eta_p^2 = 0.24$, and the main effect of target, $F(1, 30) = 5.87, p = .022, \eta_p^2 = 0.16$ were significant. These main effects were qualified by a significant Validity \times Target interaction, $F(1, 30) = 19.39, p < .001, \eta_p^2 = 0.39$, showing that the rare, green cues elicited a significantly larger validity

| Exp. | Cue | Context cues | Target | Nontargets |
|------|-----|--------------|--------|------------|
| 4 | g | w, w, w | r | g, w, w |

(A) Validity \times Frequency

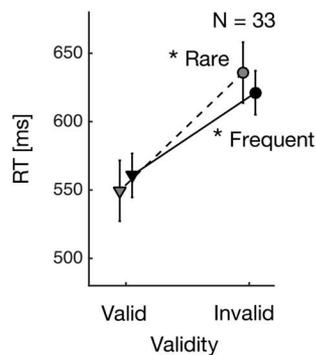


(B) Validity \times Lag (Rare condition only)



| Exp. | Cue | Context cues | Target | Nontargets |
|------|-----|--------------|--------|------------|
| 4 | r | w, w, w | r | g, w, w |

(C) Validity \times Frequency



(D) Validity \times Lag (Rare condition only)

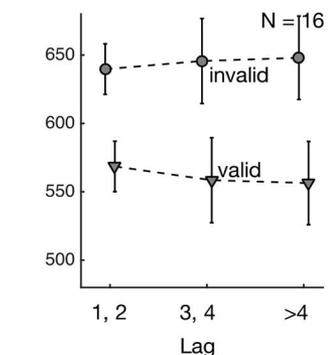


Figure 5. In Experiment 4, the same green or red color singleton cues were presented as in Experiment 3. However, the red target was presented among one green and two white nontargets. The graphs A and B show average mean RTs for green cues, and graphs C and D show the results for red cues. * $p < .05$.

effect in Experiment 3 than in Experiment 4. The target main effect was not significant ($F < 1$).

Errors. The 2 (validity) \times 2 (frequency) \times 2 (color match) mixed ANOVA on errors revealed a main effect of validity, $F(1, 61) = 24.37, p < .001, \eta_p^2 = 0.29$. As for RTs, the main effect of color match was significant, $F(1, 61) = 4.18, p = .045, \eta_p^2 = 0.06$. The Validity \times Color Match interaction was significant, $F(1, 61) = 18.41, p < .001, \eta_p^2 = 0.23$. All other main effects and interactions were not reliable ($F_s < 1$).

Pairwise comparisons of errors on valid and invalid trials showed that errors reflected the tendencies of the RT results. Nonmatching green cues elicited no reliable validity effects ($t < 1.43$). The matching red cues elicited validity effects on errors when cues were rare (3.0%), $t(15) = 4.18, p = .001, d = 1.02$, and when cues were frequent (2.2%), $t(15) = 3.75, p = .002, d = 0.94$.

The difference between those validity effects failed to be significant ($F < 1$). Finally, the Validity \times Target mixed ANOVA did not return significant results ($F_s < 3.76$).

Discussion

Validity effects by rare nonmatching green cues were eliminated. This supports the hypothesis that the salient green nontarget probably led to a task-set with a suppressive component against green, which attenuated the attention-driving signal arising from expectancy violation. Also, the somewhat surprising validity effects by the frequent nonmatching green cues, which we had observed in Experiment 3, disappeared. Hence, the task-set also allowed to cancel the attention-driving signal arising from salience alone. As in Experiment 3, the matching red cues elicited larger validity effects than the green cues, showing that the target display produced a task-set for red.

General Discussion

Is attentional capture by rare cues impenetrable by the task-set? We conducted four experiments to investigate this question (see Table 1). In Experiments 1 and 2, we asked whether attentional capture by rare onset cues can be modulated by the task-set. In Experiment 1, rare or frequent white onset cues were presented in combination with red feature targets (a red target among one green and two white nontargets; see Figure 1). We found that the rare, but not the frequent onset cues captured attention. Hence, rare onset cues potentially capture attention independently of the task-set.

However, we reasoned that attentional capture by rare onset cues might be penetrable by the task-set, because the task-set in Experiment 1 might not have been optimal to prevent attentional capture by the onset cues. In particular, task-sets might be determined not only by the target properties (Folk & Remington, 1998; Folk et al., 1992), but also by the properties of salient but irrelevant nontargets (e.g., Müller et al., 2009; Zehetleitner et al., 2012). Accordingly, the green nontarget in Experiment 1 only promoted the suppression of green, but not the suppression of the cue properties (i.e., a unique white onset). In Experiment 2, we changed the target display to contain only a single white nontarget. Hence, the nontarget properties were as similar to the properties of the onset cue as possible, thereby promoting the suppression of unique or white elements. In accordance with this expectation, we found that neither rare nor frequent onset cues captured attention.

In Experiment 3, we asked whether rare color singleton cues capture attention against the task-set. Hence, we presented rare or frequent mismatching green singleton cues in combination with red singleton targets (a red target among three white nontargets). The results showed that rare cues captured attention more than frequent cues, suggesting that frequency effects are not limited to onset cues. In Experiment 4, we changed the target display to contain also a green nontarget. Again, attentional capture by the rare nonmatching cues was eliminated. Hence, the salient green nontarget probably led to suppression of green, which allowed to prevent attentional capture by the rare green cues.

In sum, the attention-driving signal from rare onset or color cues can override the task-set. However, the above findings show that this signal can be attenuated by optimized task-sets. One way to

optimize the task-set against the properties of rare, but salient cues is to present nontargets with similar properties. The addition of the salient nontargets in Experiments 2 and 4 probably resulted in task-sets with two components. One component involved the enhancement of the target properties and the second component involved the suppression of the salient nontarget properties. Several theoretical frameworks and empirical findings support such featural suppression mechanisms (Burra & Kerzel, 2013; Gaspar & McDonald, 2014; Gaspelin, Leonard, & Luck, 2017; Navalpakkam & Itti, 2007; Vecera et al., 2014; Zehetleitner et al., 2012). Alternatively, task-sets might comprise only the enhancement of the target properties, and the salient nontargets might simply strengthen this enhancement (featural up-weighting; e.g., Folk & Remington, 2015; Barras & Kerzel, 2016) which is also similar to the idea of a feature search mode (Bacon & Egeth, 1994). Note that both accounts can accommodate the present findings, and that the two accounts might not be mutually exclusive. That is, adding salient nontargets might result in the up-weighting of the target and suppression of the nontarget features.

Finally, even though Experiments 2 and 4 suggest that optimized task-sets can override the influence of the attention-driving signals from nonmatching rare and frequent cues, this might not always be the case. If cues were presented that are more salient than those in the present study, these cues might eventually override the optimized task-sets (e.g., Noesen et al., 2014). Further, it may also be the case that effects of rarity with nonmatching cues depend on the saliency of the stimuli. For target-nonmatching singleton cues, we found stronger capture with rare than with frequent cues, but in our Experiment 3, even frequent cues captured attention, which is unusual. Typically, target-nonmatching singleton cues do not capture attention. Further experiments should investigate rarity effects in situations where frequent cues do not capture attention. We suggest that this may be possible with less salient stimuli.

Which Properties Were Suppressed in Experiment 2 and 4?

Changing the nontarget into a single white element in Experiment 2 reduced attentional capture by rare white onset cues. However, it is unclear whether this manipulation of the nontargets resulted in inhibition of the white stimulus feature and/or the inhibition of abrupt luminance changes. Yet, provided that the target display contained two abrupt luminance changes (for the red and the white letter), luminance changes probably were relatively weakly salient, and were not strongly inhibited. Consequently, we speculate that the presentation of a single white nontarget probably resulted in inhibition of white. Consistent with this interpretation, Goller, Ditye, and Ansorge (2016) showed that the effect of onset cues on onset targets is larger when they have the same color.

In Experiment 3, the red target was presented among three white nontargets. The only change in Experiment 4 was that one nontarget was presented in green. As a result, the same green cues that had produced a frequency effect in Experiment 3 did not capture attention in Experiment 4. Critically, red cues produced frequency effects in both experiments, showing that only the nontarget feature was suppressed. It is an open question whether suppression was limited to the salient nontarget feature (green) or whether suppression spread to other nontarget features (e.g., yellow, blue,

etc.). Further experimentation is required to clarify the extent of the suppressive set.

Why Do Rare Cues Capture Attention More Than Frequent Cues?

Our results show that optimized task-sets overrule the attention-driving signal from rare cues. We have used the general term “attention-driving signal” deliberately because attentional capture by rare cues can be caused by more than just one mechanism (Folk & Remington, 2015). One general hypothesis is that rare cues change the task-set. For instance, rare cues might lead to a task-set for singletons. The present findings did not provide evidence for this hypothesis. Rare cues captured attention more strongly even when the target display did not allow a singleton search mode (Experiment 1 and 4) and even when validity effects were larger with target-matching than nonmatching cues, confirming that the target display led to a task-set for the target color (Experiment 3).

A second way in which rare cues might have changed the task-set is that rare cues might relax the top-down set for the target feature (or the top-down suppression of the cue feature), relative to frequent cues (Folk & Remington, 2015). In the language of feature-weighting models (e.g., Müller et al., 2010; Navalpakkam & Itti, 2007), this means that when the target is red, as for example in Experiment 3, rare green cues might have reduced the weight for red (or increased the weight for green). However, such an account cannot explain why rare target-matching cues captured attention more than frequent target-matching cues. If the rare red cues had reduced the weight for red, rare red cues should have captured attention less than frequent cues, whereas they actually captured attention more. Thus, typical feature map-models of attentional allocation cannot account for this effect because top-down modulation of an elementary feature map is represented by a single weight (e.g., Müller et al., 2010; Navalpakkam & Itti, 2007), whereas the present results call for separate weights depending on cue frequency.

Hence, the question arises whether a feature-weighting account can accommodate the present findings at all. To account for the present findings, one may assume that separate bottom-up weights are assigned to separate feature-specific bottom-up signals. Additionally, separate top-down weights might be assigned to separate feature channels. (These assumptions are in some respects similar to the guided search model, Wolfe, 2007). In Experiment 3, for example, the target was red, which predicts that the weight for the red channel was large, so that the red channel strongly contributed to guidance. Consistent with this prediction, the red cues captured attention more than green cues. Presumably, the bottom-up signal from frequent cues interfered more (i.e., more often) with search on the initial trials of a block (Vecera et al., 2014) than those of rare cues. Therefore, one may propose that effects of cue frequency could be accommodated by reducing the bottom-up weight for frequent cues relative to infrequent cues, which would result in less attentional capture by frequent than rare cues.

However, because the model only allows down-weighting of a feature-unspecific bottom-up signal, it cannot account for the feature-specific suppression effects in the current study. In

Experiment 4, for instance, the salient green nontarget only led to the reduction of the frequency effects by green, but not by red cues. Hence, the model would need to be extended to include not only the weighting of feature-unspecific, but instead of feature-specific bottom-up signals. According to such an account, the salient green nontarget in Experiment 4 might have reduced the bottom-up weight for green, but not for red bottom-up signals, so that frequency effects only occurred for red. Further, the weights in this model correspond to the concept of the task-set in other theoretical frameworks. Therefore, the argument is consistent with the notion that rare cues change the task-set.

Throughout the article, we discuss a hypothesis explaining increased attentional capture with rare cues by an attention-driving signal separate from feature-specific or unspecific weighting. In particular, it may be that rare cues violate implicit expectations about a typical trial, and that this violation leads to a separate attention-driving signal. Because validity effects did not change across lags in the present study, we suggested that the present findings are best accommodated by an account that assumes that the expectation about a typical trial is formed in the beginning of a block of trials, that the trial model does not expect cues in the rare cue conditions, and that this expectation does not change through rare encounters with a cue (Müller et al., 2009).

A further way to explain cue frequency effects is the relaxed temporal task-set account, which is essentially a top-down account of cue-frequency effects.⁴ According to this account, cue frequency changes the width of the time interval in which the task-set is activated. When cues are rare, observers activate the task-set for broad time intervals around target presentation. Conversely, they constrain activation of the task-set to a narrow interval around target presentation when cues are frequent. Moreover, this account assumes that cue-frequency effects only occur for cues that match the top-down set. In Experiment 3, for example, the color singleton targets might have resulted in a combined task-set for red color and singletons in general. When the cues were rare, the task-set was activated more broadly around target presentation time, so that the cues captured more often than frequent cues, irrespective of the cue color. The present study cannot discriminate the weighting account from the expectancy violation account or the relaxed temporal task-set account. Nevertheless, the latter accounts appear to be less parsimonious because they propose additional sources of attention-control signals (expectancy violation signals, temporal attention allocation signals).

Conclusion

The attention-driving signal from rare onset and color cues can outweigh the top-down task-set. However, this signal can be attenuated by optimized task-sets. One way to optimize a task-set is to add a nontarget with the cue-properties to the target display. This manipulation probably leads to a task-set that involves suppression of these nontarget, and, consequently, the cue properties.

⁴ We thank an anonymous reviewer for this suggestion.

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