Abstract

Frequent target stimuli are detected more rapidly than infrequent ones. Here we examined whether the frequency effect reflected durable attentional biases towards frequent target features, and whether the effect was confined to featural properties that defined the target. Participants searched for two specific target colors among distractors of heterogeneous colors and reported the line orientation of the target. The target was more often in one specific feature (e.g., a specific color or a specific orientation) than another in a training phase. This frequency difference was removed or reversed in a testing phase. Experiments 1 and 2 showed that when frequency differences were introduced to the target’s defining feature, participants more rapidly found the high-frequency target than the low-frequency target. However, changes in attention were not durable – the search advantage vanished immediately when the frequency differences were removed. Experiments 3-5 showed that only featural properties that defined the target facilitated search of the more frequent feature. Features that did not define the target, such as the target feature that participants reported, sped up response but did not facilitate search. These data showed that when searching for multiple targets in a feature search task, people selectively and rapidly adapt to the frequency in the target’s defining feature.

Introduction

The occurrence rate of target features is an important determiner of performance in visual search. In target present-absent tasks, participants frequently miss the target if most trials are target-absent trials (Wolfe, Horowitz, Van Wert, Kenner, Place, & Kibbi, 2007; Wolfe, Horowitz, & Kenner, 2005), and they are less accurate in detecting a rarely present target relatively to a more frequently present target (Godwin, Menneer, Cave, Helman, Way, & Donnelly, 2010; Godwin, Menneer, Riggs, Cave, & Donnelly, 2015; Hon & Tan, 2013; Hout, Walenchok, Goldinger, & Wolfe, 2015). More recent work using target identification tasks has extended the target frequency effect to situations in which one of two targets is always present. The more frequent target stimulus is detected more rapidly (Kruijne & Meeter, 2015). These findings firmly establish target frequency as a modulator of attentional priority [footnote1]. In this study, we use an identification task involving two potential targets to investigate two characteristics of the target frequency effect: its durability and selectivity.

The first question that we raise is whether the frequency effect reflects relatively transient or durable changes in attentional priority. On the one hand, frequency differences

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1 In this study, target frequency refers to the occurrence rate of target stimuli in visual search. It should not be confused with word frequency effects in reading.
between target stimuli may yield long-term statistical learning about each target’s probability. On the other hand, a target that occurs more frequently than another also repeats more often across successive trials. This can induce inter-trial priming, an effect that speeds responses for immediate repetitions of a target, but that tends to diminish rapidly over a few trials (Maljkovic & Nakayama, 1994). Previous research has produced mixed results regarding the durability of the target frequency effect. In present/absent tasks with a single target, people are primarily sensitive to the target’s global prevalence across a long block rather than to its local prevalence in a short sequence (Cain, Vul, Clark, & Mitroff, 2012; Ishibashi, Kita, & Wolfe, 2012). This finding suggests that frequency effects may reflect learning of stable target statistics. Findings from two-target identification tasks have also observed long-term effects, particularly in conjunction search. Here, after finding one conjunction search target more often than the other, participants persisted in prioritizing the high-frequency target even after the target frequencies became equal. This finding was shown both when the conjunction search task was difficult and when it was easy. However, in a color singleton search task in which the target was more often one color (e.g., red among green) rather than another (e.g., green among red), the frequency effect dissipated quickly. This was the case even when the singleton search task was difficult (Kruijne & Meeter, 2015).

The findings above raise the question about conditions under which the target frequency effect is durable. Because conjunction search and singleton search differ in many respects, it is important to test other search tasks that close the gap between the two. To this end, this study tests participants in a feature search task in which participants search for a target that can be of two specific colors among distractors of heterogeneous colors and report the orientation of the target. Similar to conjunction search and unlike singleton search, the feature search task requires people to hold the specific target colors in the search template. This should produce episodic memory traces of the specific target features, a condition hypothesized to be important for establishing long-term frequency effects (Kruijne & Meeter, 2015). At the same time, the feature search task involves finding features that are exclusively associated with the target – none of the distractors possess the target features. In this regard it is similar to singleton search and different from conjunction search. The activation of the target feature can prime the same target feature on subsequent trials, without also priming distractor features. This may induce strong short-term repetition effects. Thus, the feature search task provides an important empirical test case for the durability of the target frequency effect.

A second question, that of selectivity, examines what target relationship a feature must possess for its frequency to affect search performance. Previous studies on visual statistical learning have shown that attention or task relevance is not strictly required for learning. For example, in visual search, repeating the spatial configuration formed by distractors produces robust implicit attention learning (Chun & Jiang, 1998). In addition, when a sequence of red and green shapes is presented in predictable orders, instructing participants to attend to a subset of the shapes (e.g., the red ones) does not always preclude learning of the unattended shapes (Musz, Weber, & Thompson-Schill, 2014). These findings raise the possibility that frequency effects are not restricted to relevant target features. At present, however, the role of task relevance has not been addressed in previous work on target frequency effects. The frequency differences people are sensitive to have so far come from the features that define the target. Frequency differences in an incidental feature may facilitate search, yet direct empirical evidence is lacking. Here we examined visual search reaction times as a function of the frequency of occurrence of a finding (target-defining) feature separately from the frequency of occurrence of the reported property. This work informs us whether frequency effects are confined to features relevant to a given stage of the search task.
We conducted five experiments to examine the durability and selectivity of the target frequency effect. Experiments 1 and 2 tested whether frequency differences in the target-defining feature yielded durable or transient changes in search. Subsequent experiments contrasted frequency effects in features that defined the search targets with frequency differences in the features that dictated the response to targets.

**Experiment 1**

Participants in Experiment 1 searched for a color circle that could be either Color1 (e.g., red) or Color2 (e.g., green) among distractors of various other colors. Upon finding the target participants reported the orientation of the line inside the target circle (Figure 1A). Because the display contained circles of heterogeneous colors, the target was not a color singleton and the task could not have been accomplished by adopting a singleton detection mode (Bacon & Egeth, 1994). Instead, participants would have needed to hold the specific target colors in their search template. To test whether frequency effect is durable in this task, we tested participants in a training phase followed by a testing phase. In the training phase the target was Color1 on 75% of the trials and Color2 on 25% of the trials. The frequency effect should manifest as faster search reaction time (RT) for Color1 than Color2. In the subsequent testing phase we presented the two target colors equally frequently (Figure 1B). We examined whether, and for how long, participants continued to prioritize Color1 in the testing phase.

![Figure 1. A: A schematic illustration of the search display used in Experiment 1. Participants searched for a circle defined by its color (e.g., red or green) and reported the orientation of the line inside it. For illustrative purposes, an arrow indicates this trial’s target. B: A diagram of the target’s color frequency in the training and testing phases.](image)

**Method**

**Participants.** Participants in this study were students from the University of Minnesota. They were 18-22 years old, had normal or corrected-to-normal visual acuity, normal color vision, and were naïve to the purpose of the study. Participants were compensated for their time with extra course credit or $10/hour.

Twenty-four participants, 11 females and 13 males with a mean age of 19.2 years, completed Experiment 1.

**Equipment.** Participants were tested individually in a room with normal interior lighting. The experiment was programmed using Psychtoolbox (Brainard, 1997; Pelli, 1997) implemented in MATLAB (www.mathworks.com). Stimuli were presented on a 17” CRT monitor with a resolution of 1024x768 pixels and a refresh rate of 75Hz. Viewing distance was unconstrained but was approximately 40cm.

**Materials and stimuli.** The visual search items were outline circles (size 1.5°x1.5°). Four colors comprised the target set: red, green, yellow, and blue. Two of these were randomly
chosen as the potential target colors for a participant. This assignment was counterbalanced across participants. The distractor set was comprised of the two colors not chosen to be the target colors, along with 8 other colors generated using MATLAB’s maximally distinguishable colors script (http://www.mathworks.com/matlabcentral/fileexchange/29702-generate-maximally-perceptually-distinct-colors/content/distinguishable_colors.m). Inside each circle was a white line (length 1º) oriented either vertically or horizontally (Figure 1A). All items were displayed against a black background.

Procedure. Participants were told that each trial would contain one of two potential targets, such as a red or a green circle. They underwent 24 trials of practice, during which the two targets occurred equally often. The experiment proceeded after participants had acquired this initial familiarity with the target colors.

Each trial started with a white fixation point (0.5ºx0.5º). After a random duration of 400 to 600ms, the search display appeared consisting of six colored circles positioned at equidistant locations on an imaginary circle centered at fixation at an eccentricity of 5º. Each colored circle enclosed a line segment (horizontal or vertical, randomly chosen). Each circle on a given display had a unique color. The single target was the circle in one of the two pre-specified target colors. Participants were asked to press ‘v’ if the line inside the target was vertical, or the spacebar if the line inside the target was horizontal. The search display remained in view until participants responded.

We emphasized accuracy and speed in the task instructions and in the trial feedback. Each incorrect response was followed by the computer voice speaking the sentence “That was wrong. Please try to be accurate.” Correct trials were followed by a chirp or the text “too slow” if RT was slower than 1,000ms. The next trial commenced after 1,000ms. Participants were encouraged to take a break every 48 trials. They completed 16 blocks, with 48 trials per block.

Design. The first 8 blocks constituted the training phase, during which the target appeared in one color 75% of the time (“Color1”) and the other 25% of the time (“Color2”). The last 8 blocks constituted the testing phase, during which the two targets appeared equally often (50%). We did not inform participants of the underlying target frequency.

Recognition. To examine the association between explicit awareness of the differing target frequencies and the search advantage for the more frequent target, we first asked participants whether or not the two targets appeared equally often. Participants were then asked to estimate the percentage of trials in which one target color appeared, and the percentage of trials in which the other target color appeared. Because the target frequency differed between the training and testing phases, recognition questions first asked about Blocks 1-8, then Blocks 9-16.

Results

Table 1. Percent correct in all experiments, separately for the training and testing phases. Target 1 was the high-frequency target feature in the training phase. Standard error of the mean is shown in parentheses. ns not significant; *p < .05; **p < .01; ***p < .001 when comparing Target 1 with Target 2.

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<td>Experiment 4a</td>
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Accuracy, displayed in Table 1, showed no evidence of a speed-accuracy tradeoff. This was also the case in subsequent experiments (i.e., there was either no difference in accuracy between the two targets, or that the difference in accuracy was in the same direction as the difference in RT). Throughout the paper we report the mean RT from correct trials.

(1) Training phase (Blocks 1-8)

A two-factor repeated-measures analysis of variance (ANOVA) on target frequency (high- vs. low-frequency target) and training block (Blocks 1-8) revealed a significant main effect of target frequency in the training phase. Participants were significantly faster responding to the high-frequency target than to the low-frequency target (Figure 2A), $F(1, 23) = 11.66, p < .01, \eta^2 = .34$. In addition, the main effect of block was significant. RT was faster in later blocks than earlier ones, $F(7, 161) = 12.91, p < .001, \eta^2 = .36$. Target frequency did not interact with training block, $F(7, 161) = 1.89, p > .10$. A follow-up test showed that even in the first training block, Color1 was found more quickly than Color2, $t(23) = 2.76, p < .05$.

Even though the frequency effect occurred early and was statistically strong, it was not strongly related to participants’ explicit awareness about the experimental manipulation. As shown in Appendix A, explicit recognition test showed no clear association between the participants’ awareness of the targets’ frequency and the RT advantage for Color1.

(2) Testing phase (Blocks 9-16)

The RT advantage for Color1 quickly dissipated in the testing phase. A repeated-measures ANOVA on target frequency (previously high vs. low) and testing block (Blocks 9-16) revealed no main effects of the targets’ previous frequency, $F < 1$, or testing block, $F(7, 161) = 1.05, p > .39$. These two factors did not significantly interact, $F(7, 161) = 1.39, p > .20$.

We divided the first testing block (Block 9) into four mini-blocks, with 12 trials in each mini-block. Figure 2B shows RT across the four mini-blocks. The RT advantage for Color1, the
previously high-frequency target, was no longer statistically significant in the first mini-block. An ANOVA on target frequency (previously high vs. low) and mini-block (1-4) showed that the main effect of targets’ previous frequency was not significant, $F < 1$, neither did it interact with mini-block, $F < 1$.

Discussion

Even though the target was more frequently in Color1 than in Color2 in the training phase, participants did not show evidence of a durable attentional priority for Color1. Shortly after the two target colors became equally frequent, the RT advantage for the previously high-frequency color dissipated. This pattern of results was observed previously when participants performed a color singleton search task (Kruijne & Meeter, 2015). Unlike this previous study, in our study participants could not accomplish the search task by searching for a feature singleton. Instead, they had to keep the two potential targets in their search template to find the target. This task demand should have yielded episodic traces for the two target colors. The lack of durable changes in attention suggests that searching for specific features with unequal frequencies is, in itself, insufficient for inducing long-term attentional biases. The lack of durable changes in featural attention contrasts with frequency effects in spatial attention. Frequently finding a target in some locations induces long-term changes in visuospatial attention (Jiang, Sha, & Remington, 2015; Jiang, Swallow, Rosenbaum, & Herzig, 2013). However, frequently finding a target in a specific color fails to yield durable changes in featural attention. This finding merits a conceptual replication in the next experiment.

Experiment 2

A strong test for long-term learning is the primacy effect previously documented for several types of statistical learning. After participants acquire learning of one nonrandom statistical structure (e.g., an artificial grammar, a sequence of objects), the earlier learning interferes with learning of a new statistical structure. Primacy effects can interfere with new learning even after several hundred trials (Gebhart, Aslin, & Newport, 2009; Jiang, et al., 2013; Yu & Zhao, 2015). In fact, the frequency effect in conjunction search was present after a one-week delay (Kruijne & Meeter, 2016). Here we examine whether a learned target frequency effect interferes with learning of reversed target’s frequencies. To this end, we first trained participants in a condition in which targets occurred in one color more frequently than the other color. After 8 blocks of training, we reversed the frequency of the two target colors.

Method

Participants. Twenty-four new participants, 19 females and 5 males with a mean age of 19.6 years, completed Experiment 2.

Design. In the first 8 blocks (training phase) one of the two target colors appeared on 75% of the trials (“Color1”) and the other target color appeared on 25% of the trials (“Color2”). In the last 8 blocks (testing phase) the targets’ frequencies reversed, such that the previously high-frequency target color now appeared on 25% of the trials and the previously low-frequency target color now appeared on 75% of the trials. Other aspects of the experiment were the same as in Experiment 1.

Results
(1) Training phase (Blocks 1-8)

A repeated-measure ANOVA on target frequency and training block (Figure 3A) showed a significant main effect of target frequency. Participants were significantly faster responding to targets associated with Color1 than Color2 in the training phase, $F(1, 23) = 20.52$, $p < .001$, $\eta^2 = .48$. The main effect of training block was also significant, RT became faster in later blocks than earlier ones, $F(7, 161) = 10.43$, $p < .001$, $\eta^2 = .31$. The RT advantage for Color1 became smaller with training, resulting in a significant interaction between target frequency and block, $F(7, 161) = 2.38$, $p < .05$, $\eta^2 = .09$.

(2) Testing phase (Blocks 9-16)

The frequencies of the two targets were reversed in Blocks 9-16 (Figure 3A). An ANOVA on target frequency and testing block showed a significant main effect of target frequency. Here, participants were significantly faster responding to targets associated with Color2 than Color1, $F(1, 23) = 10.19$, $p < .01$, $\eta^2 = .31$. RT became faster in later testing blocks than earlier ones, yielding a significant main effect of testing block, $F(7, 161) = 2.82$, $p < .01$, $\eta^2 = .11$. Similar to the training phase, the RT advantage for Color2 became smaller as testing progressed, resulting in a significant interaction between target frequency and block (9-16), $F(7, 161) = 2.85$, $p < .01$, $\eta^2 = .11$.

An examination of the first reversal block – Block 9 – showed that the target frequency effect reversed immediately in Block 9. A paired $t$-test comparing Color1 and Color2 showed that RT was significantly faster for Color2 than Color1 in Block 9, $t(23) = 3.57$, $p < .01$. This pattern was a reversal of the immediately preceding block – Block 8. An ANOVA on block (8 vs. 9) and target color (Color1 or Color2) revealed a significant interaction between target color and block (Blocks 8 or 9), $F(1, 23) = 24.52$, $p < .001$, $\eta^2 = .52$. The RT advantage of Color2 over Color1 in the first testing block (Block 9) was comparable in magnitude (mean = 66ms) to the RT advantage of Color1 over Color2 in the last training block (Block 8; mean = 43ms), $t < 1$.

Figure 3B displays data from Block 9 divided into 4 mini-blocks of 12 trials each. An ANOVA on target frequency and mini-block showed a significant main effect of target frequency: participants responded significantly more quickly to targets associated with Color2 than Color1, $F(1, 23) = 10.88$, $p < .01$, $\eta^2 = .32$. This effect did not interact with mini-block, $F < 1$. 

Figure 3. Results from Experiment 2. A: Data from all blocks. B: Data from Block #9, the first reversal block, divided into 4 mini-blocks of 12 trials each. Error bars represent ±1 within-subject S.E. of the RT difference between the two targets.
A follow-up test showed that RT was significantly faster for Color2 than Color1 in the first mini-block, $t(23) = 2.39, p < .05$, Thus, the reversal of the frequency effect occurred quickly.

Discussion

The first two experiments showed that participants were faster finding the target that occurred more frequently. These data provide an important empirical test for the durability of the target frequency effect. They help understand previous findings from singleton search and conjunction search tasks (Kruijne & Meeter, 2015). Our finding is similar to results from singleton search – the more frequent target was found more quickly in the training phase, but the effect diminished when the frequency difference were removed. This finding differs from previous conjunction search results, which showed durable changes in attention. Although both singleton search and our color search task involve feature search, these two tasks differ in the type of search mode participants can adopt. Singleton search can be accomplished by searching for a unique stimulus without specifying its specific features. In contrast, our task required participants to search for specific colors, which should have produced episodic memory traces of the two target colors. Findings from our task suggest that episodic traces of target features are not sufficient for inducing long-term changes in attention.

The lack of durable changes in the testing phase, along with the strong frequency effect in the training phase, implies that short-term inter-trial priming underlies the target frequency effect observed here and elsewhere (e.g., Kruijne & Meeter, 2015). During the training phase, the high-frequency target color repeats nine times more often across successive trials than the low-frequency color. According to the well-known inter-trial priming effect (Kristjánsson & Campana, 2010; Maljkovic & Nakayama, 1994; Tower-Richardi, Leber, & Golomb, 2016), the high-frequency target color should be detected more quickly. In fact, when we analyzed the training phase of Experiments 1 and 2 by classifying each trial as either a repeat (i.e., its target was the same as the preceding trial’s target) or a nonrepeat, we found that RT was approximately 40ms faster on repeat trials than nonrepeat trials, $F(1, 47) = 43.83, p < .001, \eta_p^2 = .48$. This effect – 38ms for the high-frequency color and 41ms for the low-frequency color – did not interact with target’s color frequency, $F(1, 47) = 1.79, p > .18$. Note that this calculation only included repetition effects from the preceding (N-1) trial. When we considered cumulative repetition effects from the most recent 8 trials, as was done in Appendix B, the difference in repetition priming between the high- and low- frequency target colors was comparable to the observed RT difference.

It is important to note that episodic traces, such as those established through searching for specific features, can support inter-trial repetition priming. Previous studies showed that inter-trial priming was stronger when the repeated target (e.g., a red target) yielded the same response (e.g., a “left” response corresponding to a left tilted target) than when it yielded a different response (Hillstrom, 2000; Huang, Holcombe, & Pashler, 2004; Lamy, Yashar, & Ruderman, 2010). These findings support the idea that inter-trial priming is computed on the basis of the entire target episode, not just the target’s defining feature (Hommel, 1998). These episodic traces produce short-term priming, and only sometimes, long-term changes in attention.

Experiment 3

We now turn to the question of selectivity and task relevance in producing the target frequency effects observed in the training phase. According to most theories, features comprising an object are represented initially as independent elements in separate systems before being bound into a unitary object. So far we have shown that frequency differences in
search targets facilitate search for the more frequent target. But is the frequency effect occasioned by repetition of independent features of a target or the bound object? Support for the possibility that it acts on the bound object comes from the finding that both visual attention and visual working memory retain multiple features of a single object as a unit (Duncan, 1984; Luck & Vogel, 1997). In addition, inter-trial priming often reflects the interaction between priming of the target’s defining feature and its response feature (Hillstrom, 2000; Huang et al., 2004; Lamy et al., 2010). If the frequency effect results from repetition of the bound object, then frequency differences in a feature irrelevant to finding the target should nonetheless facilitate search. Alternatively, owing to the severe capacity limits in retaining information in the target template, it is possible that visual search is sensitive to just the frequency of the target-defining features.

To examine frequency effects for various target features, Experiment 3 used the design of the first two experiments, but modified the search stimuli by combining color and orientation into a single coherent object – colored lines. In Experiment 3a, we varied the frequency of the target’s defining features to determine if the frequency effect for color seen in the previous two experiments would be obtained with the new stimuli. In Experiment 3b, we generalize the frequency effect to orientation search. Experiments 3a and 3b set up the stage for Experiment 4, which investigated frequency effects in features that did not define the targets.

Method

Participants. Twenty-four new participants completed Experiment 3, half of them in Experiment 3a (8 females and 4 males, mean age 19.3 years) and the other half in Experiment 3b (4 females and 8 males, mean age 20.2 years).

Stimuli and materials. Each display contained 6 colored lines presented at equidistant locations on an imaginary circle (Figure 4 insets). There were 1 target and 5 distractors. The eccentricity of each item was 5º. The length of each line was randomly chosen to be either 1º or 2º.

In Experiment 3a (Figure 4A inset), all the lines were either vertical or horizontal, determined randomly. Their colors were drawn from a set of 10 possible colors in the same manner as in Experiments 1-2.

In Experiment 3b (Figure 4B inset), all the lines were either red or green, determined randomly. Five of the items, the distractors, were tilted 45º either clockwise or counterclockwise. The remaining item, the target, was either horizontal or vertical.

Procedure. Each trial started with a fixation point. After a random delay of 400-600ms the search display of 6 items was presented until participants made a response.

In Experiment 3a, participants searched for a target defined by its color. It could be either Color1 (e.g., red) or Color2 (e.g., green). Upon finding the target, participants reported the target’s orientation by pressing “v” for vertical or the spacebar for horizontal. In Experiment 3b, participants searched for a target defined by its orientation. It could be either vertical or horizontal. Participants reported the target’s color by pressing ‘r’ for red or ‘g’ for green.

Design. The experiment consisted of 16 blocks (48 trials per block). The first 12 blocks were the training phase. During this phase we introduced a frequency difference to the target’s defining feature. In Experiment 3a, in which participants searched for a color target, the target was more likely to be Color1 (75% of the trials) than Color2 (25% of the trials). In Experiment 3b, in which participants searched for an orientation target, the target was more likely to be orientation1 (e.g., vertical, 75% of the trials) than orientation2 (e.g., horizontal, 25% of the trials). The last 4 blocks were the testing phase, during which the target was equally likely to be Color1 or Color2 (Experiment 3a) or Orientation1 or Orientation2 (Experiment 3b).
Results and Discussion

Figure 4. Results from Experiment 3. A. Data from the color search task of Experiment 3a. B. Data from the orientation search task of Experiment 3b. Error bars represent ±1 within-subject S.E. of the RT difference between the two targets. The insets illustrate sample search displays for the color search (Figure 4A) and the orientation search (Figure 4B) tasks.

(1) Training phase (Blocks 1-12)

Replicating Experiments 1 and 2, Experiment 3a showed that when searching for a target defined by color, participants were faster finding the high-frequency color than the low-frequency color. An ANOVA on target frequency and training block (1-12) revealed a significant main effect of target frequency, $F(1, 11) = 15.44, p < .01, \eta^2_p = .58$. This effect did not interact with block, $F < 1$ (Figure 4A).

Experiment 3b extended the target frequency effect to an orientation search task. When searching for a target defined by orientation, participants found the high-frequency orientation faster than the low-frequency orientation. An ANOVA on target frequency and training block (1-12) showed a significant main effect of target frequency, $F(1, 11) = 6.86, p < .05, \eta^2_p = .38$. This effect did not interact with block, $F < 1$ (Figure 4B).

In both versions of the experiment we observed a significant main effect of block, $ps < .05$.

(2) Testing phase (Blocks 13-16)

Even though participants took part in a longer training phase in Experiment 3 than in the first two experiments, their learning did not persist in the testing phase. An ANOVA on target frequency and testing block (13-16) showed no significant main effect of target frequency in the testing phase, $F < 1$ in Experiment 3a, $F(1, 11) = 2.61, p > .10$ in Experiment 3b.

Experiment 3 replicated and extended the findings from the first two experiments. We revealed frequency effects for the features that defined the target, be it color (Experiment 3a) or orientation (Experiment 3b).

Experiment 4

This experiment examined effects of frequency variations in a feature that did not define the search target. Participants searched for a target defined by one property (e.g., color) and
reported another property (e.g., orientation). We exerted a frequency manipulation on the target’s reported feature. For example, participants in Experiment 4a searched for a color target that could be either red or green and reported its orientation. Although the target was equally likely to be red and green, its orientation was not random. The target was three-times more likely to be vertical than horizontal. The frequency differences may contribute to visual search because participants accumulate evidence from all features in parallel in an initial “pre-attentive” stage (Treisman, 1988; Wolfe, 2007). Alternatively, the limited capacity for the target template may lead participants to use just the target defining features, in this case, color. If this is the case, then a frequency difference in the target’s reported feature should influence how people search. Experiment 4b used an analogous design but switched the roles of color and orientation.

Because the motor response was tied to the reported feature, repetition of stimulus-response mappings could produce overall RT benefits. In earlier experiments the response that participants made after finding the target was unrelated to the target’s frequency. For example, though the target was more often red than green, the response to the target (pressing the “v” key or the spacebar) was random. Therefore, frequency unambiguously affected search rather than post-search processes. In contrast, in Experiment 4a, the reported feature may be more often vertical than horizontal, leading to more frequent responses of the “v” key than the spacebar. A faster response to the high-frequency feature (e.g., vertical) may reflect one of two processes: faster search for vertical stimuli or faster response after the target was found.

To dissociate the frequency effect on search from that on post-search responses, Experiment 4 had participants make two responses on each trial. Regardless of what the target was, participants pressed the spacebar as soon as they found it. This first response terminated the display and replaced it with a visual mask. Participants then made a second response to report the target’s orientation (Experiment 4a) or color (Experiment 4b). Figure 5 shows a schematic illustration of the trial sequence used in Experiment 4a.

Because the first response (RT1) was unrelated to what the target was, in an ideal situation RT1 can serve as a proxy for the time it took participants to find the target. The second response involved mapping the target onto a motor response. Its RT is an index of the post-search response process. In reality participants may sometimes wait until a response decision is made before making the first response. In this scenario response processes can contaminate RT1. Thus, the presence of a frequency effect in RT1 may be attributed to search or post-search processes. The absence of a frequency effect in RT1, however, would suggest that search is relatively insensitive to frequency differences in a non-defining feature.

Method

Participants. Twenty-four new participants completed Experiment 4. There were 12 participants (5 females and 7 males, mean age 20.8 years) in Experiment 4a, and 12 participants (7 females and 5 males, mean age 19.9 years) in Experiment 4b.

Procedure. Experiment 4a was similar to Experiment 3a. Participants searched for a target defined by its color (Color1 or Color2; Figure 4A). They were asked to press the spacebar immediately as they detected the target. This response terminated the search display, replacing it with a mask. Participants then pressed one of two keys to report whether the target was vertical or horizontal. The mask consisted of 6 colored grid patches in the same locations as the search items (Figure 5).

Experiment 4b was similar to Experiment 3b. Participants searched for a target defined by its orientation (vertical or horizontal; Figure 4B). They pressed the spacebar immediately when they detected the target. This response replaced the search items with colored masks. Participants then pressed one of two keys to report whether the target was red or green.
To reduce the likelihood that participants would withhold RT1 until after they had mapped the stimulus onto a motor response, we gave them feedback about their speed of response. When a trial’s RT1 was slower than 700ms participants saw the words “too slow” on the display after they made both responses. A chirp followed correct responses within 700ms. All correct trials, including those with RT1 longer than 700, were included in the RT analysis.

**Design.** In both Experiment 4a and 4b the target’s defining features were random. The target was equally likely to be Color1 or Color2 in Experiment 4a (50% of trials each), and equally likely to be vertical or horizontal in Experiment 4b. However, the target’s reported features were not random. In the training phase (Blocks 1-12), the target was more likely to be one orientation (e.g., vertical, 75%) than the other in Experiment 4a, and more likely to be one color (e.g., red, 75%) than the other in Experiment 4b. In the testing phase (Blocks 13-16), both the target’s defining features and reported features were randomly assigned.

**Results**

Each trial yields two RTs. The first response (RT1) corresponded roughly to search time, the second (RT2) to post-search response processes.

(1) RT1: Training and testing phases (Figure 6)

In Experiment 4a participants searched for a target defined by color, but the target was more likely in one orientation than the other during the training phase. A repeated-measures ANOVA on search RT in Experiment 4a with factors of target orientation and block was carried out separately for the training phase and the testing phase. It showed that the frequency of reported features did not significantly influence RT1. The main effect of feature frequency was not significant in either the training phase, $F(1, 11) = 4.36, p > .06$, or the testing phase, $F < 1$. A similar ANOVA on Experiment 4b also failed to find an effect of the frequency of the reported feature on RT1 in either the training phase, $F < 1$, or the testing phase, $F < 1$. 

![Figure 5. A schematic illustration of the trial sequence used in Experiment 4a. Participants pressed the spacebar upon detecting the target. RT1 was recorded as the time between display onset and spacebar response. The search display was then replaced by a mask until participants made an identification response. RT2 was the time from mask onset to the identification response.](image)
These results showed that the time taken to find the target was relatively insensitive to the frequency of the target’s reported feature.

(2) RT2: Training and testing phases (Figure 7)

RT2 was made after the target had been found, reflecting the time it took participants to map the percept onto the response and execute the response.

In Experiment 4a’s training phase, the target was more often in one orientation than the other, leading to a higher proportion of one button press than the other. Even though the search time (RT1) was insensitive to this manipulation, a two-factor ANOVA on target orientation and block (Blocks 1-12) showed that the post-search response time (RT2) was significantly faster for the high-frequency orientation, $F(1, 11) = 10.74, p <.01, \eta^2 = .49$. A similar ANOVA on the testing phase data (Blocks 13-16) showed that this effect diminished when the two responses...
became equally often. The main effect of feature frequency was not significant, $F(1, 11) = 2.00$, $p > .18$.

Similarly, in Experiment 4b, the more frequent reported feature (and response) facilitated RT2 in the training phase, $F(1, 11) = 4.77, p < .05$, $\eta^2_p = .30$ for the main effect of feature frequency in an ANOVA with frequency and training block as factors. This effect also diminished in the testing phase, $F < 1$ for the main effect of feature frequency in the testing phase.

**Discussion**

Experiments 3 and 4 showed that frequency effects on search time were largely limited to frequency differences in the target’s defining feature. In a color search task, frequency differences in color influenced search but frequency differences in orientation did not. The reverse is true in an orientation search task. Such feature-level selectivity occurred even though participants had to respond to the target’s reported feature and therefore must have attended to it. These data showed that attending to a feature during some moments of the search task was insufficient for a generalized frequency effect. Frequency differences in the target’s defining feature, a property diagnostic for search, influenced search RT. But frequency differences in the target’s reported feature, a property not diagnostic for search, did not influence search RT. Instead, it facilitated post-search response processes. Frequency effects are not object-based. They operate at the feature level, influencing performance during the task-relevant stage of processing.

**Experiment 5**

Experiment 5 was conducted to address a methodological concern about the two-response procedure used in Experiment 4. Specifically, we would like to rule out the possibility that participants simply developed a habit of pressing the spacebar after a regular interval, producing RT1 that was insensitive to any experimental manipulation. In the absence of “catch trials” (trials without a target), a habit of rapidly making the first response could be developed. To validate the two-response procedure for isolating effects of attention on search from that on response, we conducted Experiment 5 using the two-response procedure. However, we manipulated the frequency of the target’s defining feature, which should influence search time but not post-search decision or response time. If RT1 always reflects a habit of pressing the spacebar, then we should see no difference in RT1 between high- and low- frequency targets, and that frequency effects should appear only in RT2 as in Experiment 4. However, if the two-response procedure was valid for isolating the frequency effect on search from that on response, RT1 but not RT2 should be faster for the high-frequency target than the low-frequency target.

**Method**

**Participants.** Twelve participants (eight females) with a mean age of 19.9 years, completed Experiment 5.

**Design.** Experiment 5 was the same as Experiment 3a except that we used the two-response procedure that broke down RT into two segments. Participants searched for a target that could be either Color1 or Color2. They were asked to press the spacebar as soon as they detected the target. A visual mask then replaced the display, and participants entered the response about the target’s orientation. In the training phase (Blocks 1-12), the target was more likely to be Color1 (e.g., red, 75%) than Color2 (e.g., green, 25%). In the testing phase (Blocks 13-16), the two target colors appeared with equal frequencies. The orientation of the target was always random.
Results

(1) RT1: Training and testing phases (Figure 8A)

In Experiment 5 participants searched for a target defined by color, and the target was more likely associated with Color1 than Color2 during the training phase. A two-factor ANOVA on target frequency and training block showed a significant main effect of target frequency on RT1. RT1 was faster for the more frequent target color than the less frequent target color, $F(1, 11) = 4.76, p = .05, \eta^2 = .30$. Similar to the first three experiments, the frequency effect on the target’s defining feature disappeared in the testing phase, $F < 1$ for the main effect of target frequency.

(2) RT2: Training and testing phases (Figure 8B)

A two-way ANOVA on target frequency and block, separately for the training and testing phase, did not show significant main effects of target frequency, $F(1, 11) = 2.47, p > .10$ in the training phase, and $F < 1$ in the testing phase.

Discussion

Frequency differences in the target’s defining feature significantly influenced RT1 but not RT2 in the two-response procedure. This finding validated the two-response procedure in indexing the frequency effect on search. Together with Experiment 4, these results indicate that frequency effects on the target’s defining feature manifest at the search level, but frequency effects on the target’s reported feature affect post-search decision and response.

General Discussion

Many studies on visual search focus on our inability to attend to multiple (external) visual objects at a time. Yet even more limited is our ability to maintain multiple (internal) target templates in mind (Menneer, Cave, & Donnelly, 2009; Olivers et al., 2011; Stroud et al., 2012; Wolfe, 2012). Here we revealed two mechanisms that allowed people to cope with capacity limitations. First, participants were faster finding the more frequently occurring target (target frequency effect). Second, they selectively represent task-relevant features of the target, namely, the target defining features (relevance). Furthermore, our study demonstrates that...
frequency effects are highly adaptive to recent search history. Large and stable frequency differences over several hundred trials left just a transient search advantage for the high-frequency target. The advantage diminished or reversed as soon as the frequencies of the two targets changed.

Stable visual statistics often induce long-term learning that persists after several days of delay (Anderson & Yantis, 2013; Chun & Jiang, 2003; Jiang et al., 2013; Lin et al., 2016), interferes with new learning (Gebhart et al., 2009; Jungé, Scholl, & Chun, 2007; Yu & Zhao, 2015), and requires several hundred trials to extinguish (Jiang et al., 2013). In contrast, the frequency of the target-defining feature in our experiments showed no long-term component even though one target feature was more frequent than the other over several hundred trials. Instead, nearly all findings in our experiments can be attributed to short-term trial sequence effects. For example, inter-trial priming has been shown to be strongest on the most recent trial and diminishes rapidly over 5-8 trials (Maljkovic & Nakayama, 1994). It can explain why the frequency effect emerged so rapidly during training and why it rapidly diminished or reversed during testing. In fact, the estimated repetition priming effects yielded from 8 preceding trials can account for the observed RT difference between the high- and low-frequency targets (Appendix B).

Given that frequent events tend to repeat more often (Walthew & Gilchrist, 2006), it is not surprising that short-term inter-trial priming effects are revealed in our study. Yet our study departs from the inter-trial priming work in its experimental manipulation. Rather than randomly intermixing the two possible targets and measuring the impact of accidental repetitions, we presented one target more frequently than the other. Our manipulation made it possible to observe long-term prioritization for the high-frequency target. In fact, a previous study using a similar experimental design found that the preference for the more frequent target persisted in a neutral phase administered after a one-week delay (Kruijne & Meeter, 2016). In addition, a seemingly analogous manipulation in the spatial domain yielded a persisting attentional bias towards locations that frequently contained a target (Jiang et al., 2013). What determines whether differences in the frequencies of target-relevant features produce only short-term effects or more durable effects?

One possibility relates to the nature of search. Kruijne and Meeter (2015) proposed that when people searched for specific features, such as in conjunction search, strong episodic memory was laid down for the target’s defining features. This in turn yielded durable changes in attentional priority. However, when search could be accomplished through a singleton detection mode (such as in oddball search tasks), the specific target features were not actively used for search, precluding long-term attentional biases towards the more frequent target feature. However, this account fails to explain why, in our study, searching for two specific target features did not induce durable changes in attention.

Our findings narrowed down possible conditions for durable rather than short-term changes of attention. One potential difference between Kruijne and Meeter (2015)’s conjunction search, which yielded durable changes in attention, and our task was whether features uniquely signal targets. In Kruijne and Meeter’s task, participants searched for a red diamond or a green diamond presented among distractors consisting of squares, triangles and circles in red, green, or blue. The target feature – red or green – did not uniquely signal the target because it could also appear as distractors. When one target (e.g., red diamond) was more frequent than the other (e.g., green diamond), this manipulation not only increased the featural occurrence of (say) a red target, but may have also increased the probability of red being coincided with a target (rather than a distractor). In contrast, in our task the two target colors never appeared as distractors. Both features, including the less frequent one, were maximally informative of being a target. On this account, durable changes of attention may depend on learning a feature’s value.
in signaling targets rather than distractors. Future studies are needed to directly test this possibility.

The current study may seem to be inconsistent with previous findings on the target prevalence effect. Studies using target present-absent tasks and manipulating the overall probability of target-present trials have shown that performance was influenced primarily by the overall (global) prevalence rate across a block (e.g., several hundred trials), rather than by local prevalence accumulated in the last several trials (Cain, et al., 2012; Ishibashi, et al., 2012). Notably, however, studies that examined the role of global/local target prevalence did not include multiple targets with different frequencies of occurrence. Rather, they manipulated the present (versus absent) rates of one category of targets. Therefore, they did not directly address how people learn to prioritize one target (the more frequency target) over another. Furthermore, because the present/absent task involves complex decision processes regarding when to abandon search (Chun & Wolfe, 1996), it is possible that sensitivity to the target’s global prevalence originates from the sluggish nature of decision, rather than a change in attention.

Our study also helps characterize the selectivity of the target frequency effect. Differences in the target’s defining feature induced a much stronger frequency effect than did similar differences in the reported feature, consistent with some studies on visual statistical learning (Jiang & Chun, 2001; Turk-Browne, Jungé, & Scholl, 2005). Going beyond previous findings, our data showed that task relevance, rather than attention, affected the target frequency effect. The target’s reported feature was attended when participants made a response, but such attention did not affect the next trial’s search. It appears that only information relevant to a given stage of computation is incorporated during that stage. The target’s defining feature is used during search, while its reported feature becomes relevant after the target is found and affects post-search processes. This finding is reminiscent of previous research on feature-selectivity in spatial cuing (Remington & Folk, 2001). More broadly, our finding fits with studies demonstrating that selection is often feature-based (Corbetta, Miezin, Dobmeyer, Shulman, & Petersen, 1991; Lu & Itti, 2005; Rossi & Paradiso, 1995).

The transient nature of learning shown in our study does not preclude the possibility that under other circumstances the target frequency effect may be persistent. In addition to Kruijne and Meeter’s conjunction search (2015), greater experience with one target than the other may produce perceptual learning, enhancing perceptual sensitivity to the high-frequency target. Our study used high-threshold stimuli in a task where the main constraints are in attention rather than in perception. It is possible that persistent learning effects may emerge in near-threshold conditions with few or no distractors. In addition, long-term attentional biases towards high-frequency targets may occur in search that requires activated long-term memory of the target set, such as in hybrid search (Schneider & Shiffrin, 1977). Much like the present task, participants in hybrid tasks search for several potential targets on a display. However, the number of potential targets is typically very large, exceeding what can possibly be held in working memory. The need to retain potential targets in long-term memory opens the possibility that frequency differences can induce durable attentional changes. Future studies should further explore conditions on which target frequency differences yield long-term rather than short-term changes in attention.

**Appendix A. Explicit recognition of the targets’ frequency**

Participants were classified into “aware” and “unaware” groups. The “aware” group included participants who stated that the target was more likely in one feature than the other, and went on to correctly identify the high-frequency feature. The “unaware” participants were
those who stated that the two features were equally probable, or those who mistakenly chose the low-frequency feature as the more probable one.

The “aware” group constituted 35% of the participants in Experiment 1. When this factor was included in the RT analysis, we found that awareness did not significantly interact with target frequency, $F(1, 21) = 1.21, p > .28$.

The “aware” group constituted 54% of the participants for Blocks 1-8 and 50% for Blocks 9-16 in Experiment 2. Awareness again did not interact with target frequency in Blocks 1-8 or Blocks 9-16, $F_s < 1$.

The “aware” group constituted 58% of the participants in Experiment 3. Awareness did not interact with target frequency in either the training phase or the testing phase, $F_s < 1$.

Aggregated across Experiments 1-3’s training phase, the target frequency effect was 105ms in the aware participants (N=35), and 73ms in the unaware participants (N=37), a difference that was not significant, $t(70) = 1.11, p > .27$.

The “aware” group constituted 100% of the participants in Experiment 4 and 92% of the participants in Experiment 5. This suggests that frequency differences in the target’s reported feature and the target’s defining feature were highly salient. Nonetheless, no long-term change was observed in either RT1 or RT2.

Recognition tests suggest that the frequency effects were largely implicit. This finding does not preclude the possibility that top-down control can further enhance the frequency effect. In one previous study, Müller, Heller, & Ziegler (1995) gave participants explicit knowledge about the frequencies of three potential targets, all of which differed from the distractors in a single feature. Participants were able to use this information to facilitate search for the high-frequency target. Our study shows that explicit instructions may not be necessary to enhance search. This is consistent with Hasher and Zacks (1984)’s characterization of the frequency effect as automatic.

### Appendix B. Repetition analysis across 8 preceding trials in Experiments 1 and 2

Previous studies showed that inter-trial repetition priming diminished over 8 trials (Maljkovic & Nakayama, 1994). Here we tested whether the cumulative repetition priming from the preceding 8 trials could account for the RT difference between the high- and low-frequency targets.

To do this, it is necessary to estimate repetition priming when the target on trial N matches or mismatches the target on trial $N+j$, where $j$ ranges from 1-8 (Step 1). Ideally the estimation should come from an experiment that decouples frequency from repetition. To this end, we obtained data from 24 new participants in the same task used in Experiment 1, except that the two targets occurred equally often (50%). This experiment allowed us to estimate repetition effects in the absence of frequency differences between the two targets. We then computed the RT on trials $N+j$ (where $j$ ranges from 1-8), as a function of whether the target on trial $N+j$ was the same or different from that on trial N. Repetition priming was the RT difference between the mismatch trials and the match trials. As show in Figure Appendix B1, a match on the next trial ($N+1$) was associated with a 45ms facilitation in RT, a match two trials later ($N+2$) a 17ms facilitation, a match three trials later ($N+3$) a 10ms facilitation, and so on. These values are comparable to previous findings (Maljkovic & Nakayama, 1994). They can be modeled by a power function. The goodness of fit, as assessed by the adjusted $R^2$, was 0.96.

$$45.05 \times j^{-1.473}$$

Next we applied the repetition priming estimates from the power function to the actual trial sequence participants experienced in Experiments 1 and 2 (Step 2). For example, suppose participants experienced a 12-trial sequence with the following targets: $rrrrgggrrrrr$, where red
(r) appears 9 times and green (g) 3 times. On the first trial, the first red, priming would be zero. On the second trial (red again), RT should be facilitated by matching the preceding trial’s color, a 45ms gain. On the third trial (red), RT should be facilitated by matching the preceding two trials’ color (a 45ms gain from trial N-1 and an additional 16ms gain from trial N-2). The fourth trial is green; it receives no repetition priming from any of the preceding three trials. The fifth trial is red, it does not receive repetition priming from the immediately preceding trial, but receives priming from trials N-2, N-3, and N-4. This calculation can be applied to all trials based on its repetition relationship to the preceding 8 trials. We now have a measure of the RT benefit from repetition priming on a trial-by-trial basis.

Finally, to examine whether repetition priming could account for the observed target frequency effects, we removed the repetition priming obtained from Step 2, from the observed RT (Step 3). This was done for each participant. For example, suppose on trial x the observed RT was 700ms, and the estimated repetition priming for that trial was 65ms. Then we assume that the 700ms included a facilitation of 65ms. Removing the priming facilitation led to an adjusted RT of 765ms. If repetition priming fully accounted for the target frequency effect, then adjusting for repetition priming should eliminate any RT differences between the high- and low- frequency targets. This was indeed the case. As shown in Figure Appendix B2-3, RT for the two targets was similar following the adjustment. The main effect of the target frequency was not significant: Experiment 1 training phase, \( F(1, 23) = 1.80, p > .19 \); testing phase, \( F < 1 \). Experiment 2 training phase, \( F(1, 23) = 1.62, p > .21 \); testing phase, \( F < 1 \). Thus, short-term repetition priming appeared to fully account for the target frequency effects.

![Figure Appendix B. 1: Observed (solid line) and fitted (dash line) repetition priming from trial N to the next 8 trials in an independent dataset in which the two targets appeared equally often. 2. Adjusted RT from Experiment 1, with repetition priming removed from the observed RT. 3. Adjusted RT from Experiment 1, with repetition priming removed from the observed RT.](image)

References


