Informative cues can slow search: the cost of matching a specific template

Mary J. Bravo[1]
Psychology Department, Rutgers-Camden

Hany Farid
Department of Computer Science, Dartmouth College

During visual search, observers hold in mind a search template, which they match against the stimulus. To characterize the content of this template, we trained observers to discriminate a set of artificial objects at an individual level and at a category level. The observers then searched for the objects on backgrounds that camouflaged the features that defined either the object's identity or the object's category. Each search stimulus was preceded by the target's individual name or its category name or by an uninformative cue. The observers' task was to locate the target, which was always present and always the only figure in the stimulus. The results showed that name cues *slowed* search when the features associated with the name were camouflaged. Apparently, the observers required a match between their mental representation of the target and the stimulus, even thought this was unnecessary for the task. Moreover, this match involved all distinctive features of the target, not just the features necessary for a definitive identification. We conclude that visual search for a specific target involves a verification process that is performed automatically on all of the target's distinctive features.

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[1] Corresponding Author: Mary Bravo, mbravo@camden.rutgers.edu, (856) 225-6732, Armitage Hall, Rutgers-Camden, 311 North Fifth St., Camden, NJ 08102

Introduction

When preparing to search for an object, observers call to mind a visual representation, or "search template", of that object (Tinbergen, 1960; Duncan & Humphreys, 1989; Bundesen, 1990; Rao, Zelinsky, Hayhoe & Ballard, 2002; Hamker, 2005; Vickery, King, & Jiang, 2005; Zelinsky, 2008; Castelhano, Pollatsek & Cave, 2008; Malcolm & Henderson, 2009; Bravo & Farid, 2009; Eckstein, 2011; Bravo & Farid , 2012). This template is thought to serve two functions: it is used to enhance the representation of stimuli that resemble the target, and it is used as a reference to verify potential matches.The first role of the search template, the enhancement of sensory representations, has received considerable attention, especially among neuroscientists. This enhancement is thought to originate in prefrontal cortex, the area of the brain that represents behavioral goals. The prefrontal cortex sends top-down signals that enhance the gain on visual neurons that are selective for the target. This enhancement creates a "biased competition" in visual areas that favors the representation of stimuli that resemble the target (Desimone & Duncan, 1995). The extent to which this bias pervades visual processing depends on the specificity of the search template: if observers know only the category of the target, then the bias affects only high-level object representations (Peelen & Kastner, 2011). If observers know the features of the target, then the bias can extend to lower visual areas. (Chelazzi, Duncan, Miller & Desimone, 1998).

An important behavioral effect of biased competition is that it directs the eyes to potential targets (Chelazzi et al., 1998). Foveating the target allows the visual system to acquire an uncrowded, high-resolution representation that can be matched against the search template. If the match between the stimulus and the template meets some decision criterion, then the potential target is accepted as the intended goal. There have been relatively few studies of the decision process involved in matching, but it is thought to involve neurons in prefrontal cortex (Hamker, 2005) and perirhinal cortex (Pagan, Urban, Wohl & Rust, 2013).

The origin of the information represented in the search template depends on the task. In many experiments, observers are pre-cued with the target image prior to the presentation of the search array. In these cases, the search template could originate from position-invariant neural activity evoked by the pre-cue. Real-life tasks typically do not involve pre-cues, however, and so for these tasks the search template must be extracted from object representations stored in long-term memory. The nature of our object representations is a topic of enduring debate, but it is clear that these representations must be highly versatile. Versatility is needed to accommodate the changes in appearance that arise due to changes in viewing conditions (occlusion, background clutter, changes in pose or lighting). Versatility is also needed to meet the variable demands of every-day visual tasks, which range from discriminating among highly similar individuals to generalizing across broad categories.

The current study examines the nature of the object representations used for visual search. We are particularly interested in whether these representations

weigh all features equally or whether they emphasize distinctive features. The idea that object representations should emphasize distinctive features seems obvious; after all, distinctive features distinguish objects from one another. Several studies have shown that when an observer learns to discriminate a set of objects based on a particular feature, the neural representation of that feature becomes more selective (Sigala, & Logothetis, 2002; Baker, Behrman & Olson, 2002, Yang & Maunsell, 2003; Nielsen, Logothetis &Rainer, 2006).   But what is distinctive about an object in one context may not be distinctive in a different context. So, a versatile visual system might also learn features that are irrelevant for the current task in anticipation of future tasks with different demands. There is evidence for the incidental learning of task-irrelevant features (Fiser & Aslin, 2002), and this makes it plausible that object representations could give similar weight to all object features.

In this study, we ask whether distinctive features are given prominence in the object representations used for visual search. Unlike previous studies, we did not try to assess how discrimination learning alters the selectivity and sensitivity of feature representations. Instead, we examined how this learning alters the search template that observers hold in mind when they subsequently search for the learned objects. As noted above, we conceptualize the search template as the set of features that are favored in biased competition and that are required for a match decision (Eckstein, Beutter, Pham, Shimozaki & Stone, 2007; for a different view see Wolfe and Horowitz, 2004.)   As with previous studies, our objects shared some features but not others, and so each object possessed both common and distinctive features. Once observers learned to discriminate these objects, we asked them to locate each object on a textured background. Two background textures were used, one that concealed the common features and one that concealed the distinctive features. In this task, the target object was cued by name, and, because this cue was always valid, observers could base detection on any, or all, of the target's features. By examining how the textures affected search, we were able to determine which features observers use in their detection decision.

Experiment 1: Distinctive versus Common Features

During an hour-long training session, observers learned to associate names with three butterfly stimuli. These butterflies all had the same shape but varied in their surface markings. For half of the observers, the markings on the top wings varied across the butterflies, while the markings on the bottom wings were fixed. For the other half of the observers, the markings on the bottom wings varied and the markings on the top wings were fixed. We will refer to the wings with varying markings as "distinctive" and the wings with fixed markings as "common".

Soon after training, the observers were tested on a visual search task with the butterfly names as cues. Each search stimulus contained one butterfly on a textured background; the observer's task was to locate this butterfly. We used two types of background textures, one with the same image statistics as the top wings, and the other with the same image statistics as the bottom wings. Thus
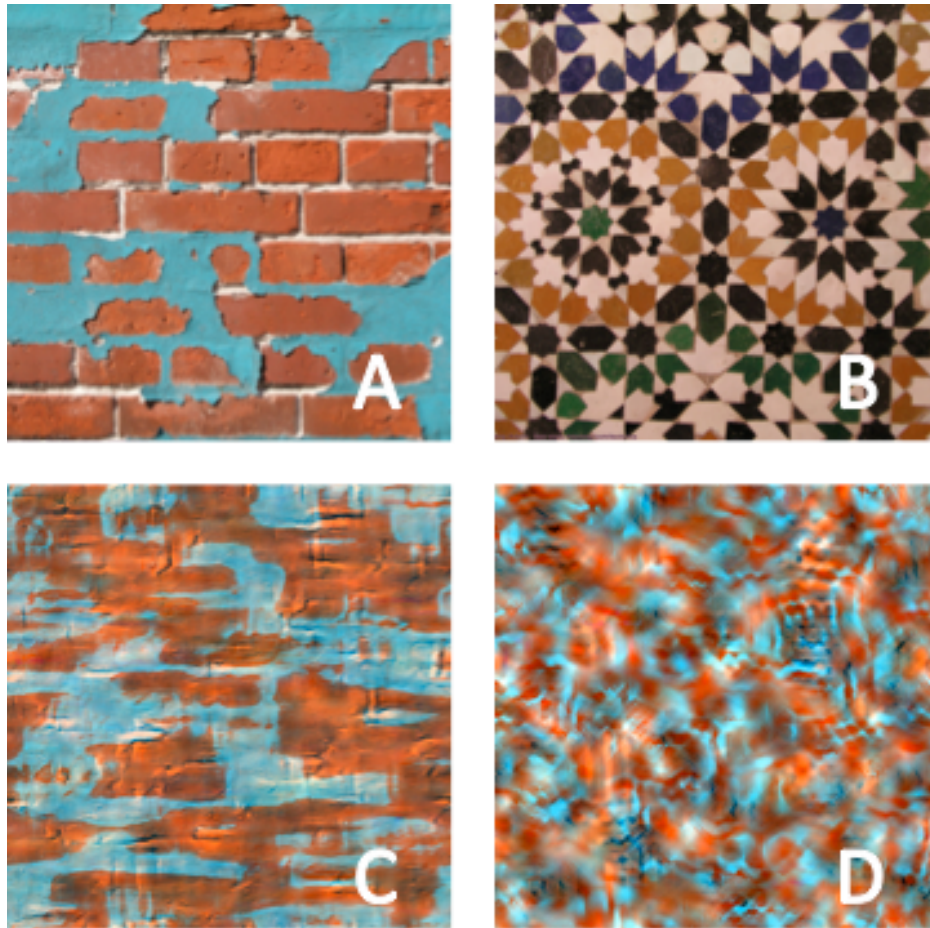
Figure 1. An image of a brick wall (A) supplied the magnitude values for both synthetic textures (C & D), and the phase values for one texture (C). An image of a tile mosaic supplied the phase values for the other texture (D).

each texture camouflaged the common wings for one set of observers and the distinctive wings for the other set of observers.

To learn which features the observers were using to detect the butterflies, we compared performance on the two types of backgrounds. If distinctive features are given special prominence in object representations, then search should be slow when these features are camouflaged. This would produce an interaction between observer group and background texture. If common features are given special prominence, possibly because they are seen more frequently, then search should be slow when these features are camouflaged. This would produce a different interaction pattern. Finally, if both sets of features are given equal weight, then the two sets of observers should perform similarly on the two backgrounds.
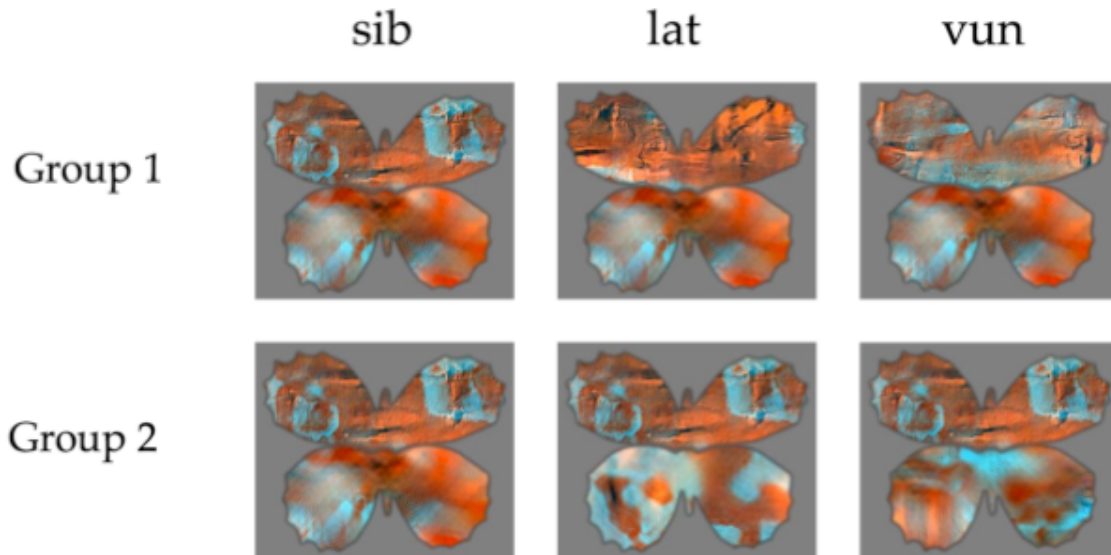
Figure 2. The butterfly stimuli used in Experiment 1.   One observer group was trained to associate names with three butterflies that differed in their top, brick wings. The other observer group was trained to associate names with three butterflies that differed in their bottom, tile wings. The "sib" butterfly was common to both groups.

Methods

Stimulus. The butterfly stimuli and the textured backgrounds were created from two synthetic textures (Portilla & Simoncelli, 2000). The textures were synthesized using image statistics extracted from photographs of a painted brick wall (Figure 1A) and a tile mosaic (Figure 1B). The brick wall supplied the magnitude values for both textures. The brick wall also supplied the phase values for one texture (the brick texture, Figure 1C), while the tile mosaic supplied the phase values for the other (the tile texture, Figure 1D).   Because the brick and tile textures shared the same magnitude values they had the same colors, spatial frequencies, and orientations, but because they had different phase values they were still discriminable.

Using the brick and tile textures, we created two sets of three butterflies. At their largest extent, the butterflies were 300x300 pixels. Each butterfly was composed of a pair of top wings cut from a brick texture and a pair of bottom wings cut from a tile texture. For one stimulus set, the markings on the top, brick wings varied across butterflies because they were cut from different locations on the tile texture. The markings on the bottom, tile wings were fixed. For this set of butterflies, the brick wings were distinct and the tile wings were common. This situation was reversed for the other stimulus set, so that the brick wings were common and the tile wings were distinct (Figure 2). The stimulus sets had one butterfly in common ("sib").

Observers. The observers were twenty-four participants recruited from the subject pool at Rutgers-Camden. All observers reported having normal or

corrected to normal acuity and normal color vision. The observers participated in a 50-minute training session and, one or two days later, a 50-minute testing session.

Training. The observers were randomly assigned to one of the two stimulus sets (distinct brick wings, distinct tile wings). During a one-hour training session, observers learned to associate one-syllable names ("sib", "lat", "vun") with the three butterflies in their stimulus set. The butterflies were presented on a gray background near the center of the computer screen. Across trials, the butterflies' horizontal and vertical positions were randomly jittered by +/-128 pixels to discourage observers from focusing on a specific location on the butterflies.

Initially, observers passively observed 36 name and butterfly pairings. Each trial began with a 200 msec name cue followed by an 800 msec blank interval. After the blank interval, a butterfly was displayed for 5 sec. Following this block of passive observation, observers completed 5 blocks of 36 trials in which they were tested on the name-butterfly pairings. Each trial again consisted of a name followed by a butterfly, and eighty percent of these pairings were correct. Observers judged the correctness of the pairings by pressing one of two keys on the computer keyboard. Auditory feedback was given after an incorrect response. To keep observers engaged in the task, the duration of the images was reduced over successive blocks of trials from unlimited time, to 500 msec, 300 msec, and 200 msec. To graduate from one training block to the next, observers were required to perform with at least 90% accuracy. About a quarter of the observers needed to repeat the first block of trials; no observers needed to repeat subsequent blocks.

Observers concluded their training by practicing the localization task that would be used during the testing session. In this task, the name cue was always valid and the butterfly appeared in one quadrant of an otherwise blank screen. The observer's task was to indicate the butterfly's location using four keys mapped to the display quadrants (the "F", "V", "J" , "N" keys on a computer keyboard). Observers practiced this localization task for two blocks of 24 trials.

Testing. One or two days after training, observers returned for a testing session in which they located the butterflies on textured backgrounds (Figure 3). The backgrounds were randomly drawn from 40 synthetic brick textures and 40 synthetic tile textures, each 1024x1024 pixels in extent. The butterfly targets were centered in one quadrant of the background and then jittered by +/- 80 pixels horizontally and vertically.

During each search trial, observers were first presented with the name of the butterfly that would appear in the upcoming search array. These cues were always valid. This 200 msec cue was followed by an 800 msec blank interval, followed by the search stimulus. The search stimulus remained on until the observer responded by pressing one of four keys to indicate the quadrant location of the butterfly. Auditory feedback was given after incorrect responses. Observers performed 6 blocks of 36 trials, and the first two trials of each block were discarded.
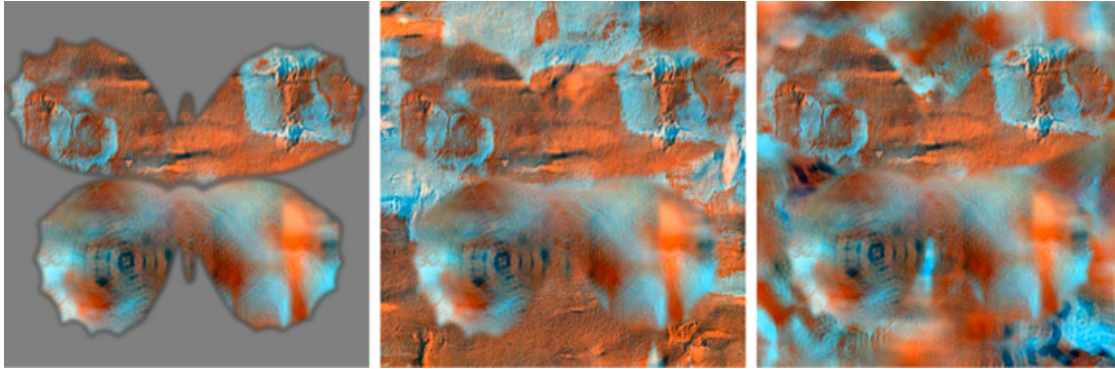
Figure 3. Search stimuli were created by superimposing the butterflies on textured backgrounds with the same image statistics as either the top wings (middle) or the bottom wings (right). The images in this figure have been cropped around the target; in the actual stimuli, the area of the background was 11.5 times greater than the area of the butterfly.

Results & Discussion

This experiment examined whether observers base target detection on distinctive features. To test this, we trained half of our observers on a butterfly discrimination task in which the top, brick wings were distinctive, and we trained the other half on a discrimination task in which the bottom, tile wings were distinctive. We then placed the butterflies on brick and tile backgrounds so as to camouflage the brick and tile wings, respectively. If observers were relying on the distinctive wings to detect the butterflies, then we expected search times to show an interaction between the observer group and the background.

Figure 4 shows response times as a function of the background for the two observer groups. (In each condition, fewer than 5% of the responses were excluded either because they were incorrect or because they exceeded 12 seconds.) On the left (A) are the results for the "sib" butterfly that was common to both groups. A two-way ANOVA indicated that there were no significant main effects of observer group or background, and that there was a significant group X background interaction ($F(1,22) = 34.5$, $p < 0.01$). Although all observers performed the same search task, they were affected by the backgrounds in different ways. The tile background was especially detrimental for observers who had trained on distinctive tile wings, while the brick background was especially detrimental for observers who had trained on distinctive brick wings. Similarly, an ANOVA of the data for all butterflies (Figure 4B) showed no main effects for observer group or background, but a significant group X background interaction ($F(1,22) = 9.67$, $p < 0.01$). Backgrounds that matched the distinctive wings slowed search more than backgrounds that matched the common wings. These results indicate that observers base the detection of a target in camouflage on the detection of its distinctive features.

In this experiment, object features were either distinctive or common. With real objects this division is rarely so clean. Observers may discriminate among objects at different levels, and the features that are common to objects within a
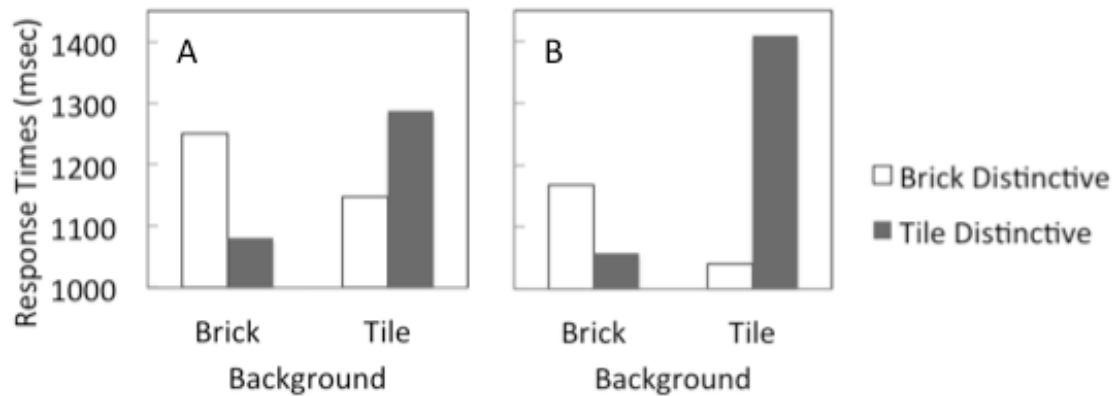
Figure 4. Results from experiment 1. "Brick distinctive" observers were trained to discriminate the butterflies using markings on the brick wings. "Tile distinctive" observers were trained to discriminate the butterflies using markings on the tile wings. These graphs show the observers' average response times for a search task in which the butterflies were presented on either a brick texture or a tile texture. (A) "Sib" butterfly, common to both observer groups, (B) All butterflies.

category may be the very features that distinguish that category from other categories. Given our finding that the search template consists of distinctive features, and assuming that distinctive features vary depending on the level of categorization, we next asked whether the search template varies depending on whether the target is called by its category name or by its individual name.

Experiment 2a: Individual versus Category Features

The first experiment compared performance between two groups of observers who had been trained to discriminate different sets of stimuli. This second experiment compared performance within a single group of observers who had been trained to discriminate a set of stimuli at both a category level and an individual level.

Methods

Stimulus. Six new butterflies were created for this experiment. As with the previous experiment, the top half of the butterflies was cut from the brick texture and the bottom half was cut from the tile texture. The markings on the top wings were unique to each butterfly, whereas the markings on the bottom wings were shared by the three butterflies within each category. Each butterfly was associated with a category name and an individual name: The "remun" category consisted of "sib", "lat" and "vun" and the "cabur" category consisted of "fim", "mog" and "ped" (Figure 5).

Observers. Twelve observers from the Rutgers-Camden subject pool participated in this experiment. All observers reported having normal or
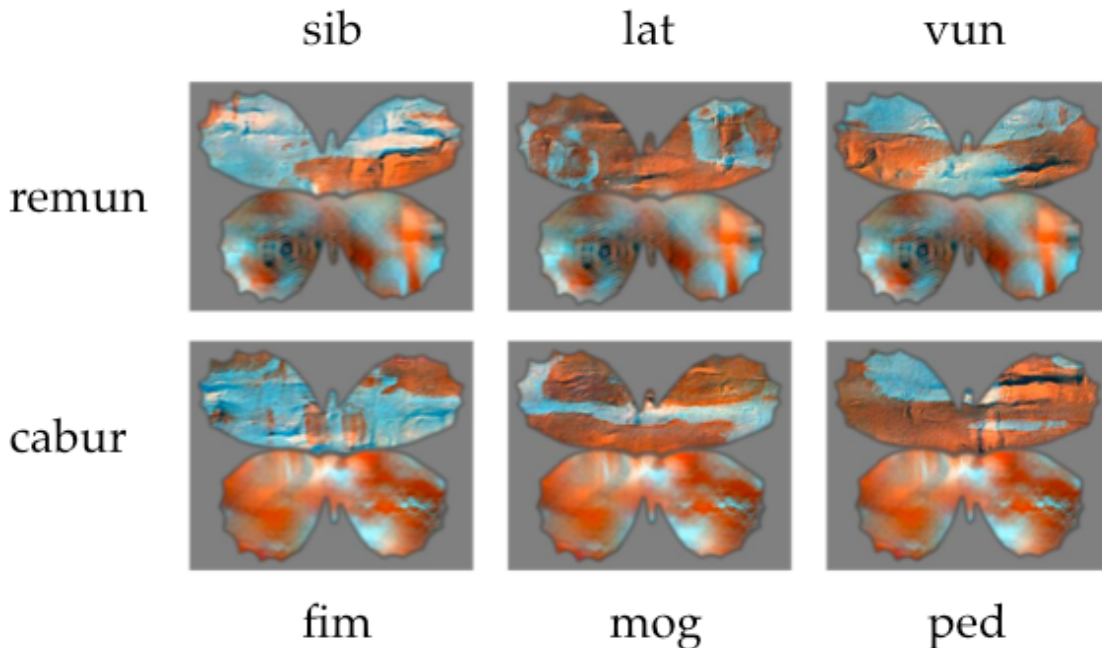
Figure 5. The six butterfly stimuli used in Experiment 2. The bottom wings define two butterfly categories ("remun", "cabur"), the top wings define the six individuals.

corrected to normal acuity and normal color vision. The experiment involved two training sessions and a testing session within a one-week period.

Training. Training involved three distinct discrimination tasks: discriminating the two categories, and, then, within each category, discriminating the three individuals. The observers were explicitly told about the relationship between the tasks. (Excerpts from the instructions read: "In this experiment you will learn to identify six butterflies that come from two categories. First you will learn the two categories: the caburs and the remuns." "Now you will learn to discriminate the three remun butterflies: sib, lat, and vun" "Now you will learn to discriminate the three cabur butterflies: fim, mog, ped.")

The training tasks followed a similar procedure as the first experiment. Initially, observers passively viewed name and butterfly pairings. Then they were tested on these pairings over the course of several blocks with progressively shorter stimulus durations (from unlimited time, to 500 msec, to 300 msec). As before, eighty percent of the pairings were correct. To proceed to the next block of trials, observers needed to perform with 90% accuracy. Observers practiced discriminating the categories and the individuals within the categories during both training sessions.

Testing. During the same week as the two training sessions, observers returned for a testing session. The testing session followed a similar procedure as in the previous experiment except now each search trial was cued either with the individual name of the target butterfly (as before), or with the category name of

the butterfly, or with the word "butterfly". The cues were never misleading. The cues were followed by a search array in which one butterfly target appeared against a camouflaging background that concealed half of the butterfly. The observer's task was to use one of four keys to indicate the display quadrant in which the butterfly appeared. Auditory feedback was given after incorrect responses. Observers performed 6 blocks of 36 trials, and the first two trials of each block were discarded.

Results & Discussion

In this second experiment, observers were pre-cued with either the butterfly's individual name, or its category name, or the word "butterfly". The observers then searched for the butterflies on backgrounds that selectively concealed either the butterfly's distinctive individual features or its distinctive category features. The results for this experiment are shown in Figure 6. To determine how the three cue conditions and the two background conditions affected search times, we performed a 2x3 repeated measures ANOVA on the reaction time data. (In each condition, fewer than 5% of the responses were excluded either because they were incorrect or because they exceeded 12 seconds.) This analysis showed a significant main effect of cue , $F(2, 22) = 10.7$, $p < 0.01$; a marginal effect of background, $F(1,11) = 4.6$ $p = 0.054$; and a significant cue X background interaction $F(2,22) = 7.937$ $p < 0.01$.

The main effect of cue appears to be largely due to a difference between the informative and uninformative cues. The uninformative cue, the word "butterfly", specified no particular target, and so no particular target features. In this case, observers likely based detection on a discontinuity in the background texture. It is noteworthy that informative name cues generally produced slower search times than the uninformative cue (the "name cost" in Figure 6B). In previous studies, informative cues facilitate search, presumably because they invoke a search template that guides top-down selection processes. Because we used targets and backgrounds with the same image statistics, we likely prevented top-down selection, a possibility that we consider in the general discussion.

Because the interaction between the name cues and the backgrounds was central to our hypothesis, we performed a 2x2 ANOVA on just the informative cue conditions. This analysis showed a significant main effect of background $F(1, 11) = 7.69$, $p < 0.05$; and a significant cue X background interaction $F(1, 11) = 4.9$, $p < 0.05$. To understand the implications of this interaction, we first examine the results for the brick background. The left side of the graph in Figure 6A shows that the brick background slowed search more when a target was cued by its individual name rather than its category name. This result was expected: the brick background matched the features distinctive to individual butterflies, and category cues do not specify individual butterflies.

In contrast, the right side of Figure 6A shows that the tile background slowed search equally whether the target was cued by its individual name or its category name. The tile background matches the features that are distinctive to
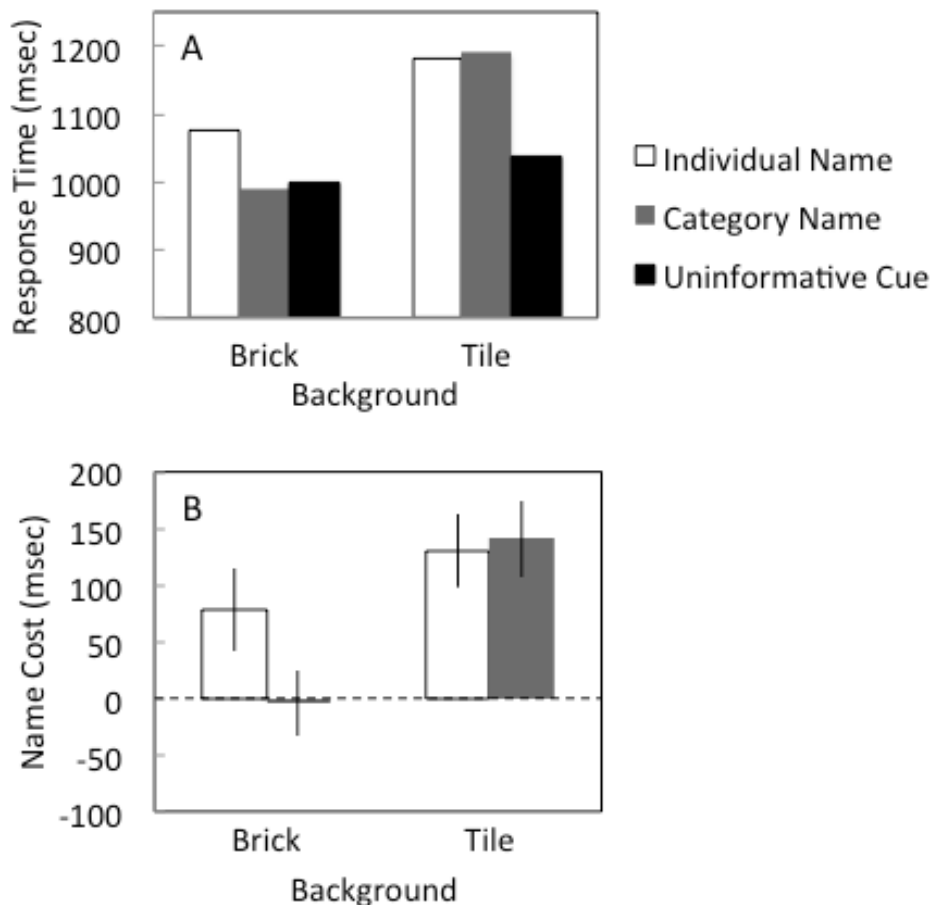
Figure 6. Results from Experiment 2a. (A) Average response times to locate the butterfly on the brick and tile backgrounds. Observers were cued with either the butterfly's individual name, or its category name, or the word "butterfly" (the uninformative cue). Individual butterflies could be identified by the texture on the brick wings; butterfly categories could be identified by the texture on the tile wings. (B) The response cost of the informative name cues relative to the uninformative cue (error bars indicate +/- one standard error).

categories, and these features are expected to be included in the search template elicited by category cues. The results also indicate that category features are included in the search template elicited by individual cues. This result was not expected: when observers learned to discriminate individual butterflies, they did so within categories, never across categories, and so the category features were irrelevant to the task. Nonetheless, it appears that when observers were cued with an individual name, they called to mind a search template that included both individual features and category features.

Experiment 2b: Concealed Categories

As a check on our methods, we repeated the experiment with a change in the training procedure that we expected would produce a change in the results. In this control experiment, the observers performed the same training tasks, but the

tasks were portrayed as three unrelated discriminations. The intention of this control was to give the observers the same training on the butterfly names as in the previous experiment, while obscuring the fact that each butterfly could be categorized at both an individual level and a category level. We assumed this change would prevent observers from incorporating category features into their search templates for individual butterflies.

Twelve observers participated in this experiment, which was identical to the previous experiment except for the training instructions and the order of the training conditions. At the beginning of the training sessions, the observers were told that they would learn to discriminate three sets of butterflies that varied on either their top or bottom wings.   Then, during an extended initial session, the observers were trained on the {sib, lat, vun} discrimination, followed by the {fim, mog, ped} discrimination. During a second, briefer session, they were trained on the {cabur and remun} discrimination.

The results for Experiment 2b are shown Figure 7. A 2x3 repeated measures ANOVA revealed a main effect of cue $F(2,22) = 10.8$, $p < 0.01$; a marginal effect of background $F(1, 11) = 4.5$ $p = 0.06$, and a cue X background interaction $F(2,22) = 7.7$, $p < 0.01$. As with Experiment 2a, the uninformative cue condition produced faster response times than some of the informative cue conditions. A 2x2 ANOVA on just the informative name cue conditions showed no main effect of cue, a main effect of background, $F(1,11) = 6.554$, $p < 0.05$; and a cue X background interaction $F(2,22) = 5.747$, $p < 0.05$.   Unlike Experiment 2a, the data from Experiment 2b show a similar cross-over pattern as was observed in Experiment 1: the background that matched the individual features selectively impaired search with individual name cues, and the background that matched the category features selectively impaired search with category name cues. Obscuring the relationship between the categories and the individuals prevented observers from incorporating category features into their search templates for individuals.

General Discussion

We designed this experiment to determine whether the search template includes all features of the target or just the features that had distinguished the target in previous tasks. The results addressed this question, but they also showed something unexpected: observers generally performed the task faster when they did not know which search target would appear in the stimulus. In previous research, informative cues consistently facilitated search, with more informative cues producing greater facilitation (Wolfe, Horowitz, Kenner, Hyle & Vasan, 2004; Schmidt and Zelinsky, 2009;   Malcolm and Henderson, 2009; Bravo & Farid, 2009). To understand why knowledge of the target would slow search, it is useful to consider the two functions of the search template.

One function of the search template is to enhance the neural representation of stimuli that possess the target's features.   In this study the search targets appeared on a background with the same low-level features as the targets themselves.   Thus, top-down attention to the target features would
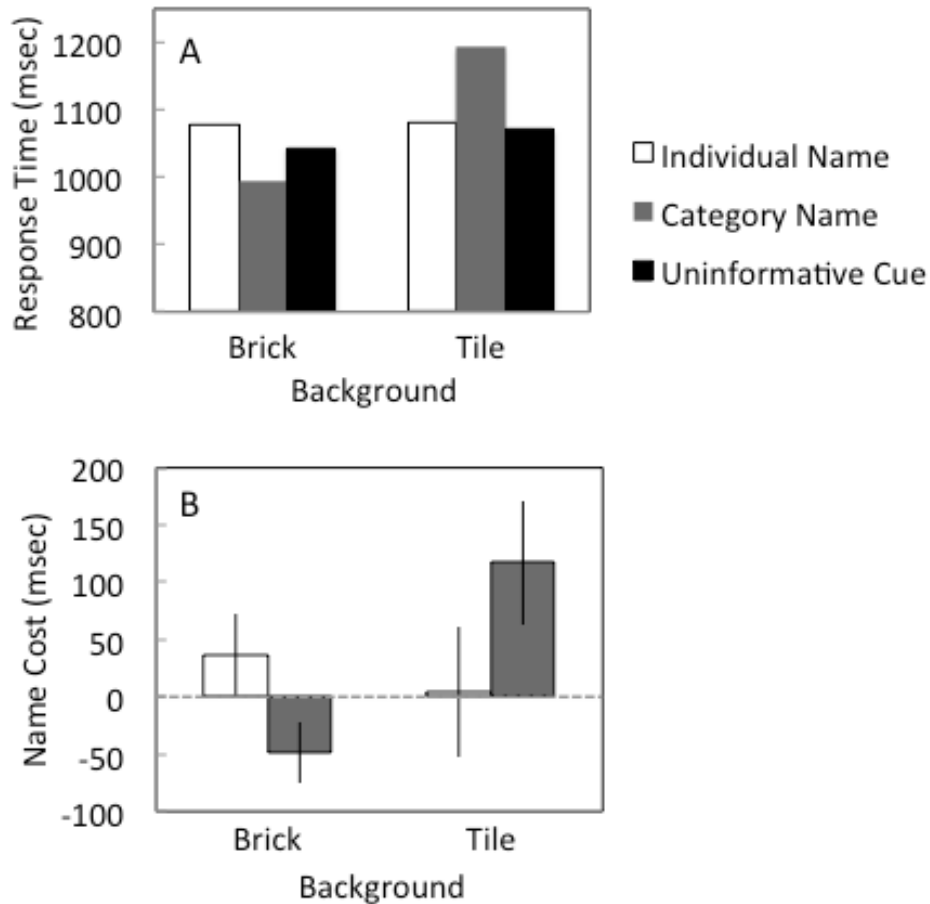
Figure 7. Results from Experiment 2b in which the relationship between individuals and categories was concealed. (A) Average response times to locate the butterfly on the brick and tile backgrounds. (B) The response time cost of the informative name cues relative to the uninformative cue (error bars indicate +/- one standard error).

likely enhance the representation of the background as well as the target. If the camouflage prevented top-down selection of the target, then observers must have located the targets using bottom-up cues like texture discontinuities.

The elimination of top-down selection may explain why informative cues did not facilitate search, but it does not explain why they slowed search.   We attribute the slowing of search to the second function of the search template: its role as a reference for verifying potential matches.   In this experiment, the observer's task was to locate the single target butterfly, not to verify its identity. Nonetheless, observers may have automatically performed this verification step. Previous research by Kotowicz, Rutishauser, and Koch (2010) has shown that as soon as an observer acquires a target during visual search, they can perform a present-absent judgment with near perfect accuracy. Even so, observers continue to fixate the target before responding. This previous study showed that while continued fixation has little effect on observer accuracy, it does increase observer confidence. Thus, even when observers are instructed to respond

quickly in a search task, they may delay their response until they verify the target's identity.

We offer, then, the following interpretation of our results. Prompted by a name cue, observers activated a search template. This high-level visual representation of the target in turn activated lower-level feature representations. Because our targets appeared on a background with similar features, this top-down activation was ineffective for target selection. Observers instead located the targets using bottom-up processes that detected texture discontinuities. Once the target was located, observers verified its identity by matching the stimulus against the search template. This matching process was delayed when the background blended with the stimulus features that corresponded to template features. By assessing which backgrounds affected search, we could infer which features were included in the observer's search template.

Our results indicate that the search template emphasizes the features that had played a critical role in previous tasks involving the target. In our first experiment, the discrimination task required observers to attend to distinctive features and ignore common features, and this training was clearly reflected in the content of the search template: search was slower when the background camouflaged distinctive features rather than common features.

In our second experiment, each target butterfly appeared in two discrimination tasks, one task involving differences in the butterfly's top wings, the other task involving differences in its bottom wings. It is important to emphasize that observers never performed a conjoint task that involved both wings and that the top wings alone were sufficient for identifying individual butterflies. Nonetheless, when observers called to mind an individual butterfly, they activated a representation that included distinctive features from both wings – that is, both the individual features of the top wings and the category features of the bottom wings.

The observers in our experiment seem to be adopting a suboptimal strategy: Even though the task can be performed without verifying the target's identity, observers appear to perform this verification step. Furthermore, even though individual targets can be identified without reference to their category features, observers appear to verify both individual and category features. The finding that observers verify more features than are strictly required for identification suggests a new wrinkle for attempts to understand object recognition in terms of task constraints. For example, Gosselin & Schyns (1997) have proposed a model that successfully explains many aspects of categorization performance, and a basic assumption of the model is that observers verify the minimal number of features necessary to make a category decision. The results from Experiment 2a appear to contradict this assumption: when cued with the target's individual name, observers appear to verify all distinctive features of the target, not just the features necessary to identify it as a particular individual. Not all target features are verified, however. The results from Experiment 1 indicate that common, non-distinctive features are ignored.

It is surprising that the observers in our experiment would adopt a strategy that is both slow and unnecessary. But previous research suggests that for most

visual search tasks, utilizing a search template greatly improves performance. Because search templates are usually so effective, observers may automatically generate them in response to a name cue, and, once generated, these templates may automatically trigger a verification process. Normally, verification might be speedy: recognition can sometimes occur simultaneously with figure detection (Grill-Spector & Kanwisher, 2005). Moreover, verification serves the generally useful function of confirming the reliability of associations and the successful completion of the task. Perhaps it is only under rare conditions, such as extreme camouflage, that this process is slow enough that it can be readily observed.

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