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On the Precision of Goal-Directed Attentional Selection

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Abstract

Attention selects objects in a scene for cognitive processing. A growing body of evidence has been used to argue that observers are able to narrowly restrict attentional selection to stimuli that match a feature-based target template while ignoring similar-looking distractors. For example, visual search for a target among feature-similar nontargets is highly efficient. Here, I demonstrate that observers are substantially impaired at selecting a target among feature-similar nontargets when stimuli are compared with a target template serially in time. The results argue that goal-directed attentional selection is distinctly imprecise, and that comparing stimuli with a target template reflects an inefficient mechanism of selection that cannot fully explain visual search performance under demanding conditions.

Keywords

selective attention; visual search; target template

The representational capacity of perception is limited, such that only a small number of objects in a scene can be processed by the visual system at any one moment. This limitation gives rise to the need to select which objects receive perceptual representation, and attention serves this function. Attention selects which stimuli are processed to the level of awareness and which are ignored (Desimone & Duncan, 1995).

The attentional selection of stimuli within a scene often involves an active process in which we pursue search goals that are guided by knowledge of our surroundings. For example, when searching through the refrigerator for a particular food item, we conduct our search with an understanding of what that food item should look like (i.e., a target template) and use this information to guide search accordingly. Models of selective attention seek to characterize the ways in which the visual system is able to use goal representations to select a particular target of visual search efficiently.

Evidence That Attentional Selection Is Guided by Feature-Based Target Templates

Early models of attention emphasized an inefficient selection mechanism that, under most conditions, directed attention from item to item serially until the target of visual search was found, with minimal guidance from search goals (e.g., Treisman & Gelade, 1980). A major breakthrough came when Wolfe and colleagues showed that visual search can be largely restricted to stimuli that possess a target-defining feature, such as a particular color (Wolfe, 1994; Wolfe, Cave, & Franzel, 1989). Findings such as these demonstrate that the visual system can leverage search goals to more efficiently guide attentional selection.

The selection component of visual search has also been studied using attentional capture paradigms. In attentional capture paradigms, observers search for one or more targets that can be identified on the basis of a particular feature or conjunction of features. Prior to, or simultaneously with, the presentation of the target, a known-to-be-irrelevant stimulus (referred to as a distractor) is presented, which observers try to ignore. If the distractor impairs performance in target detection, the distractor is said to have been selected by attention involuntarily, which is referred to as attentional capture.

Seminal work by Folk and colleagues using attentional capture paradigms has demonstrated that distractors that share an identifying feature with the searched-for target capture attention while distractors that do not share this feature are ignored (Folk & Anderson, 2010; Folk, Leber, & Egeth, 2002, 2008; Folk & Remington, 1998; Folk, Remington, & Johnston, 1992; Folk, Remington, & Write, 1994). In the presence of such a dichotomy, attentional capture is said to be contingent on whether a visual stimulus possesses a goal-relevant feature. Findings such as these demonstrating *contingent attentional capture* suggest that the visual system can make use of a target template (i.e., attentional control settings) to restrict attentional selection to stimuli that match this template (although see Theeuwes, 2010, for a postselection account of goal-directed attentional control).

Evidence That Attentional Selection Is Precise

A growing body of recent findings suggests that goal-directed attentional selection can be narrowly restricted to only target-relevant stimuli. For example, observers can restrict attentional selection on the basis of separate attentional control settings for different regions of space, both in the domain of color (e.g., red on the right, green on the left; Adamo, Pun, Pratt, & Ferber, 2008) and even across feature dimensions (e.g., green on the right, triangles on the left; Adamo, Wozny, Pratt, & Ferber, 2010). Although such complex and narrowly defined attentional control settings likely influence postselection attentional processing (Adamo, Pun, & Ferber, 2010; Parrott, Levinthal, & Franconeri, 2010), others have forwarded evidence suggesting that they can specifically guide attentional selection as well.

Navalpakkam and Itti (2006) demonstrated that observers could largely restrict visual search to stimuli within an intermediate and narrowly defined range of a particular feature dimension, efficiently selecting the target. For example, observers could rapidly orient to a target of intermediate brightness when presented among both brighter and darker nontargets

of similar luminance in a large array. Using a rapid serial visual presentation (RSVP) task in which observers searched for a target defined by one of two colors among differently colored nontargets, only color distractors matching a possible target color impaired performance, whereas other-colored distractors did not (Moore & Weissman, 2010). This selectivity in attentional selection is evident even when the two target-defining colors change from trial to trial and thus cannot be explained by feature priming (Roper & Vecera, 2012). Findings such as these suggest that attentional control settings can be narrowly tuned to one or more discrete regions of feature space, efficiently restricting attentional selection to stimuli possessing a target-relevant feature while ignoring feature-similar distractors.

Irons, Folk, and Remington (2012) provided a strong test of fine-grained attentional control settings using the spatial cuing paradigm. In their experiments, observers searched for one of two color-defined targets among nontargets of different colors, and the results showed that only cues matching either target color captured attention and produced a cuing effect. These results could not be explained by an attentional set that linearly separated targets from nontargets in color space (see also Moore & Weissman, 2010; Navalpakkam & Itti, 2006, and Roper & Vecera, 2012, for a similar conclusion). Most prominently, observers could ignore distractors similar in color to the targets, suggesting that they were able to restrict attentional selection to stimuli falling within two distinct and narrowly defined regions of color space. Collectively, the above findings have led to the conclusion that goal-directed attentional control settings can be narrowly tuned to accommodate the demands of target identification in visual search.

The Precise Template Hypothesis and Its Alternative

The aforementioned findings clearly show that the processing of task-related stimuli can be efficient and highly selective, even under demanding search conditions in which the feature space separating the target from nontargets is small. How does the attention system accomplish this impressive feat? One possibility, which I will refer to as the *precise template hypothesis*, predicts that the attention system selects stimuli falling within a narrowly defined region of feature space. By this account, the efficiency of visual search reflects when attention is and is not engaged by the detection of a match to a template. However, it is also possible to account for such highly efficient search without the need for precise template matching.

Additional computations beyond template matching guide goal-contingent attentional selection. For example, the efficiency of visual search is influenced by the heterogeneity among nontargets (Duncan & Humphreys, 1989; Wolfe, 2007, 2010), suggesting display-wide computations by which different objects of visual search are compared with each other and rejected as nontargets. How much do such display-wide computations matter in selecting a simple feature-defined target? Does comparing different stimuli with a goal-defined target template itself serve as an efficient mechanism of guiding attentional selection, or are other comparison processes needed to allow for the identification of a target among similar looking nontargets?

The Present Study

In the present study, I provide a direct test of the precise template hypothesis. My approach was to make the identification of a target strongly reliant on template matching by minimizing participants' ability to perform display-wide computations in which different stimuli are compared with each other. To this end, I employed a novel RSVP paradigm in which the feature similarity between the target and nontargets was manipulated. My dependent measure of interest was how well participants are able to detect a target, inferring limitations in goal-directed attentional control from selective failures to perform the task.

My findings challenge the precise template hypothesis. I begin each experiment by replicating evidence that has been used to argue for the precision of attentional control settings by showing that visual search for a target among feature-similar nontargets is highly efficient (Navalpakkam & Itti, 2006). In these same observers, however, I also demonstrate a substantial decrement in target identification for the same color-defined target among feature-similar nontargets in an RSVP paradigm in which observers must serially compare different stimuli with a target template (with limited opportunity for simultaneous comparison among stimuli). Both spatial (e.g., visual search) and temporal (e.g., RSVP) selection tasks are thought to rely on the same underlying mechanism of selection: Both have been used to argue for the precision of goal-directed attentional selection (e.g., Irons et al., 2012; Moore & Weissman, 2010; Navalpakkam & Itti, 2006; Roper & Vecera, 2012), and selection in one task primes selection in the other (Levinthal & Lleras, 2008; Yashar & Lamy, 2010). The observed failure to restrict attentional selection to the target-defining feature in the RSVP task highlights a distinct and previously unrecognized limitation of the attentional system, and argues against the efficiency with which target templates can be used to make fine-grained distinctions among targets and feature-similar nontargets.

Experiment 1

In Experiment 1, observers began by performing visual search for a color-defined (orange) target among similar-colored (red and gold; see Anderson & Folk, 2010) nontarget letters. Participants indicated whether a target was present or absent in the display. This visual search task was performed to both replicate previous findings that have been used to argue that goal-directed control over attentional selection is precise, as well as ensure that each individual participant was capable of easily discriminating the target color from the similar-color nontargets when presented simultaneously. Following this visual search task, observers performed an RSVP task in which they searched for a letter defined by the same previous target color (orange) while ignoring other letters and symbols presented in other colors. This task required participants to select the target on the basis of its match to a target template, as the successive presentations of stimuli minimize the ability of observers to employ a strategy of comparing and rejecting nontargets. Participants performed the RSVP task amid non-targets that were either all of a color that was distinct from the target color (blue, purple, white, and green), or amid nontargets of these same colors with the addition of others that were similar in color to the target (red and gold), in alternating blocks. If attentional control settings allow observers to restrict attentional selection only to features that precisely match a target template, observers should perform well regardless of the

presence of similar-color nontargets. If, however, attentional selection via template matching is distinctly imprecise and cannot efficiently discriminate between targets and feature-similar nontargets, observers should have substantial difficulty selecting only the target and not similar-color nontargets when such nontargets are present, resulting in a large decrement in performance.

Method

Participants—Eight Johns Hopkins University undergraduate students (18 to 20 years of age; $M = 18.8$; five males) participated and were compensated with extra credit toward a variety of psychology courses.

Apparatus—A Mac Mini equipped with Matlab software and Psychophysics Toolbox extensions was used to present the stimuli on a Dell P991 monitor. The participants viewed the monitor from a distance of 75 cm in a dimly lit room, and head position was stabilized using a chin rest. Manual responses were entered by participants using a standard U.S. layout keyboard.

Visual Search Task

Stimuli: Each trial began with a fixation display, followed by a search array comprising 8, 16, or 24 colored “X”s and “O”s (each letter $0.8^\circ \times 1.3^\circ$), and then by a blank intertrial interval (intertrial interval [ITI]; see Figure 1A). The target was an orange “X” (RGB: 250 130 0) among red (RGB: 255 0 0) and gold (RGB: 192 192 0) nontargets. A colored letter could appear in one of 30 positions in a 6×5 grid centered at fixation. Letters in neighboring grid positions were separated by 2.6° center to center. Two different letters were used to create heterogeneity in a feature dimension other than color, thereby reducing any potential for the target to pop out as a result of its unique color.

Design and procedure: All participants began the experiment by performing the visual search task. The task consisted of three blocks of 96 trials. Half of the trials within each block contained an orange target and half did not. Participants indicated whether a target was present or absent by pressing the “M” and “Z” key, respectively. On each trial, a fixation display consisting of a central white cross was presented for 400, 500, or 600 ms (randomly determined on each trial); the letters comprising the search array then appeared and remained on screen until a response was made or 2000 ms had elapsed, after which the trial timed out. A blank ITI followed the termination of the search array and lasted 500 ms. Display size (8, 16, or 24 items) and target presence (present or absent) were fully crossed and counterbalanced in each block, and trials were presented in a random order. An equal number of red and gold letters were presented on target-absent trials, and one of these letters was replaced by the target on target-present trials. The position of the letters in the grid was randomized on each trial. Participants received a 500-ms 1,000-Hz tone as feedback when they responded incorrectly or too slowly. The task began with 25 practice trials using the same parameters.

RSVP task

Stimuli: A steady stream of two colored letters (each letter $0.8^\circ \times 1.3^\circ$), one on each side of fixation at an eccentricity of 6.8° , were presented at a rate of 117 ms (see Figure 1B). Each letter was surrounded by four identical colored symbols (&, +, #, or outline diamond, each $0.9^\circ \times 0.9^\circ$). The colors that were used were green, blue, purple, white, gold, red, and orange. The target consisted of an orange letter presented for a single frame; only targets were ever presented in orange. Four small boxes were always visible at the center of the screen, with two on each side of fixation (each pair $1.1^\circ \times 0.8^\circ$, 0.8° center to center from fixation). Following the presentation of the target, a small white letter ($0.3^\circ \times 0.5^\circ$) appeared in each box, one of which was the identity of the previous target.

Design and procedure: Participants completed six blocks of the RSVP task. The color and identity of each nontarget letter and symbol was randomly generated on each frame from the set of available features, with the constraint that no color or identity was repeated on consecutive frames. Fifty-two orange targets were presented in each block, equally often on each side. Targets were separated by 30, 40, 50, or 60 frames, equally often and randomly determined for each intertarget interval; the RSVP stream continued until the end of the block. Five hundred milliseconds after the presentation of the target, the four white letters appeared in the four boxes and remained on screen for 15 frames or until a response was made. Participants reported which letter they thought was the target by pressing one of four keys that mapped onto the four boxes (“Z,” “X,” “N,” and “M,” left to right). The position of the white previous-target letter was selected at random with the constraint that it appeared in each of the four boxes equally often in each block. Participants were instructed to guess if they were unsure what letter the target was. Blocks alternated between containing only green, blue, purple, and white nontarget letters and symbols (nonsimilar color block), and containing these colors in addition to red and gold (similar color block; see Figure 1D). Which block was presented first was counterbalanced across participants. Trial-by-trial feedback concerning accuracy was not provided. All participants began by performing a practice block containing 32 targets, during which all of the nontargets were white in order to acquaint them with the task and response requirements.

Data analysis—Participants were scored as committing an error if an incorrect response was made or the trial timed out. Only accuracy was measured in the RSVP task. In the visual search task, response times three standard deviations above or below the mean in a given condition for a given participant were trimmed. Search slope was computed via a linear fit to response time as a function of set size. Target-present search slopes were used as an indication of search efficiency because they would be less influenced by any double-checking that would proceed in serial fashion, thus giving a more reliable estimate of how quickly the process of target selection occurs, which was of primary interest.

Results and Discussion

Mean accuracy in the visual search task was 95.4%. The mean search slope on target-present trials was 1.2 ms/item, reflecting highly efficient visual search and replicating previous results (Navalpakkam & Itti, 2006). This also confirms that observers could easily discriminate the target from the feature-similar nontargets in visual search. The search slope

was significantly above zero on target-present trials, $t(7) = 2.46$, $p = .043$, $d = 0.87$, suggesting that the target did not pop out of the display and thus the selection of the target involved some top-down guidance. The search slope on target-absent trials was 6.7 ms/item, which was also significantly above zero, $t(7) = 3.88$, $p = .006$, $d = 1.37$.

Importantly, in the RSVP task, the selection of the same color-defined target was substantially impaired by the presence of similar-colored nontargets, $t(7) = 11.26$, $p < .001$, $d = 3.98$, and this decrement in performance between similar color blocks and nonsimilar color blocks was present for all eight observers (see Table 1). If participants were capable of restricting attentional selection to stimuli falling within a narrowly defined region of color space, they should have been able to easily identify the target regardless of whether the similar-color nontargets were present. Contrary to this view, the results demonstrate a marked impairment in the ability to report the target when it must be selected from among feature-similar nontargets. This suggests that computing whether visual stimuli match a goal-defined target template is an inefficient mechanism of guiding attentional selection that breaks down under conditions in which comparisons with the template are made successively in time.

Experiment 2

Experiment 1 showed that observers are largely unable to restrict attentional selection to features that match a target template when doing so is necessary to perform the task accurately. Performance in the RSVP task was substantially impaired by the presence of feature-similar nontargets, demonstrating a marked lack of precision in goal-directed attentional selection mechanisms. This impairment occurred despite the fact that observers were able to efficiently discriminate these same colors to rapidly localize the target in a visual search task. In Experiment 2, a less stringent version of the precise template hypothesis was tested by using only one similar-color nontarget (red). Without the gold nontargets, the target color was no longer “sandwiched” between two similar-color nontargets in feature space, as in Experiment 1 and in Navalpakkam and Itti (2006). This allowed participants to linearly separate targets from similar-color nontargets in feature space, potentially making it easier to restrict attentional selection to only the target and thereby overcome any impairment by feature-similar nontargets.

As not to disrupt the probability of each nontarget color being presented, the gold nontargets were eliminated from the critical condition without making red nontargets occur twice as often in their place. Note that this alone would predict that any observed decrement caused by similar-color nontargets would be reduced compared with Experiment 1, as there were only half as many similar-color nontargets presented that could be confused with the target.

Method

Participants—Eight Johns Hopkins University undergraduate students (18 to 22 years of age; $M = 20.0$; five males) participated and were compensated with extra credit toward a variety of psychology courses. None of the participants had participated in the previous experiment.

Experimental tasks—The methods for the visual search task were identical to Experiment 1. The methods for the RSVP task were identical to Experiment 1, with the exception that the color gold was removed from the set of possible colors in the similar color blocks (see Figure 1D).

Results and Discussion

Data for one observer were replaced because of a comparatively large search slope of >16 ms/item on target-present trials. Although this observer showed the same decrement in the RSVP task as the other observers, it is unclear whether this decrement was the result of difficulty discriminating between the colors that were used. Mean accuracy in the visual search task was 97.3%, and the mean search slope on target-present trials was 2.7 ms/item, again reflecting highly efficient search. Target-present search slopes were significantly above zero, $t(7) = 4.23$, $p = .004$, $d = 1.50$; mean search slope on target-absent trials was 10.6 ms/item and also significantly above zero, $t(7) = 5.65$, $p = .001$, $d = 2.00$. Importantly, all eight observers were impaired at reporting the orange target in the presence of red nontargets in the RSVP task, $t(7) = 4.41$, $p = .003$, $d = 1.56$, with the impairment being roughly half that of Experiment 1 (see Table 2). Thus, even when only one type of similar-color nontarget was presented, observers were unable to utilize a target template capable of efficiently discriminating the target from this nontarget feature.

Experiment 3

Experiment 2 replicated the results of Experiment 1, again demonstrating a decrement in target selection caused by similar-color nontargets in an RSVP task. However, it could be argued that the decrement observed in Experiments 1 and 2 was caused by relatively less popout of the target in the presence of similar-color nontargets. This might occur because more total colors were presented when similar-color nontargets were included, making the nontargets more heterogeneous, which is known to decrease the efficiency of visual search (Duncan & Humphreys, 1989). Indeed, nontarget heterogeneity and the presence of similar-color nontargets have thus far been confounded in the experimental design.

Experiment 3 provides a strong test of the precise template hypothesis of goal-directed attentional selection. Participants performed the same visual search task, followed by an RSVP task in which the nontargets in the critical condition were only red and gold. This dramatically decreased the nontarget heterogeneity to well below that of the baseline nonsimilar color condition. Indeed, an RSVP task with only these two nontarget colors is the closest possible analog to the visual search task in which observers must select the target from among only similar-color nontargets. If goal-directed attentional selection via template matching is precise, performance in this RSVP task should be very high, mirroring the efficiency evident in the visual search task. However, if such goal-directed attentional selection is imprecise, observers will be largely unable to select and identify the target in the critical condition.

Method

Participants—Four Johns Hopkins University undergraduate students (18 to 21 years of age; $M = 19.0$; two males) participated and were compensated with extra credit toward a variety of psychology courses. None of the participants had participated in any of the previous experiments.

Experimental tasks—The methods for the visual search task were identical to Experiment 1. The methods for the RSVP task were identical to Experiment 1, with the exception that the possible nontarget colors only consisted of red and gold in the similar color blocks (see Figure 1D), and the color of the nontargets could be repeated on consecutive frames.

Results and Discussion

Overall visual search accuracy was 93.9%. Visual search for an orange target among similar-colored red and gold nontargets was again highly efficient, with a mean search slope of 1.9 ms/item on target-present trials that was significantly above zero, $t(3) = 3.28$, $p = .046$, $d = 1.64$. Mean search slope on target-absent trials was 5.1 ms/item, which was above zero for all four observers, $t(3) = 2.98$, $p = .058$, $d = 1.49$. When these same targets and nontargets were presented in an RSVP task, however, target identification was near chance level (25.8% vs. 25% chance) and more than twice as high when no such similar-colored nontargets were presented, $t(3) = 4.66$, $p = .019$, $d = 2.33$ (see Table 3). The results demonstrate that observers were essentially unable to select a target from among feature-similar nontargets on the basis of a match to a target template.

Experiment 4

So far, I have interpreted the decrement caused by similar-color nontargets in the RSVP task as reflecting limitations in template matching that were imposed by the sequential presentation of stimuli. By this account, the precision of selection was high in the static search task because other search mechanisms beyond template matching could be recruited to a greater extent. However, this comparison between tasks might be complicated by the raw difficulty of the RSVP task, which exceeds that of the static search task and indeed all other tasks that have been used to investigate the precision of attentional selection (e.g., Adamo et al., 2008; Adamo, Pun, et al., 2010; Adamo, Wozny, et al., 2010; Irons et al., 2012; Moore & Weissman, 2010; Roper & Vecera, 2012). This RSVP task involved a more demanding perceptual judgment (target identification vs. detection), greater crowding of stimuli (given the proximity of the flanking distractors), and the stimuli were presented comparatively far out in the periphery. Thus, although Experiments 1 to 3 have succeeded in demonstrating a limitation in the precision of template matching in visual search, the locus of this limitation (i.e., whether it is perceptual or attentional) is unclear.

To address this issue, Experiment 4 employed an RSVP task that was designed to be more comparable in its perceptual demands with the static search task. Four RSVP streams were used, which amounts to fewer items than even the smallest set size in the static search task. The flanking distractors were removed, eliminating crowding. Each RSVP stream was

presented closer to fixation than the average item in the static search task, and participants performed a simple present-absent judgment as in the static search task. A replication of the decrement in performance caused by similar-color nontargets in this version of the RSVP task would suggest that this decrement is specifically the result of attentional rather than perceptual limitations.

Method

Participants—Ten members of the Johns Hopkins University community (19 to 28 years of age; $M = 21.9$; three males) participated and were compensated with \$10. None of the participants had participated in any of the previous experiments.

Experimental tasks—The methods for the visual search task were identical to Experiment 1. The RSVP task now involved discrete trials; participants completed eight blocks of 48 trials each. Each trial began with a display in which only the fixation cross was visible for 1,000 ms (see Figure 1C). Then, four RSVP streams were presented for 16 frames, with the colored letters now being presented 3.7° above, below, to the left, and to the right of fixation. As in the prior experiments, letters in the RSVP streams were presented at a rate of 117 ms. On half of the trials, one of the letters in one of the RSVP streams was orange (target-present trials), which appeared equally often in each of the four locations within a block. Targets could appear in Frames 3 to 14 (each frame equally often within a block). Once all 16 frames of the RSVP streams had been presented, participants were immediately presented with a display that reminded them of the response keys (“Z” for absent and “M” for present) and the computer waited for them to indicate their response. Responses were not timed in the RSVP task, and participants were informed that responses were only recorded after the response prompt was presented. As in all prior experiments, participants alternated between blocks in which red and gold were included among the nontarget colors (order of blocks counterbalanced across participants). In the similar color blocks, the nontarget colors consisted of red, gold, blue, and green; in the nonsimilar color blocks, these colors consisted of blue, green, white, and purple (thus, four nontarget colors were used in each block; see Figure 1D).

Results and Discussion

The results from the static visual search task closely replicate the results from the first three experiments. Overall accuracy was 92.4%, mean target-present search slope was 2.7 ms/item, and mean target-absent search slope was 6.8 ms/item. Search slopes were significantly above zero on both target-present, $t(9) = 4.90$, $p = .001$, $d = 1.55$, and target-absent, $t(9) = 4.27$, $p = .002$, $d = 1.35$, trials. Importantly, the results from the RSVP task replicate the severe impairment in performance on similar color blocks observed in Experiments 1 to 3, $t(9) = 16.40$, $p < .001$, $d = 5.19$ (see Table 4).

This observed decrement in performance is consistent with a limitation in the precision of attentional selection via template matching. Given the sequential presentation of stimuli in the RSVP task, the ability to employ other selection mechanisms, such as comparing and rejecting nontargets, was minimized compared with the static search task, which once again replicated evidence for highly precise selection. With perceptual demands better equated

between the two tasks, the difference in the precision of selection between them likely reflects attentional rather than perceptual limitations.

General Discussion

Attention selects objects in a scene for perceptual representation, and the attentional selection of objects in visual search is guided by the goals of the observer (e.g., Wolfe, 1994; Wolfe et al., 1989). Attention can select the target of visual search very efficiently, even under highly demanding conditions in which the separation between the target and nontargets in feature space is small (Navalpakkam & Itti, 2006), reflecting optimal and adaptive behavior. Furthermore, studies using attentional capture paradigms have repeatedly shown that attentional selection can be optimally restricted to target-relevant features such that feature-similar non-targets can be ignored (e.g., Adamo et al., 2008; Adamo, Pun, et al., 2010; Adamo, Wozny, et al., 2010; Irons et al., 2012; Moore & Weissman, 2010; Roper & Vecera, 2012). One way to account for this high level of selectivity is to appeal to the precision of the attentional template, such that attention is directed to a stimulus on the basis of whether it falls within a narrowly defined range of a particular feature space.

The present results provide a striking dichotomy that challenges the precise template hypothesis. Although visual search is very efficient under demanding conditions in which the target and nontargets are perceptually similar in feature space, a profound failure to select this same target is observed when these stimuli are presented successively in time. If attentional selection proceeds from a process of computing whether a stimulus matches a precise representation of a goal-defined target template, attentional selection should be restricted to the target and highly efficient regardless of whether feature-similar nontargets are presented. However, the results of the present study show that this is clearly not the case.

These findings suggest that a goal-defined target template provides information that can only be used at a coarse perceptual level to guide selection. Such goal representations are insufficient to guide attentional selection under perceptually demanding conditions, as they cannot discriminate between targets and feature-similar nontargets. This previously unrecognized limitation of the attentional system, in which observers fail to utilize search goals to efficiently guide selection, suggests an account in which goal-directed attentional control settings cannot be narrowly tuned.

If visual search for a target among feature-similar nontargets is highly efficient, what other mechanisms might contribute to this efficiency beyond selection based on template matching? One likely possibility, as described earlier, is nontarget rejection. The rejection of nontargets has long been hypothesized to play an important role in facilitating goal-directed attentional selection, particularly when nontargets can be rejected as groups, based on similarity to each other (e.g., Duncan & Humphreys, 1989; Wolfe, 2007). Despite the recognized role of nontarget rejection in visual search (e.g., Moher & Egeth, 2012; Moher, Lakshmanan, Egeth, & Ewen, 2014), many recent accounts of goal-directed attentional control highlight the apparent precision of target selection processes (e.g., Irons et al., 2012; Moore & Weissman, 2010; Roper & Vecera, 2012). By substantially reducing the ability of observers to employ a strategy of rejecting nontargets through the use of an RSVP paradigm,

I show that nontargets possessing a feature similar to that which defines the target substantially impair the ability to restrict attention to just the target. Thus, without the ability to first find and reject nontargets, the process of target selection notably breaks down when the feature space that separates targets from nontargets is small. Recent theories also emphasize the use of relational target templates (e.g., the reddest stimulus) in mediating goal-directed attentional selection (Becker, 2010; Becker, Folk, & Remington, 2010, 2013). The observed decrement in performance is broadly consistent with such relational theories, in that the ability to select the target becomes much more difficult when the separation between targets and nontargets in feature space is minimized. The present findings argue that the process of template matching is subject to severe limitations in the precision of selection, and that other display-wide computations are necessary to perform even very basic target detection.

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Figure 1.

Experimental paradigm. (A) Example trial for the visual search task. Participants reported the presence or absence of an orange “X,” which was present on half of all trials. Set sizes of 8, 16, and 24 items were used. (B) Example sequence of events for a target presented in the rapid serial visual presentation (RSVP) task of Experiments 1 to 3. Participants monitored two streams of letters for an orange target while ignoring other-colored letters and surrounding symbols. After the presentation of an orange target, participants indicated its identity by selecting one of four letters appearing within the boxes surrounding fixation. (C) Example sequence of events for a target-present trial in the RSVP task of Experiment 4. Participants reported the presence or absence of an orange letter in any of the four letter

streams, which was present on half of all trials. (D) The colors used in the RSVP task of each experiment. Participants completed alternating blocks of trials in which similar-color nontargets (red and gold) either were or were not included in the stimulus set. Note: Stimuli are not drawn to scale and the colors depicted are only approximate representations of the colors as they appeared on the monitor used in the actual experiments.

Table 1

Accuracy in the RSVP Task of Experiment 1

Participant	Block type		Difference
	Similar colors absent	Similar colors present	
1	76.3%	39.7%	36.6%
2	72.4%	36.5%	35.9%
3	78.8%	45.5%	33.3%
4	77.6%	42.3%	35.3%
5	54.5%	41.7%	12.8%
6	67.9%	35.9%	32.0%
7	60.3%	30.1%	30.2%
8	82.1%	45.5%	36.6%
	71.2%	39.7%	31.6%

Note. Bold values represent column averages.

Table 2

Accuracy in the RSVP Task of Experiment 2

Participant	Block type		Difference
	Similar colors absent	Similar colors present	
1	66.0%	55.8%	10.2%
2	60.3%	40.4%	19.9%
3	60.9%	55.8%	5.1%
4	66.7%	55.1%	11.6%
5	53.2%	46.2%	7.0%
6	80.8%	53.2%	27.6%
7	72.4%	46.8%	25.6%
8	55.1%	49.4%	5.7%
	64.4%	50.3%	14.1%

Note. Bold values represent column averages.

Table 3

Accuracy in the RSVP Task of Experiment 3

Participant	Block type		Difference
	Similar colors absent	Similar colors present	
1	60.3%	31.4%	28.9%
2	62.2%	19.2%	43.0%
3	37.8%	24.4%	13.4%
4	68.6%	28.2%	40.4%
	57.2%	25.8%	31.4%

Note. Bold values represent column averages.

Table 4

Accuracy in the RSVP Task of Experiment 4

Participant	Block type		Difference
	Similar colors absent	Similar colors present	
1	96.9%	68.8%	28.1%
2	95.3%	63.5%	31.8%
3	95.8%	62.5%	33.3%
4	94.8%	55.7%	39.1%
5	94.3%	51.0%	43.3%
6	95.3%	64.6%	30.7%
7	93.8%	57.8%	36.0%
8	100%	75.5%	24.5%
9	100%	74.5%	25.5%
10	100%	73.4%	26.6%
	96.6%	64.7%	31.9%

Note. Bold values represent column averages.