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Simultaneous Control of Attention by Multiple Working Memory Representations

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Abstract

Working memory representations play a key role in controlling attention by making it possible to shift attention to task-relevant objects. Visual working memory has a capacity of three to four objects, but recent studies suggest that only one representation can guide attention at a given moment. We directly tested this proposal by monitoring eye movements while observers performed a visual search task in which they attempted to limit attention to objects drawn in two colors. When the observers were motivated to attend to one color at a time, they searched many consecutive items of one color (long run lengths) and exhibited a delay prior to switching gaze from one color to the other (switch cost). In contrast, when they were motivated to attend to both colors simultaneously, observers' gaze switched back and forth between the two colors frequently (short run lengths), with no switch cost. Thus, multiple working memory representations can concurrently guide attention.

Keywords

attention, visual search, eye movements

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The mechanisms of selective attention fall into two classes, those involved in determining relevant sources of information (*attentional control* mechanisms) and those responsible for enhancing the processing of relevant sources and inhibiting competing sources (*attentional selection* mechanisms; Luck & Vecera, 2002). Multiple factors contribute to attentional control; these factors include bottom-up salience, trial-by-trial priming, associative learning, and long-term knowledge (Chun & Turk-Browne, 2006; Kristjansson, 2008; Torralba, Oliva, Castelhano, & Henderson, 2006; Van der Stigchel et al., 2009). However, the guidance of attention toward task-relevant objects is thought to depend primarily on working memory representations (Soto, Hodsoll, Rotshtein, & Humphreys, 2008). Working memory guidance makes it possible for attention to "change gears" rapidly, because information can be loaded into visual working memory (VWM) in as little as 50 ms (Vogel, Woodman, & Luck, 2006), which leads to changes in the control of attention in 200 ms or less (Vickery, King, & Jiang, 2005; Wolfe, Horowitz, Kenner, Hyle, & Vasan, 2004).

The typical storage capacity of VWM is three to four items (Cowan, 2001; Luck, 2008). Consequently, one might expect that observers could maintain three to four simultaneous search templates, which would be useful in many natural tasks (e.g., finding either an orange or an apple on the counter). However, several researchers have argued that not all working memory representations are equal (Cowan, 2001) and that only a single object is in a fully active state (McElree, 2001; Oberauer, 2002). This view has led to a theory of attentional control in which only a single VWM representation can control attention at any given time (Olivers, Peters, Houtkamp, & Roelfsema, 2011). A similar claim is made by Huang and Pashler (2007), whose Boolean-map theory of attention proposes that the visual input can be subdivided into to-be-attended and to-be-ignored regions on the basis of just one feature value.

These proposed limits on VWM control could reflect a fundamental bottleneck in the architecture of the brain. It is possible that, despite the ability to represent multiple objects, only one control signal can be sent from working memory processes to attentional mechanisms that implement visual selection. However, an architectural division of this kind is difficult to reconcile with evidence that VWM and perceptual processes are closely integrated. VWM representations can be stored within the visual system itself (Luck, 2008), including within primary visual cortex (Harrison & Tong, 2009; Serences, Ester, Vogel, & Awh, 2009). If multiple VWM representations are active within

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the visual system, it should be possible for them to simultaneously control attention. In line with this possibility, a recent study found that observers could search selectively for targets matching two different templates (Stroud, Menneer, Cave, & Donnelly, 2012). However, the targets remained constant over the entire session, which made it likely that attention was guided by long-term memory rather than by working memory. It is also possible that observers switched back and forth between the templates rather than concurrently searching for both targets. Thus, it is unknown whether observers can use two working memory representations simultaneously to guide attention.

The present study addressed this fundamental issue by measuring the pattern of eye movements as observers searched for a target presented in either of two colors. If observers maintain only one search template at a time, they should tend to search many items of one color before switching to search items of the other color, with a brief pause as they switch from one control signal to the other. However, if observers can keep two templates active concurrently, then they should switch back and forth between objects in the two colors, with no delay when switching from objects in one color to objects in the other.

Experiment 1

Before testing observers' ability to search arrays of two different colors concurrently, we examined the pattern of eye movements when the task explicitly encouraged observers to search objects of one color and then switch to objects of another color. That is, Experiment 1 was designed to reveal the signatures of a single attentional template during search.

Each search array contained 12 red Landolt Cs, 12 blue Landolt Cs, and a cue square (Fig. 1). Observers searched for a target C with a gap on the top or bottom and reported the gap location. There were three conditions, in which the predictability of the target color was varied. In the 80-20 condition, observers were told that the target was 80% likely to be the same color as the cue square (which alternated between blue and red, depending on the trial block). These probabilities encouraged observers to search first among objects in the color with the 80% probability of containing the target (the *80% color*) and then, if the target had not been found, switch to objects of the other color (the *20% color*). We also included a 50-50 condition, in which the target was equally likely to be red or blue, and a 100-0 condition, in which the target was 100% likely to be either red or blue, depending on the trial block. The 50-50 and 100-0 conditions assessed the limits of attentional control when the color of the target was maximally and minimally uncertain.

In the 80-20 condition, we predicted that observers would fixate many items of the 80% color consecutively, more than would be predicted if observers switched back and forth between items of each color randomly (but with 80% of fixations directed toward the 80% color). We further predicted that observers would switch to the 20% color if they did not find the target in the 80% color, which would require updating the search template and therefore produce a delay in making the next saccade (such a delay would be analogous to switch costs in the task-switching literature; Monsell, 2003).

Method

Observers. Twelve observers (7 female, 5 male; age range = 18–30 years) from the University of California, Davis, completed the experiment. They reported normal color vision and normal or corrected-to-normal visual acuity.

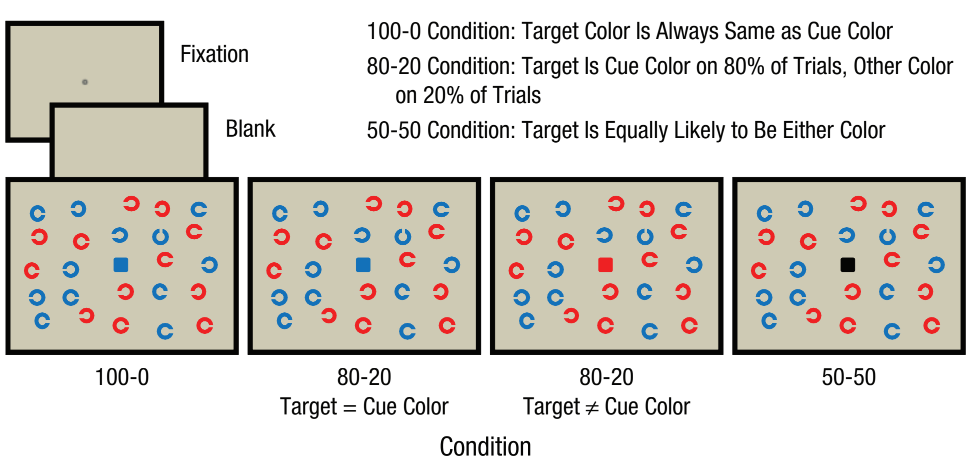

Fig. 1. Example trial sequence and search arrays for Experiment 1. Observers began each trial by gazing at a central fixation region for 300 to 500 ms. After a blank interval, a cue square and search array appeared. The cue color was the same in every stimulus array for a given block of trials. Each search array contained 24 Landolt Cs—half of which were red, and half of which were blue—presented on a light gray background. In the 100-0 condition, the target was always the cue color. In the 80-20 condition, the target was the cue color on 80% of trials and was the other color on the remaining 20% of trials. In the 50-50 condition, the cue was black, and the target was equally likely to be blue or red.

Stimuli and procedure. Stimuli were presented on a CRT monitor at a viewing distance of 70 cm. Each search array contained 24 Landolt Cs—12 red (8.12 cd/m^2) and 12 blue (8.96 cd/m^2)—presented against a gray background (42.31 cd/m^2; see Fig. 1). Color coordinates were quantified using the Commission Internationale de l'Éclairage (CIE) 1976 color-space diagram (red: u' = 0.479, v' = 0.514; blue: u' = 0.180, v' = 0.158; Wyszecki & Stiles, 1982). Each circle was 0.33° in diameter, had a line width of 0.10°, and a gap measuring 0.07°. Circles were assigned randomly to locations within a 5 × 5 grid (excluding the center location) and jittered within each cell by ±0.96° vertically and ±0.82° horizontally. There was one target circle (in which the gap was on the top or bottom) and 23 distractors (in which the gap was on the left or right).

Observers began each trial by directing their gaze to a central fixation region (a square 1.55° in width) for 300 to 500 ms. Then the cue square (0.65° in width) and search array appeared and remained on screen until the observer's response. In the 100-0 and 80-20 conditions, the cue square provided a constant reminder of the cued color throughout the search task. The cue square was black in the 50-50 condition. The different cue colors and probability conditions were presented in separate blocks (in counterbalanced order), and observers were informed of both factors at the beginning of each block.

Observers reported the location of the target gap by pressing a button. The gaps in the circles were so small that discriminating them required object fixation, and the task therefore implicitly required observers to translate covert attentional control into overt shifts of gaze. There were two blocks of 42 trials each in the 100-0 and 50-50 conditions and four blocks of 52 trials each in the 80-20 condition. There was a 1,000-ms delay between trials. The first two trials in each block were considered buffer trials and were excluded from all analyses.

Eye movements were recorded at 2000 Hz using an EyeLink 1000 eye tracker (SR Research, Kanata, Ontario, Canada). Saccades were defined by a combined velocity (> 30°/s) and acceleration (> 9500°/s^2) threshold.

Results and discussion

Manual response accuracy was uniformly high (M = 99% correct) across all conditions.

Selectivity of search. Observers used the cue to limit their gaze to the most likely target color. As Figure 2a shows, manual correct reaction time (RT) was fastest in the 100-0 condition and slowest when the target appeared in the 20% color of the 80-20 condition. All pairwise differences were significant ($p < .05$), except the difference in RT between the 50-50 condition and the trials from the 80-20 condition in which the target appeared in the 20% color. The same pattern was observed for the time required for gaze to reach the target item (all ps < .05; Fig. 2a) and for the number of items fixated prior to fixating the target (all ps < .05; Fig. 2b). The strong correspondence between eye movement measures and manual RTs validates the use of eye tracking to probe search efficiency in this paradigm. All subsequent eye movement analyses reported here are limited to fixations prior to the target fixation.

Selectivity was nearly perfect in the 100-0 condition, with almost all fixations directed to the cued color instead of the uncued color, $t(11) = 22.12$, $p < .001$. In the 80-20 condition, gaze was directed to the 80% color much more often than to the 20% color when the target was in the 80% color, $t(11) = 7.00$, $p < .001$, and somewhat more often when the target was in the 20% color, $t(11) = 4.57$, $p < .001$. In the 50-50 condition, gaze was directed nearly equally to the red and blue items, $t(11) = 0.90$, $p = .39$. Thus, observers used the color probability information to control the search process.

Run length. Next, we examined whether observers maintained a consistent color template in the 80-20 condition, producing several consecutive fixations on items in the same color. In this condition, observers might use a *sequential-exhaustive* strategy, in which they search the 80% color exhaustively and then switch to the 20% color if the target had not been found. Alternatively, observers might use an *independent-search* strategy, in which they select each successive saccade target independently, with an 80% probability of selecting the 80% color and a 20% probability of selecting the 20% color. To distinguish these possibilities, we examined the number of items of a particular color fixated consecutively (*run length*). The sequential-exhaustive strategy should result in a greater mean run length than the independent-search strategy. Monte Carlo simulations were used to assess whether the observers conformed to these strategies (see the Supplemental Material available online). We examined the initial run at the beginning of each trial. In addition, we focused on trials in which the target appeared in the 20% color and observers started by searching items in the 80% color, as this circumstance required observers to switch colors to detect the target (similar results were obtained when the target appeared in the 80% color).

The mean initial run length was 6.61 items, which was significantly greater than the run length of a simulated observer (4.63 items) that independently selected each saccade destination according to the 80-20 probabilities, $t(11) = 2.203$, $p = .05$. Observed run length was also significantly greater than the initial run length of 2.07 in the 50-50 condition, $t(11) = 5.12$, $p < .001$. Run length for the 50-50 condition was nearly identical to the value expected if red and blue items were fixated randomly (2.00 items). Thus, run length can be a signature of search template use.

Monte Carlo analyses demonstrated that the optimal strategy in the 80-20 condition would be to first search all 12 items in the 80% color, but the mean initial run length (6.61 items) was significantly less than 12, $t(11) = 5.98$, $p < .001$. Although observers maintained a template of the 80% color, they tended to switch to the 20% color sooner than was optimal. This may

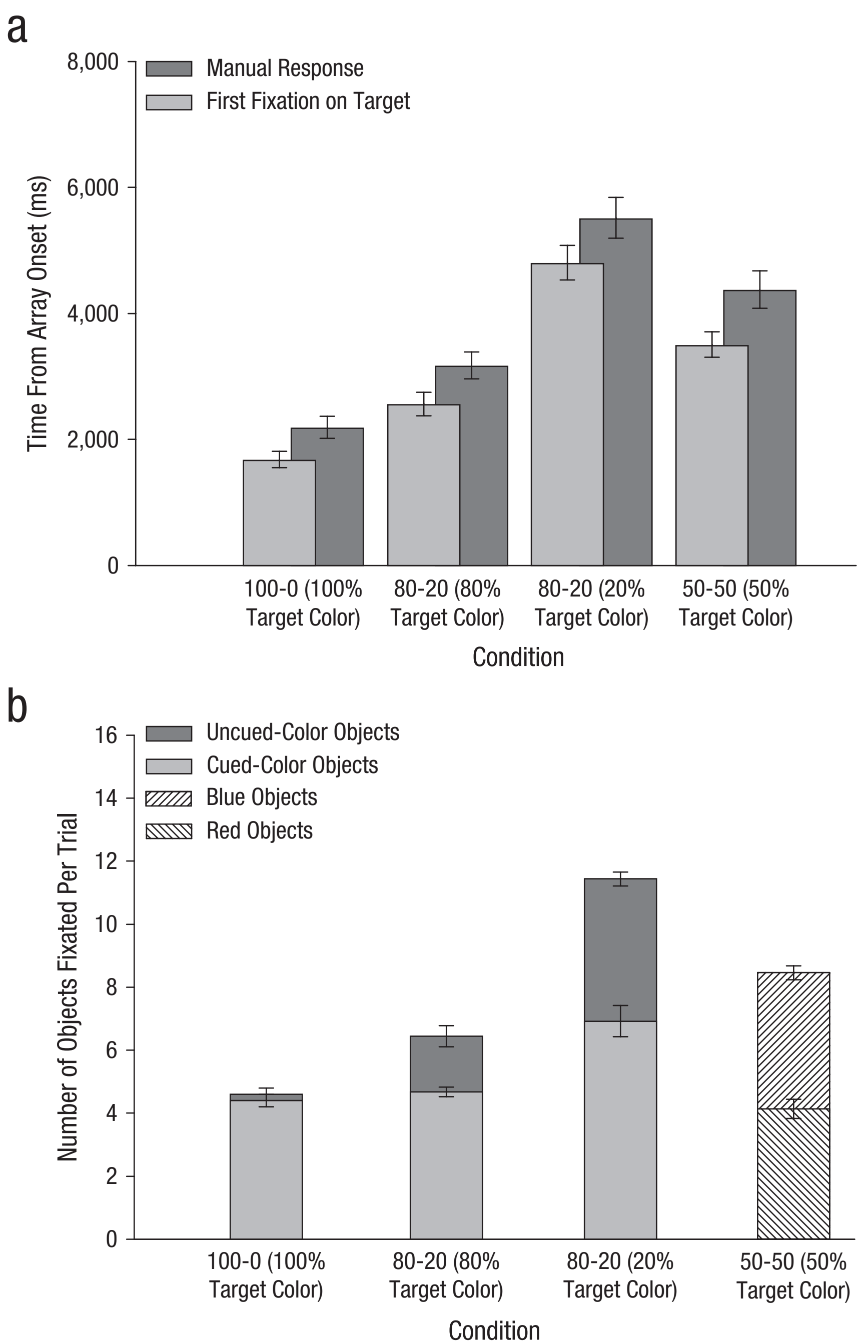

Fig. 2. Response times (a) and number of objects fixated per trial (b) in Experiment 1. Mean manual response times and mean times to target fixation are shown as a function of condition. The mean number of objects fixated per trial is shown as a function of condition and whether items were cued or uncued; the height of each bar indicates the total number of objects fixated, and the shading indicates how that total was divided between cued- and uncued-color objects (in the 100-0 and 80-20 conditions) or between red and blue objects (in the 50-50 condition). Error bars in both panels show within-subjects 95% confidence intervals (Morey, 2008).

reflect limits on the ability to keep track of which items have already been searched (Horowitz & Wolfe, 1998; Peterson, Kramer, Wang, Irwin, & McCarley, 2001) or it may reflect a tendency to engage in suboptimal probability-matching strategies (Vulkan, 2000).

Switch cost. We next examined the process of switching from one template to another. As Figure 3 shows, the duration of the fixation immediately before switching (preswitch fixation) was significantly greater than both the duration of the fixation immediately prior to the preswitch fixation (preswitch fixation

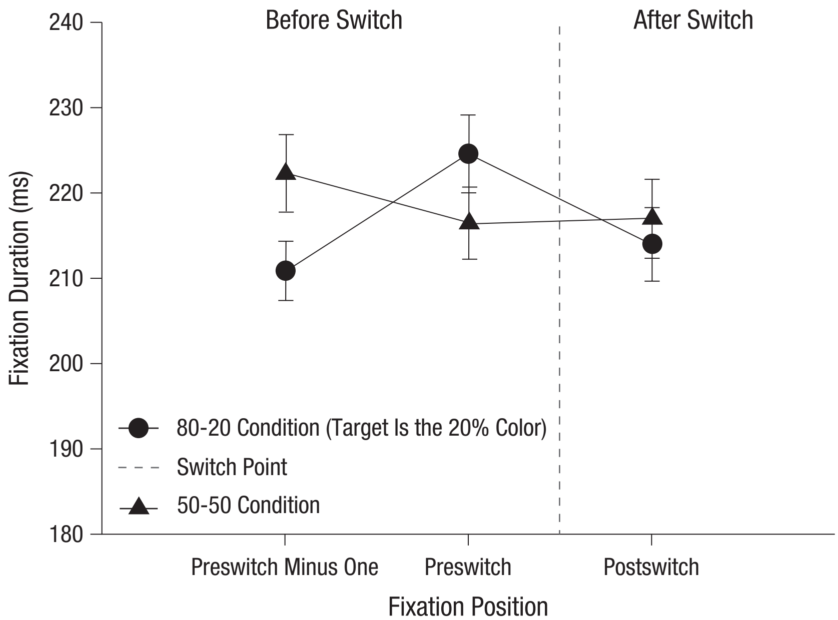

Fig. 3. Mean duration for fixations immediately prior to and following switches from fixating objects of a given color to fixating objects of the other color in Experiment 1. Durations are shown for the two fixations prior to the switch and the fixation after the switch in the 80-20 and the 50-50 conditions. In the 80-20 condition, this analysis was restricted to trials on which observers switched from a run of cued-color items to a run of uncued-color items. In the 50-50 condition, we analyzed trials on which observers switched from a run of one color to a run of the other color. A run occurred when two or more objects of the same type were fixated consecutively. Error bars show within-subjects 95% confidence intervals (Morey, 2008).

minus one), $t(11) = 3.12$, $p = .01$, and the duration of the first fixation on the new color (postswitch fixation), $t(11) = 2.16$, $p = .05$. A key finding is that this switch cost was not present in the 50-50 condition, in which observers often switched randomly from one color to the other. The difference in switch costs between the 80-20 and 50-50 conditions was confirmed by an analysis of variance (ANOVA) with condition (80-20 vs. 50-50) and fixation position (preswitch fixation minus one vs. preswitch fixation) as factors. There was a significant interaction between condition and fixation position, $t(11) = 2.61$, $p = .02$, but there were no significant main effects. Thus, observers produced a switch cost only when they were actively selecting on the basis of color; this finding provides a second signature of a search template use.

Summary. Together, these results provide strong evidence that observers can form a strong search template when the task encourages it, limiting gaze almost perfectly to cued-color items when the cue is 100% valid and limiting gaze primarily to cued-color items when the cue is 80% valid. Moreover, observers consecutively searched many items of the cued color, and they exhibited a cost when they switched from searching items of one color to items of the other. When color was nonpredictive, however, observers ignored color and switched randomly between red and blue with no switch cost. These patterns serve as signatures of search template use that can be applied to the main question of the study: Can observers maintain two templates concurrently in VWM?

Experiment 2

In Experiment 2, a cue was presented before the onset of the search array, and the cued colors changed randomly from trial to trial (Fig. 4). Consequently, it was necessary to store the cued colors in VWM and use the VWM representation to guide attention (Chelazzi, Miller, Duncan, & Desimone, 1993; Vickery et al., 2005; Wolfe et al., 2004; Woodman, Luck, & Schall, 2007). Each search array contained eight items in each of four colors, and either one or two of these four colors was indicated by the cue. The target was always a cued color. We tested whether observers would concurrently search items in two of the four colors when two colors were cued or, alternatively, search multiple items of one color and then switch to the other color (as they typically did in the 80-20 condition of Experiment 1).

Because observers may be able to strategically control whether they maintain two simultaneous templates or switch between one template and another, we gave observers explicit instructions about which strategy to use. In half of the trial blocks, they were instructed to search items of one color and then switch to the other. In the other half, they were instructed to search items of both of the two cued colors concurrently.

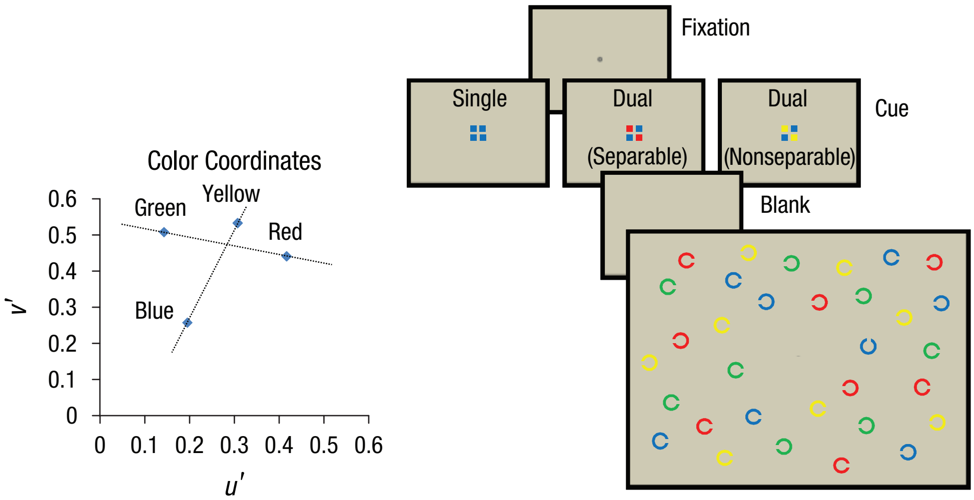

Fig. 4. Color coordinates for the search objects and trial sequence in Experiment 2. The graph shows the values of the four colors used in the experiment; these colors were quantified using the Commission Internationale de l'Éclairage 1976 color-space diagram (Wyszecki & Stiles, 1982) to form a quadrangle in color space. Observers began each trial by gazing at a central fixation region for 300 to 500 ms, after which a cue appeared in the center of the screen for 500 ms. On single-cue trials, all four squares in the cue were the same color; on dual-cue trials, the two cued colors were presented in diagonally opposed squares. There were two types of dual-cue trial: On separable trials, the two cued colors were drawn from one side of the quadrangle. On nonseparable trials, the two cued colors were drawn from opposite sides of the quadrangle. A 500-ms blank interval followed presentation of the cue, after which the search array appeared. Each array contained 32 Landolt Cs—8 red, 8 blue, 8 yellow, and 8 green—presented at randomly selected locations on a gray background.

The goal was to determine whether they could actually search both cued colors concurrently when instructed to do so.

Method

Eleven new observers (8 female, 3 male; age range = 18–30 years) participated in Experiment 2. Stimuli were presented on a CRT monitor at a viewing distance of 70 cm. Each trial began with the presentation of a cue square, which subtended 0.79° and was composed of four smaller squares, each subtending 0.36°. On single-cue trials, all four squares in the cue were the same color; on dual-cue trials, two diagonally opposed squares were presented for each of the two cued colors.

On all trials, the cue square was followed by a search array containing 32 Landolt Cs—8 red (CIE 1976 colors: $u' = 0.414$, $v' = 0.443$; 18.75 cd/m^2), 8 blue (CIE 1976 colors: $u' = 0.193$, $v' = 0.259$; 18.60 cd/m^2), 8 yellow (CIE 1976 colors: $u' = 0.305$, $v' = 0.535$; 18.67 cd/m^2), and 8 green (CIE 1976 colors: $u' = 0.141$, $v' = 0.510$; 18.60 cd/m^2)—presented against a gray background (39.65 cd/m^2). As in Experiment 1, each circle was 0.33° in diameter, had a line width of 0.10°, and a gap measuring 0.07°. Landolt Cs were assigned randomly to locations within a 20.85° × 15.82° region, with a minimum inter-item distance of 2.10° and a minimum distance from the region's center of 1.96°.

To ensure that observers focused on the cue colors and did not simply search for an item with a top or bottom gap, one item of an uncued color contained a top or bottom gap. The target was therefore defined as having both the cued color and a top or bottom gap.

When two colors are cued, observers might form a single template that covers a broad area of color space including both colors, but this is possible only when the cued colors are linearly separable from the uncued colors (Duncan & Humphreys, 1989; D'Zmura, 1991). Color values were selected to form a quadrangle in CIE 1976 color space (see Fig. 4). On separable dual-cue trials, the two cued colors were on one side of the quadrangle (e.g., red and yellow), and the two uncued colors were on the other (e.g., green and blue); presenting them in this fashion made it possible for observers to form a single template that was closer to the two cued colors than to the two uncued colors. On nonseparable dual-cue trials, the two cued colors were diagonally opposed in color space (e.g., red and green), and the two uncued colors were diagonally opposed along the orthogonal direction (e.g., blue and yellow). Presenting the colors in this manner ensured that no single color value was closer to the cued colors than to the uncued colors. It has been well established that this method precludes the use of a single template for both cued values (Duncan & Humphreys, 1989; D'Zmura, 1991). Single-cue, separable dual-cue, and nonseparable dual-cue trials were randomly intermixed.

Observers began each trial by directing their gaze to a central fixation region (1.55°) for 300 to 500 ms, after which the cue appeared in the center of the screen for 500 ms. After a 500-ms blank interval, the search array appeared. Observers were instructed to search items in one color at a time in half of the trial blocks (sequential-search condition) and to search items in the two colors simultaneously in the other half (simultaneous-search condition). They reported whether the gap on the target circle was on the top or the bottom by pressing a button. Observers performed 16 blocks of 32 trials each, which yielded a total of 120 single-cue, 240 separable dual-cue, and 120 nonseparable dual-cue trials (after excluding two warm-up trials in each block). Block order was counterbalanced, and there was a 1,200-ms delay before each trial. Eye movements were recorded and saccades were defined as in Experiment 1.

Results and discussion

Overall search performance. Manual response accuracy was uniformly high across all conditions (M = 97% correct). Search RT was lower on single-cue trials than on dual-cue trials (Fig. 5a), $t(10) = 18.27$, $p < .001$, which reflected the fact that attention was limited to 8 items on single-cue trials versus 16 items on dual-cue trials. The single-cue trials replicated the results from the 100-0 condition of Experiment 1.

For dual-cue trials, there was no significant effect of instructions (sequential search vs. simultaneous search) on

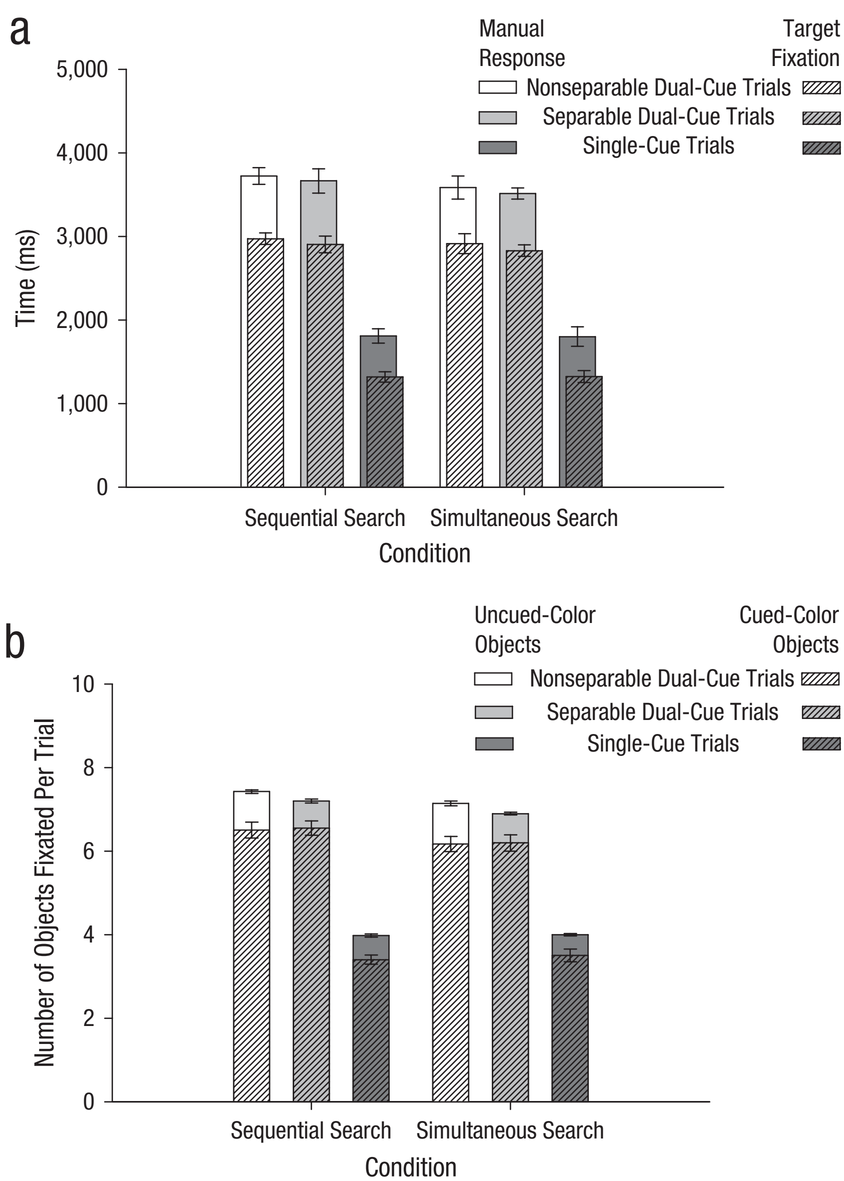

Fig. 5. Response times (a) and number of objects fixated per trial (b) in Experiment 2. Mean manual response times and mean times to target fixation are shown as a function of condition and cue type. The mean number of objects fixated per trial is shown as a function of condition and cue type, separately for objects of the cued and uncued colors. The height of each bar indicates the total number of objects fixated, and the shading shows how that total was divided between cued- and uncued-color objects. Error bars in both panels show within-subjects 95% confidence intervals (Morey, 2008).

manual RT, elapsed time to target fixation, or the number of items fixated prior to target fixation (Fig. 5a; all ps > .22). For all three of these measures, there was no difference between separable and nonseparable trials (all ps > .25). A Bayes factor analysis (Rouder, Speckman, Sun, Morey, & Iverson, 2009) indicated that the null hypothesis was substantially more probable than the hypothesis that performance in the separable and nonseparable dual-cue trials differed (odds ratio of 4.0 for RT, 3.4 for time to target fixation, and 2.3 for number of fixations). Consequently, we collapsed the data for separable and nonseparable dual-cue trials in all subsequent analyses.

Selectivity and speed of search. Observers fixated fewer items on single-cue trials than on dual-cue trials (Fig. 5b), which reflects the smaller number of potential targets on single-cue trials. Fixation durations were 18 ms faster on single-cue trials than on dual-cue trials, $t(10) = 9.00$, $p < .001$. Thus, there was an advantage to having a single target color. This does not imply that observers were unable to maintain multiple templates; it may simply indicate that maintaining multiple templates requires additional resources.

Observers were just as selective and just as fast when instructed to search both colors simultaneously as when instructed to search the two colors sequentially (Fig. 6). To

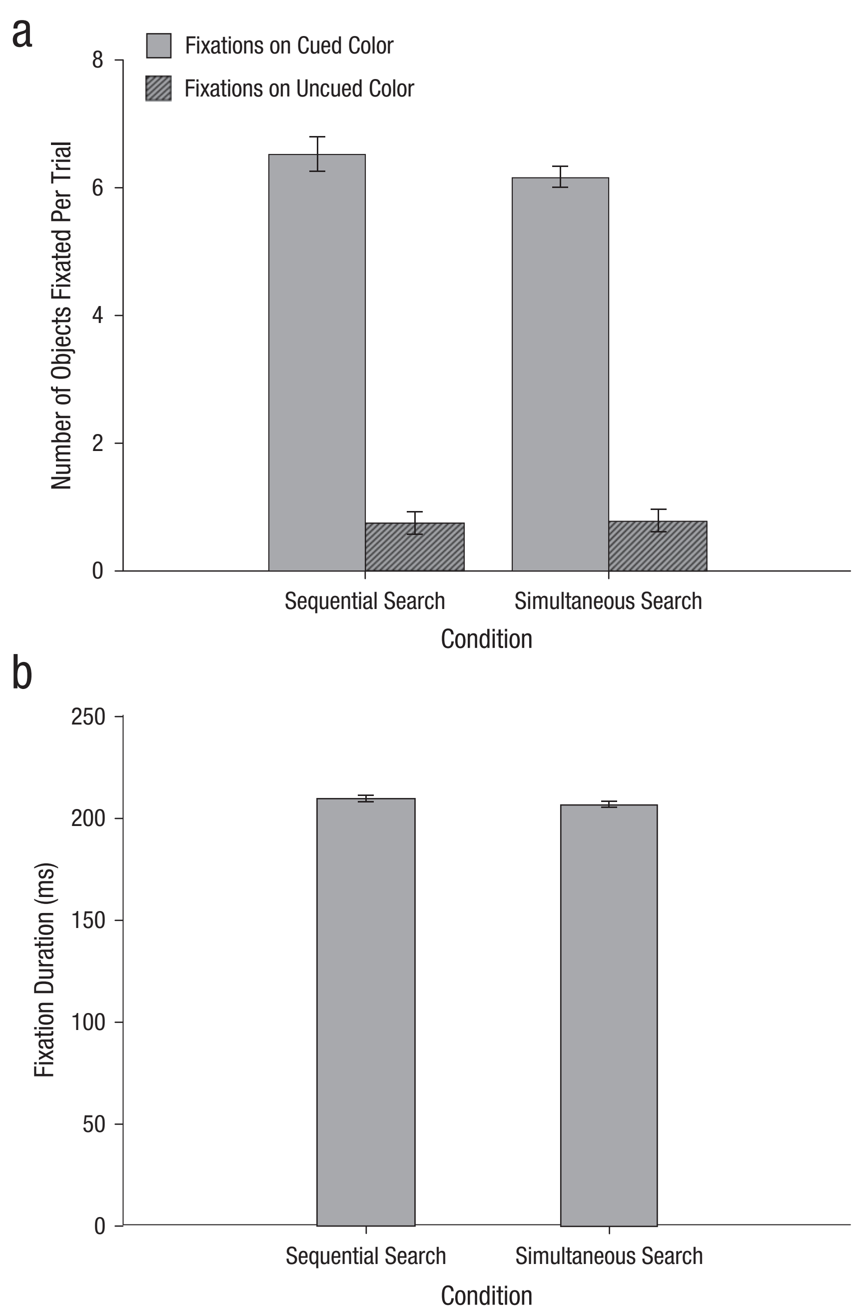

Fig. 6. Mean number of cued-color and uncued-color objects fixated per trial (a) and mean fixation durations for cued-color objects (b) as a function of condition in Experiment 2. Results are shown for dual-cue trials only; data are collapsed across separable and nonseparable trials. Error bars show within-subjects 95% confidence intervals (Morey, 2008).

quantify selectivity, we computed the proportion of fixations that were directed to the cued color (fixations to cued color/(fixations to cued color + fixations to uncued color)). These values did not differ significantly between the sequential- and simultaneous-search conditions, $t(10) = 0.52$, $p = .62$, and Bayes factor analysis indicated that the null hypothesis was 3.9 times more probable than the alternative hypothesis. Fixation durations were nearly identical in the sequential- and simultaneous-search conditions, $t(10) = 1.34$, $p = .21$, with the null hypothesis 2.0 times more likely than the alternative hypothesis. Thus, attempting to search both cued colors simultaneously produced no disruption in the ability to search rapidly or selectively.

Run length. Figure 7 shows representative scan paths from individual trials on which red and green were cued in the sequential-search and simultaneous-search conditions. The observer was highly selective in both conditions, limiting gaze to the two cued colors. The observer searched seven consecutive red items and then five consecutive green items in the sequential-search example, but went back and forth between red and green items multiple times with short runs in the simultaneous-search example. To quantify this difference, we computed mean initial run length, as in Experiment 1. Mean run length was significantly smaller in the simultaneous-search condition (2.4 items) than in the sequential-search condition (3.4 items), $t(10) = 2.72$, $p = .02$. Mean initial run length for the simultaneous-search condition was quite close to the value expected if observers randomly selected items in the two cued colors (1.8 items), whereas the mean run length for the sequential-search condition (3.4 items) was significantly greater than would be expected by random selection, $t(10) = 4.27$, $p = .002$.

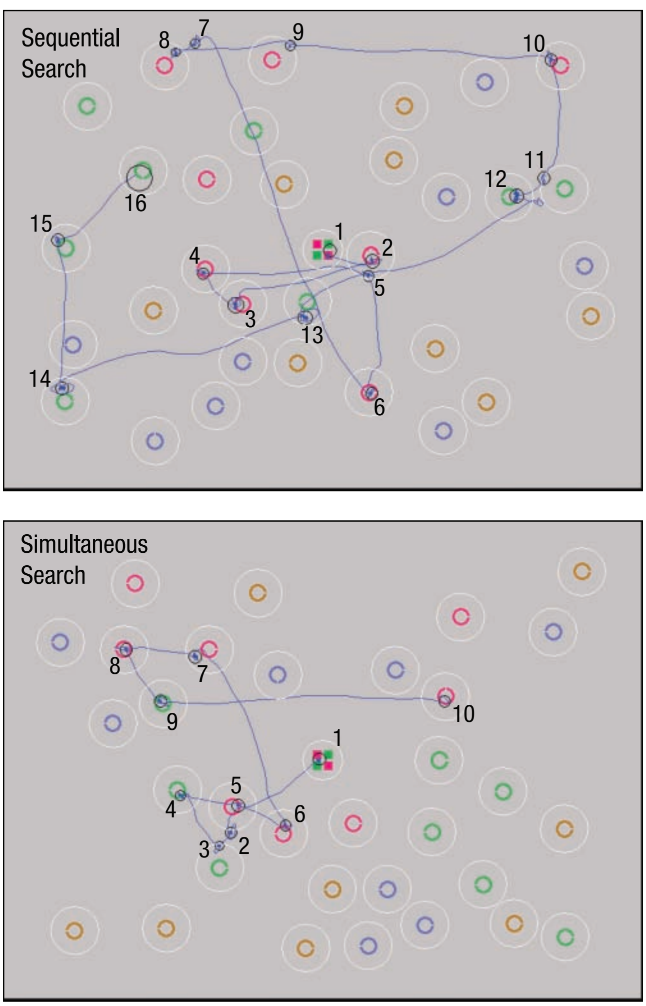

Fig. 7. Sample scan paths for a sequential-search trial (upper panel) and a simultaneous-search trial (lower panel) in Experiment 2. In both trials, the observer was cued to search for a target among both red and green objects. The order of fixations (indicated by the small black circles) is numbered.

Switch cost. There was a significant switch cost (increase in the duration of preswitch fixations relative to the preceding fixations) in the sequential-search condition (23-ms difference), $t(10) = 2.57$, $p = .03$; this finding indicates that observers actively switched from one template to the other in this condition (Fig. 8). However, there was no significant switch cost in the simultaneous-search condition (1.5-ms difference), $t(10) = 0.23$, $p = .82$. Bayes factor analysis indicated that the null hypothesis was 4.4 times more likely than the alternative hypothesis, which indicates that observers were not switching between templates in this condition. An ANOVA with instruction condition and fixation position as factors yielded a significant interaction, $t(10) = 2.35$, $p = .04$; this interaction indicates that there was a smaller switch cost in the simultaneous-search condition than in the sequential-search condition.

One possible alternative explanation for a lack of switch cost is that, in the simultaneous-search condition, the preparation for switching was spread out over several fixations instead of being limited to the preswitch fixation. If this were the case, and the switch cost in the simultaneous-search condition was incorporated into many fixations, the overall mean fixation duration should be greater in that condition than in the sequential-search condition. As Figure 6b shows, however, there was no difference in mean fixation durations across the simultaneous- and sequential-search conditions.

Summary. These results indicate that observers can either activate two templates sequentially or activate them both simultaneously, depending on the task instructions. When asked to search items in two colors sequentially, observers exhibited relatively long runs of items in a given color and a switch cost when they shifted from items in one color to items in the other. When asked to search items in the two colors simultaneously, they shifted back and forth between items in both colors more frequently, and there was no switch cost when they shifted from items in one color to items in the other. In addition, the overall speed and selectivity of search was virtually equivalent for these two search tasks. These results demonstrate that people are able to maintain two active representations in VWM that guide attention concurrently.[1]

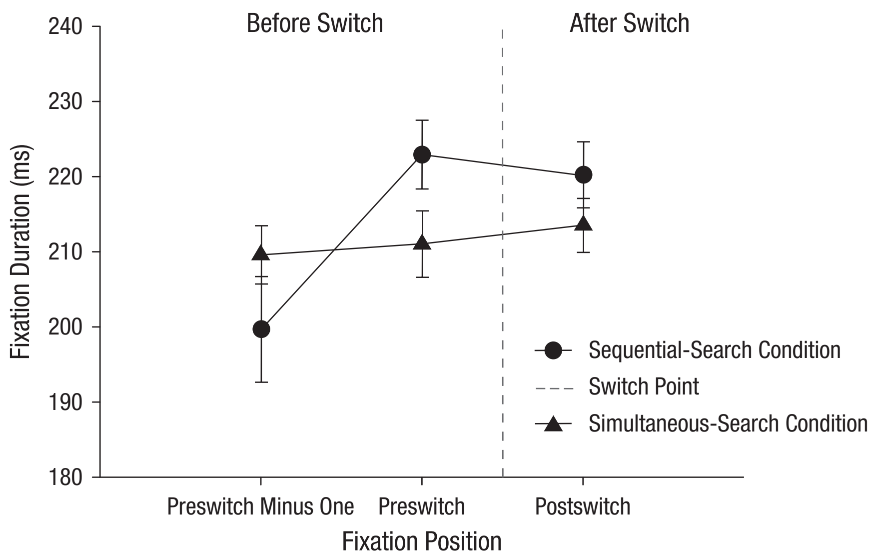

Fig. 8. Mean duration for fixations immediately prior to and following switches from searching objects of one cued color to searching objects of the other cued color in Experiment 2. Durations are shown for the two fixations prior to the switch and the fixation after the switch in the sequential-search and simultaneous-search conditions. This analysis was restricted to trials on which the target color was not initially searched, and it was limited to trials on which observers switched from a run of nontarget cued-color items to a run of target-color cued-color items. A run occurred when two or more objects of the same type were fixated consecutively. Error bars show within-subjects 95% confidence intervals (Morey, 2008).

General Discussion

The results of the experiments reported here directly demonstrate that people can use multiple attentional templates to simultaneously guide search toward relevant objects. In Experiment 1, we identified two signatures of the use of a single attentional template to guide search: long runs of fixations on items that matched the template and a switch cost when observers shifted from one template to another. In Experiment 2, we used these signatures along with other measures to demonstrate that observers can maintain two concurrent templates when asked to do so. Searching objects in either of two colors concurrently led to no impairment in the time required to find and report the target compared with searching objects in either of the two colors sequentially. Moreover, in the simultaneous-search condition, observers shifted their gaze back and forth between the two cued colors over short run lengths, and no switch cost was present when they shifted from one color to the other. Thus, searching for two distinct features concurrently led to no cost relative to searching for these features sequentially, and gaze patterns indicated that both templates were concurrently active.

These results provide an important constraint on the architecture of cognition. Specifically, they demonstrate that the multiple representations that are concurrently stored in VWM (Cowan, 2001; Luck, 2008) can simultaneously be linked to the control of attention. In other words, there is no single-channel bottleneck in top-down attentional control. Instead, multiple VWM representations may interact directly with the flow of sensory information through the visual system, a finding consistent with the fact that visual perception and VWM operate within the same regions of visual cortex (Harrison & Tong, 2009; Serences et al., 2009).

It is difficult to know with certainty why previous studies failed to find evidence of multiple simultaneous templates (see reviews by Huang & Pashler, 2007; Olivers et al., 2011). The present study found that observers could voluntarily decide whether to search for items in two cued colors sequentially or simultaneously, so it is possible that previous studies simply failed to induce the observers to activate the templates simultaneously. Indeed, one previous study found a switch cost that was comparable with the cost observed in the sequential condition of our study (Dombrowe, Donk, & Olivers, 2011). Moreover, the present results indicate that there is a cost to maintaining multiple templates, and this cost may have motivated observers in previous studies to use other strategies (e.g., using singleton-detection mode in the study of Eimer & Kiss, 2010). In other cases, the task required observers to link particular features with particular locations (Adamo, Pun, Pratt, & Ferber, 2008; Parrott, Levinthal, & Franconeri, 2010; Wolfe et al., 1990), and this may be more difficult than merely activating two features. In any case, the present results demonstrate that people can, under some circumstances, activate multiple search templates simultaneously, even if there are limits on the situations in which they can do so.

Declaration of Conflicting Interests

The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

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Supplemental Material

Additional supporting information may be found at http://pss.sagepub.com/content/by/supplemental-data

Note

1. We frame this ability as the simultaneous maintenance of two templates in VWM. An equivalent formulation would be to say that a single template composed of multiple, individual color values is maintained in VWM. The only difference between these descriptions is whether one applies the term "template" to the entire system of VWM or to the individual representations maintained within VWM.

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