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Interactions between space-based and feature-based attention

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Abstract

Although early research suggested that attention to nonspatial features (*i.e.*, red) was confined to stimuli appearing at an attended spatial location, more recent research has emphasized the global nature of feature-based attention. For example, a distractor sharing a target feature may capture attention even if it occurs at a task-irrelevant location. Such findings have been used to argue that feature-based attention operates independently of spatial attention. However, feature-based attention may nonetheless interact with spatial attention, yielding larger feature-based effects at attended locations than at unattended locations. The present study tested this possibility. In two experiments, participants viewed a rapid serial visual presentation (RSVP) stream and identified a target letter defined by its color. Target-colored distractors were presented at various task-irrelevant locations during the RSVP stream. We found that feature-driven attentional capture effects were largest when the target-colored distractor was closer to the attended location. These results demonstrate that spatial attention modulates the strength of feature-based attention capture, calling into question the prior evidence that feature-based attention operates in a global manner that is independent of spatial attention.

Keywords

Attentional capture; spatial attention; feature-based attention

Introduction

To cope with the large quantity of incoming sensory information, attention can be directed toward spatial locations or toward nonspatial features, such as the color red (Egeth & Yantis, 1997). This nonspatial attention is often called *feature-based attention*, and it can guide spatial attention toward relevant objects in visual scenes (e.g., Leonard, Lopez-Calderon, Kreither, & Luck, 2013).

Two theoretical perspectives have been proposed to describe the relationship between spatial attention and feature-based attention. One perspective proposes that feature-based attention operates later than spatial attention. For example, Hillyard and Münte (1984) found electrophysiological evidence that feature-based attention was gated by spatial processing.

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Specifically, neural activity differed for task-relevant features compared to task-irrelevant features at an attended location, but not at an unattended location (see also, Anllo-Vento & Hillyard, 1996; Eimer, 1995).

A second perspective proposes that feature-based attention is spatially global, operating independently of spatial attention. For example, Folk, Leber, and Egeth (2002) showed that distractors possessing an attended feature at unattended peripheral locations can impair performance on a central task. Similarly, when observers attend to a specific motion direction at one location, adaptation effects spread to unattended locations (Liu & Mance, 2011). Feature-based attention effects have also been observed at unattended locations with neural measures (Bichot, Rossi, & Desimone, 2005; Saenz, Buracas, & Boynton, 2002; Serences & Boynton, 2007; Treue & Martinez Trujillo, 1999; Zhang & Luck, 2008). However, the mere finding of feature-based attention effects at unattended locations is not sufficient to claim that feature-based attention is global and independent of spatial attention: Spatial attention often falls off gradually, and “unattended locations” may not be completely unattended. To demonstrate that feature-based attention is spatially global, it would be necessary to demonstrate that feature-based attention is independent of distance from the attended location.

The present study therefore used the Folk et al. (2002) attentional capture task to determine whether a target-colored distractor would capture attention more strongly when it was closer to the attended location. Participants monitored a central RSVP stream for a target letter of the attended color, with peripheral distractors appearing at one of two lags before target presentation (Figure 1). Previous research shows that a peripheral target-colored distractor will capture attention, leading to impaired performance for the central target when the distractor-target delay is short. If the capture effect is independent of the distance between the distractor and the RSVP stream, then this would support the claim that feature-based attention is independent of spatial attention. However, if the capture effect decreases with increasing separation between the distractor and the attended location, this would call into question the proposal that feature-based attention is spatially global.

To preview the results, we found that feature-based attentional capture declined as the distance between the target and the RSVP stream increased (Experiment 1A), even when distractors were scaled for cortical magnification (Experiment 1B). This falloff was also observed when both the RSVP stream and the distractor were presented at equal eccentricities in the periphery, which controls for reduced color discriminability in the periphery (Experiment 2).

Experiment 1

Methods

Participants—In Experiment 1a, 16 undergraduate students (7 females; mean age 21.6 years) with normal or corrected-to-normal acuity and normal color vision participated in a 60-minute session in exchange for course credit. For Experiment 1b, 16 additional students were recruited (10 females; mean age 22.5 years). One participant misunderstood the task and was excluded.

Stimuli and Task—Participants viewed a 53-cm CRT monitor (60 Hz) with a gray background (47 cd/m^2, CIE XY: 0.28/0.31) from a 70 cm viewing distance. The experiment was run using Psychtoolbox-3 (Kleiner, Brainard, & Pelli, 2007).

On each trial, an RSVP stream of randomly selected letters (excluding Q, I, O, W, and M) was presented in Arial font, with an average letter size of 0.9° × 0.66°. Each stream contained one color-defined target letter and 14 nontarget letters, each presented for 83 ms followed by a 17-ms blank screen (Figure 1). The target appeared with equal likelihood at positions 8, 9, 10, 11, and 12. The target was either red (16.3 cd/m^2, CIE XY: 0.61/0.34) or blue (11.8 cd/m^2, CIE XY: 0.15/0.09) in separate blocks of 200 trials (with order counterbalanced). Each nontarget letter could be magenta (12.5 cd/m^2, CIE XY: 0.29/0.16), yellow (8.3 cd/m^2, CIE XY: 0.38/0.50), or green (9.4 cd/m^2, CIE XY: 0.28/0.56), randomly selected for each letter.

The task was to detect a target defined by its color (red or blue) and report its identity with an unspeeded keyboard response. A blank intertrial interval (1.0–1.4 s) followed the response.

A pair of peripheral distractors ("#" symbols) was present in 80% of trials. One distractor in each pair was dark gray (8.1 cd/m^2, CIE XY: 0.28/0.33), and the other was either red or blue with equal likelihood. Thus, the colored distractor either matched or mismatched the current target color. Distractor onset preceded target onset by either 200 or 500 ms. The distance between the peripheral distractors and the center stream varied such that the edges of the center letter were 0.33°, 0.80°, 1.23°, or 3.68° away from the inside edges of the symbols. In Experiment 1A, the distractor symbol was 0.9° × 0.6°. In Experiment 1B, the distractor sizes were scaled for eccentricity according to the cortical magnification factor (Rovamo & Virsu, 1979). At the closest distance, distractor was the same size as in Experiment 1A.

Results

In the distractor-absent trials, mean accuracy was 77.7% in Experiment 1A and 76.9% in Experiment 1B. The results for distractor-present trials are presented as *capture cost*, which is the reduction in accuracy on distractor-present trials relative to the distractor-absent baseline. Capture cost is shown in Figure 2 as a function of distractor distance, distractor type, and distractor lag. Target-colored distractors produced a much larger capture cost than irrelevant-colored distractors at the 200-ms lag, but very little capture cost was observed for either type of distractor at the 500-ms lag (as is typical in this paradigm). Critically, the capture cost at the 200-ms lag declined substantially as the distance between the distractors and the RSVP stream increased. For example, a target-colored distractor produced a drop in accuracy of ~30% when it was 0.33° from the RSVP stream, whereas the drop in accuracy was only ~10% at a distance of 3.68°. Irrelevant-colored distractors did not produce sizable capture at either lag, regardless of distance.

For each experiment, capture cost was subjected to a repeated-measures analysis of variance (ANOVA) with factors of distractor type (target-colored versus irrelevant-colored), lag (200 versus 500 ms), and distance. For both experiments, there were significant main effects of type (1A: $F(1,15) = 36.5$, $p<0.001$; 1B: $F(1,14) = 35.5$, $p<0.001$), lag (1A: $F(1,15) = 25.1$,

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$p<0.001$; 1B: $F(1,14) = 16.4$, $p=0.001$), and distance (1A: $F(3,45) = 8.3$, $p<0.001$; 1B: $F(3,42) = 9.6$, $p<0.001$). There were also a significant interactions between type and lag (1A: $F(3,45) = 29.5$, $p<0.001$; 1B: $F(3,42) = 31.8$, $p<0.001$) and between lag and distance (1A: $F(3,45) = 4.7$, $p=0.006$); 1B: $F(3,42) = 3.6$, $p=0.022$). The interaction between type and distance was marginally significant for Experiment 1A ($F(3,45) = 2.4$, $p=0.083$) but was significant for Experiment 1B ($F(3,42) = 6.0$, $p=0.002$).

Critically, both experiments showed a significant 3-way interaction between distractor type, lag, and distance (1A: $F(3,45) = 4.8$, $p=0.005$; 1B: $F(3,42) = 7.4$, $p<0.001$). This reflects the finding that capture cost was low at the 500-ms lag, such that performance was relatively unaffected regardless of distractor distance or type. At the 200-ms lag, capture cost was greater for the target-colored distractor than the irrelevant-colored distractor and also varied across distance. This was further examined with separate ANOVAs for the target-color distractor and irrelevant-color distractor trials. The lag × distance interaction was significant for the target-colored distractor trials (1A: $F(3,45) = 6.6$, $p=0.001$; 1B: $F(3,42) = 10.8$, $p<0.001$), but not for the irrelevant-color distractor trials (1A: $F(3,45) = 2.1$, $p=0.118$; 1B: $F<1$). This supports the conclusion that capture cost varies over distance for the target-colored distractors but not for the irrelevant-colored distractors. In addition, separate one-way ANOVAs were conducted for target-colored distractor trials at both lags. The main effect of distance was significant at the 200-ms lag for both experiments (1A: $F(3,45) = 11.4$, $p<0.001$; 1B: $F(3,42) = 24.2$, $p<0.001$) but was not significant at the 500-ms lag for either experiment (1A: $F<1$; 1B: $F(3,42) = 1.1$, $p = 0.355$).

Discussion

In this experiment, target-colored distractors captured attention significantly more than irrelevant-colored distractors, providing clear evidence of feature-based attention and replicating prior research (Folk et al., 2002). However, the magnitude of this feature-based capture fell off quickly as the distance between the distractors and the task-relevant RSVP stream increased. The occurred even when distractor size was scaled for cortical magnification, which has been shown to largely eliminate differences in detection across eccentricities (e.g., Carrasco & Frieder, 1997).

These results provide strong evidence that feature-based attention is not uniform across the visual field. However, distractor distance in both experiments was confounded with eccentricity, and it is well known that cone density and color discriminability declines with increasing eccentricity (e.g., Mullen, 1991). Therefore it is necessary to demonstrate that target-distractor distance per se impacts attentional capture.

Experiment 2

To show that target-distractor distance is a key factor, we presented the RSVP stream at a peripheral location with the distractors at the same eccentricity but at varying distances from the RSVP stream (see Figure 3). An eye tracker was used to ensure that gaze remained at the screen center. We predicted that capture cost would fall off as the distance between the covertly attended location and the distractor increased.

Methods

Experiment 2 was identical to Experiment 1A except as described here, with 16 new participants (10 female; mean age 22.0 years). The RSVP stream and the distractors were centered 3° from the fixation point on an imaginary circle. The RSVP stream was presented at one location on a given trial (directly above, below, left, or right of fixation, with equal probability). When presented, the two distractor elements occurred at one of four distances relative to the RSVP stream (1°, 1.6°, 3°, or 3.5°, measured from center to center).

On each trial, a fixation cross appeared at the center of the screen as well as a marker that indicated the location of the upcoming RSVP stream. After gaze was within 1° of the central cross for 300 ms, there was a 400-ms delay before the RSVP stream began to provide time for spatial attention to be covertly allocated.

Each participant completed 640 trials, which included 128 distractor-absent trials. Half of the distractor-present trials contained a target-colored distractor, and the remaining contained an irrelevant-colored distractor. For each distractor type, there were 32 trials at each distance for both the 200-ms and 500-ms lag.

To ensure central fixation, an SR Research Eyelink 1000 eye tracker recorded eye position from the right eye at 2000 Hz. Saccades were detected using a minimum eye velocity threshold of 30°/s and a minimum acceleration threshold of $9500°/s^2$, with the default Eyelink algorithm used to parse fixation events. Trials were excluded if participants fixated more than 1° away from center before distractor onset on distractor-present trials or before target onset on distractor-absent trials. One participant had over 45% of trials rejected and was excluded from further analysis. An average of 14.8% of trials (range = 0.6–30%) were excluded in the remaining participants.

Results and Discussion

Accuracy for the distractor-absent trials was 76.0%, which was nearly identical to performance in Experiments 1A and 1B. As in Experiments 1A and 1B, the irrelevant-colored distractor produced little capture cost regardless of its distance or lag (Figure 3). The target-colored distractor produced a capture cost of almost 30% when close to the target location, but the cost dropped to nearly zero when the distractors were 3° or farther from the RSVP stream. These results are similar to those observed in Experiments 1A and 1B, even though both the target and distractors were presented at the same eccentricity.

This pattern of results was confirmed using a 3-way ANOVA. There were main effects of all factors (type: $F(1,13) = 26.0$, $p<0.001$, lag: $F(1,13) = 8.0$, $p=0.014$, distance: $F(3,39) = 16.8$, $p<0.001$). Critically, there was a significant 3-way interaction ($F(3,39) = 3.2$, $p=0.032$), consistent with the finding of a distance-dependent capture effect for the target-colored distractors at the 200-ms lag.

A significant interaction was observed between lag and distance in a 2-way ANOVA on the target-colored distractor trials ($F(3,39) = 7.7$, $p<0.001$), but no significant interaction was found for the irrelevant-colored distractors ($F(3,39) = 1.3$, $p=0.295$). In addition, a one-way ANOVA yielded a significant effect of distance for the target-colored distractors at the 200-

ms lag ($F(3,39) = 20.7$, $p<0.001$). This main effect was also significant for the irrelevant-colored distractors at the 200-ms lag ($F(3,39) = 4.9$, $p < 0.006$), but the magnitude was much smaller. This was verified with a 2-way ANOVA on the data from the 200-ms lag, with factors of type and distance, which yielded significant main effects of distractor type ($F(1,13) = 19.0$, $p=0.001$) and distance ($F(3,39) = 30.0$, $p<0.001$), as well as a significant interaction ($F(3,39) = 5.3$, $p=0.004$). Thus, the capture cost at the 200-ms lag was larger for the target-colored distractor than for the irrelevant-colored distractor, and the falloff with increasing distance was also greater for the target-colored distractor.

General Discussion

The present results clearly demonstrate that feature-based attention interacts with spatial attention. The feature-based attention capture effects were approximately three times larger when the target-colored distractor was adjacent to the attended location than when the distractor was a few degrees away, with little effect of distance for the nontarget-colored distractor. These results therefore demonstrate a substantial interaction between spatial attention and feature-based attention capture.

The present findings call into question the proposal that feature-based attention is spatially global and independent of spatial attention. Almost all prior evidence for this proposal comes from experiments in which feature-based effects were observed at a single unattended location. However, such findings are also compatible with a gradual falloff in feature-based attention effects as the distance from the attended location increases, as observed in the present study. Two prior studies found that feature-based effects were invariant across distances (Liu & Mance, 2011; White & Carrasco, 2011), but only compared distances of >5°. These studies may therefore have missed the interaction with spatial attention, which we found occurs within just a few degrees of the attended location.

Our findings suggest that the specific distribution of spatial attention will influence the spatial extent of capture costs driven by feature-based attention. For example, when distractors never occur near the attended RSVP stream, participants may adopt a broader focus of attention, leading to large capture effects even for distractors located far from the RSVP stream (see, e.g., Folk et al., 2002). Similarly, manipulations that change the intensity of focus at an attended location, such as spatial precueing (Yantis & Jonides, 1990) and perceptual load (Cosman & Vecera, 2009; Lavie, 1995) modulate attentional capture to salient distractors and may also influence feature-driven attentional effects.

It should be noted that the present results do not rule out all possible models of spatially global feature-based attention. For example, feature-based attention may be spatially global, such that the location of any object containing an attended feature is boosted within a spatial priority map (e.g., Moore & Egeth, 1998). This facilitation could then interact with spatial attention mechanisms within the priority map, perhaps making it difficult to suppress a high-priority object that is nearer to the attended location. This would suggest that there is an interaction between spatial attention and the output of the feature-based attention process. Nonetheless, the present results clearly demonstrate changes in feature-driven capture as a function of spatial distance, indicating that the mere presence of feature-based attention effects at an unattended location is not by itself strong evidence that feature-based attention is global.

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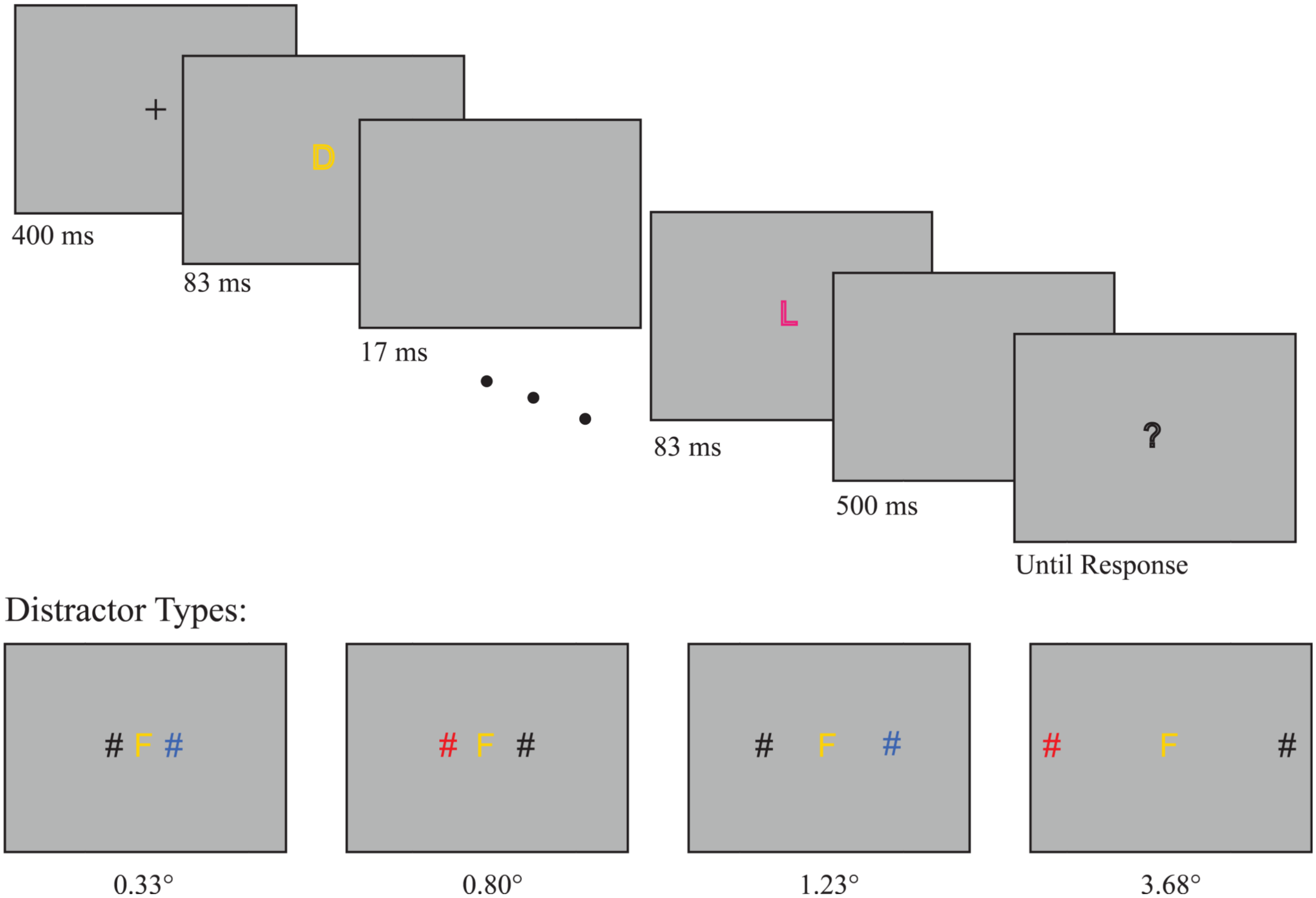

Figure 1.
Basic trial sequence (top) and examples of distractor types in Experiment 1A (bottom). Participants attended either to red or blue in the central stream. At the end of each stream, they reported the identity of the one target letter presented in that color. Each distractor display contained a dark gray object and a colored object that either matched or mismatched the target color.

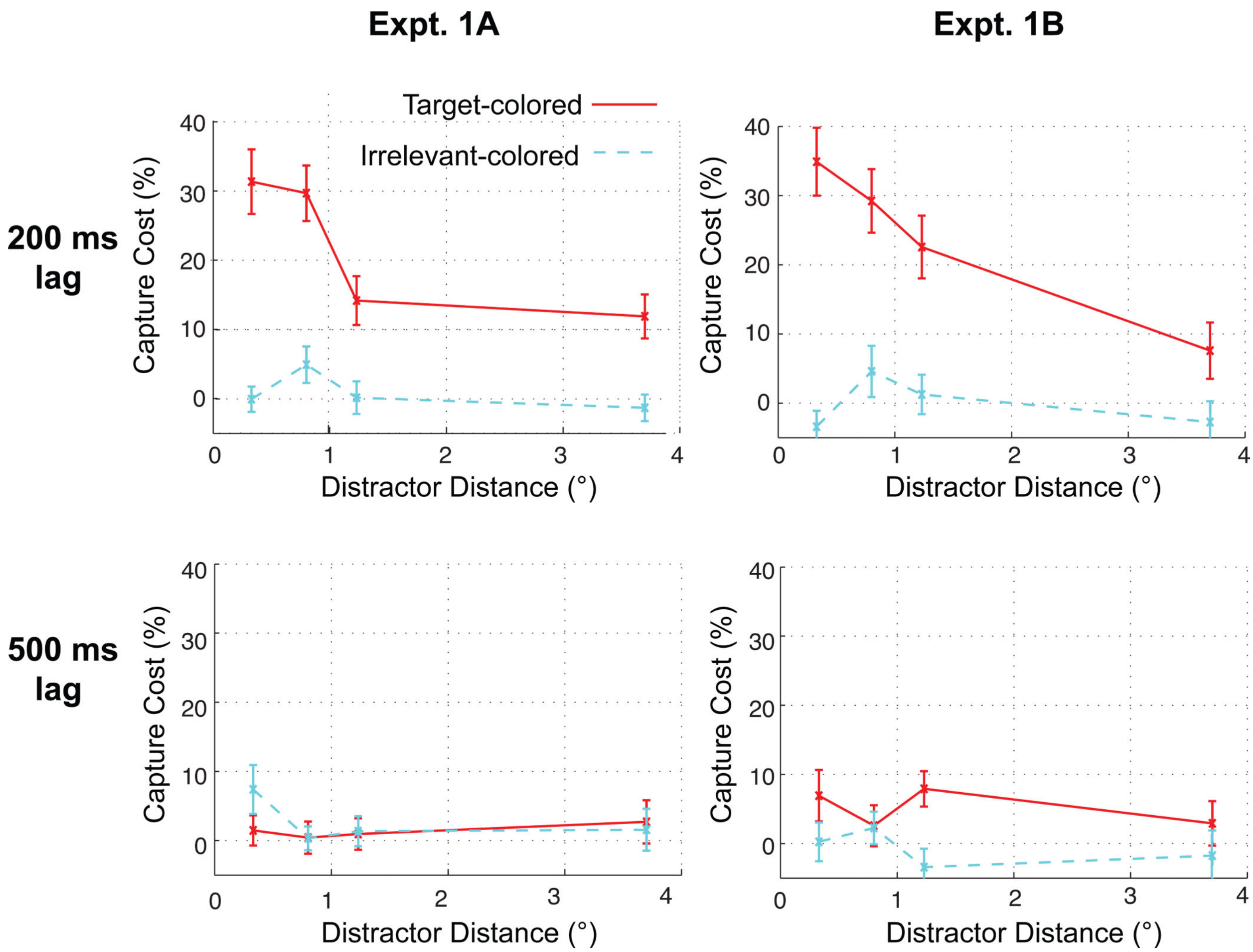

Figure 2.

Task accuracy data for Experiments 1A and 1B expressed as capture cost, which is the decline in performance compared to accuracy for distractor-absent trials (1A: 77.7%, 1B: 76.9%). The 200-ms lag is shown in the top row and the 500-ms lag is shown in the bottom row.

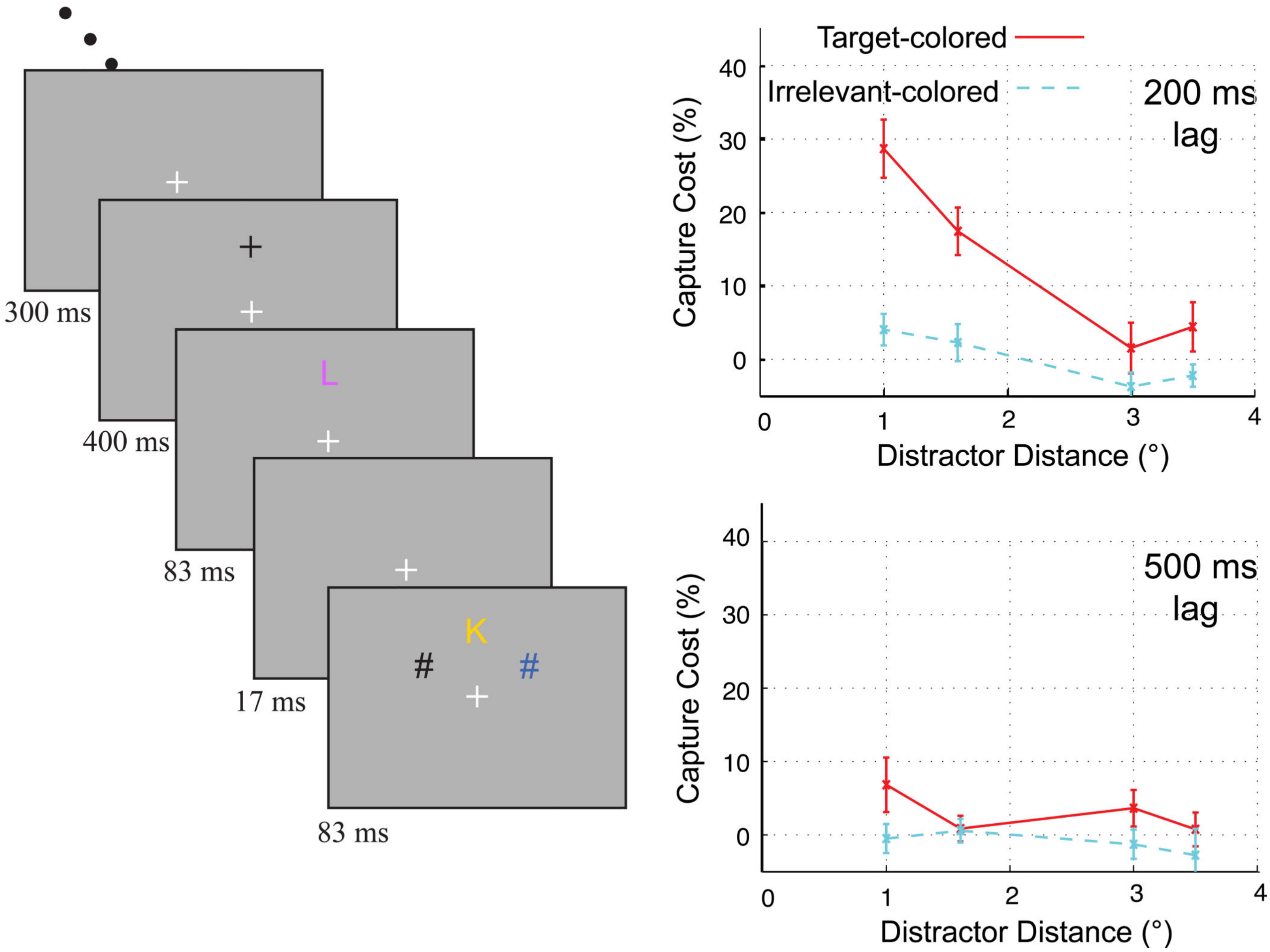

Figure 3.

Stimuli (left) and capture cost results (right) from Experiment 2. Performance for distractor-absent trials was 76.0% correct.