

Research Article

OUR EYES DO NOT ALWAYS GO WHERE WE WANT THEM TO GO: Capture of the Eyes by New Objects

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Abstract—Observers make rapid eye movements to examine the world around them. Before an eye movement is made, attention is covertly shifted to the location of the object of interest. The eyes typically will land at the position at which attention is directed. Here we report that a goal-directed eye movement toward a uniquely colored object is disrupted by the appearance of a new but task-irrelevant object, unless subjects have a sufficient amount of time to focus their attention on the location of the target prior to the appearance of the new object. In many instances, the eyes started moving toward the new object before gaze started to shift to the color-singleton target. The eyes often landed for a very short period of time (25–150 ms) near the new object. The results suggest parallel programming of two saccades: one voluntary, goal-directed eye movement toward the color-singleton target and one stimulus-driven eye movement reflexively elicited by the appearance of the new object. Neuroanatomical structures responsible for parallel programming of saccades are discussed.

It is well-known that the visual system is sensitive to events that exhibit sudden change (Breitmeyer & Ganz, 1976). When a person is engaged in a particular task (e.g., reading a book), something might happen in the environment (e.g., someone switches on a desk lamp at a nearby library table) that immediately captures the person's attention even when he or she had no particular intention to look for such events. Directing attention to these events may merely seem to distract the person from the intended task. It has been argued, though, that detecting these sudden changes in the environment is significant for behaving organisms because these events may require immediate identification and action (Todd & Van Gelder, 1979; Yantis, in press).

A number of studies have demonstrated that an abrupt-onset object (an object presented with a transient luminance change) captures attention automatically (Jonides, 1981; Müller & Rabbitt, 1989; Theeuwes, 1990; Yantis & Jonides, 1984). These studies show that even when observers have no intention to look for an onset, an abrupt onset among other nononset elements is processed first. On the basis of these findings, it has been argued that sudden luminance changes, such as the appearance of a new object in a scene, capture attention in a purely stimulus-driven fashion (note that for attentional capture to occur, it is not necessary that the new object has a luminance increment; see Yantis & Hillstrom, 1994).

Even though there is a large body of evidence which suggests that the appearance of a new object may capture attention, it is largely unknown whether such an event also triggers a subsequent eye movement. There is, however, ample evidence to suggest that there is a close relationship between the oculomotor and attentional systems. Studies have shown that before a voluntary eye movement is made, attention is covertly shifted to the location of the object of interest (e.g., Hoffman & Subramaniam, 1995; Kowler, Anderson, Doshier, & Blaser, 1995; Shephard, Findlay, & Hockey, 1986). The eye typically will land at the position at which attention is directed (Deubel & Schneider, 1996).

EXPERIMENT 1

In the present study, we used a visual search task in which observers were required to make a voluntary, goal-directed saccade to a color-singleton target. In half of the trials, simultaneously with the presentation of the color-singleton target, a new object presented with an abrupt onset appeared somewhere in the display. In contrast to previous studies investigating the effect of onsets on attentional deployment (e.g., Yantis & Jonides, 1984), in the current study, the onset was never relevant for the task. The question addressed was whether the appearance of a new yet irrelevant object would disrupt the planning and execution of the goal-directed saccade toward the singleton target.

Method

Observers viewed displays containing six gray circles (3.7° in diameter), each containing a small gray figure-eight premask (0.4° × 0.2°), equally spaced around an imaginary circle with a radius of 12.6°. After 1,000 ms, all circles except one changed to red, and at the same time, the small premasks inside the circles changed to letters. Observers were instructed that as soon as the colors of the circles changed, they were to quickly and accurately make a saccade directly to the only gray circle left (a color singleton) and to determine whether the letter inside the gray circle was a *c* (to which they responded by pressing a button with their left hand) or a reverse *c* (to which they responded by pressing a button with their right hand). The letters inside the red circles were distractor letters randomly sampled without replacement from the set *S*, *E*, *H*, *P*, *F*, and *U*. A pilot study was conducted to ensure that accurate target identification could be achieved only when the letter was fixated. Eye movements were recorded by means of an Eye Link tracker (250-Hz temporal resolution and 0.2° spatial resolution) from 8 naive observers each performing 64 practice and 256 experimental trials.

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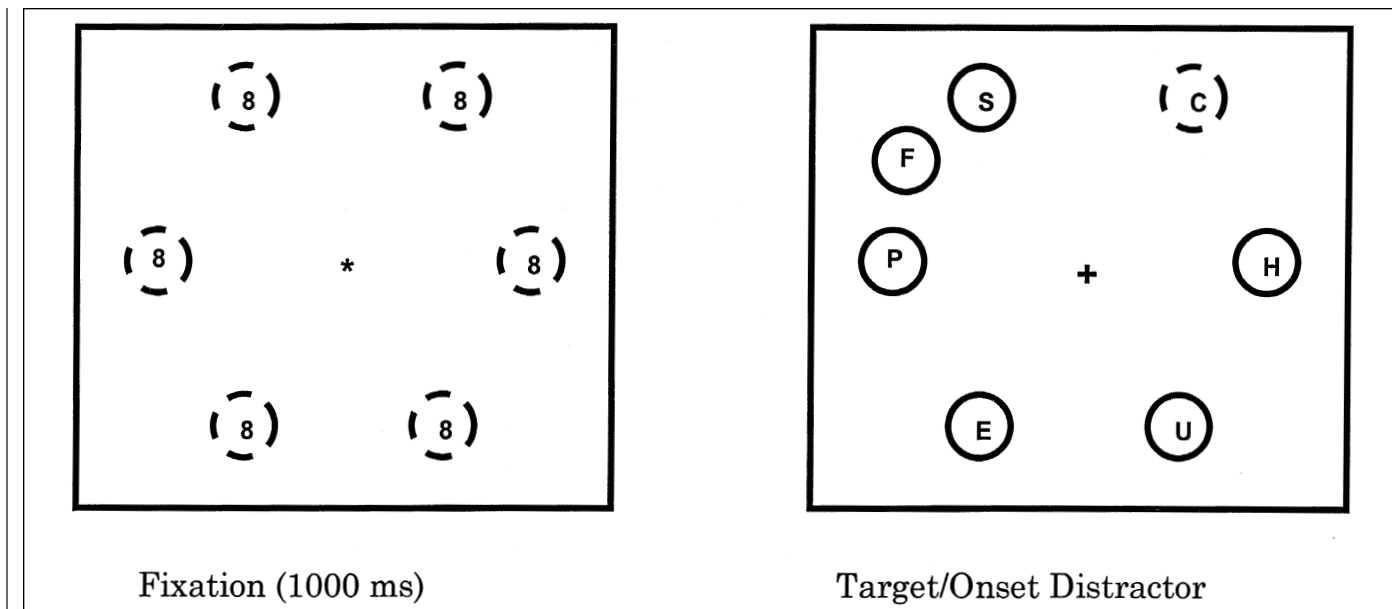


Fig. 1. Graphic illustration of the displays and the temporal sequence of an experimental trial (from left to right). Note that the target is defined simultaneously with the appearance of the onset distractor. The gray circles are indicated by the dashed lines. The red circles are indicated by the solid lines.

On half of the trials, at one of four possible locations in the visual field, an additional red circle was added to the display at the same time that the color singleton was revealed (see Fig. 1 for examples of the stimulus materials).¹

Results and Discussion

Approximately 7.4% of the trials were discarded because observers were not fixating the fixation dot at the beginning of the trial (anticipation saccades). Those trials on which observers made errors (i.e., pressed the wrong response key) were also excluded (4.4%). Because the error rate was so low, error scores were not analyzed further.

Figure 2 presents the eye movement behavior of one representative observer. The results displayed are sample points (every 4 ms) of the path of the first saccade (additional saccades are not shown). When no new object was added to the display (control condition), saccades generally went directly to the color-singleton target (Fig. 2a). In those trials in which a new object was added to the display, however, the eyes

often went in the direction of the new object, stopped briefly, and then went on to the target (Figs. 2b, 2c, and 2d).

The appearance of the new object (i.e., the abrupt onset) affected not only eye movement behavior, but also reaction time (RT) to identify the letter inside the color singleton (RT of 785 ms without the new object vs. 840 ms with the new object, $F[1, 7] = 22.08, p < .01$). The sudden appearance of the new object did not affect the time it took the eye to start moving from the centrally located fixation point (saccade latency of 238 ms without the new object vs. 230 ms with the new object); rather, the increase in manual RT was caused by the need for an additional saccade to be made from the irrelevant onset stimulus to the location of the color-singleton target on many trials.

Figure 3 summarizes the effect of the appearance of a new but task-irrelevant object on the scan path of the eye. The maximum angular deviation of the eye from a linear path between the fixation and the target object was calculated over observers. As is clear from Figure 3a, in the control condition, in which no new object was added to the display, the eyes tended to go directly to the color-singleton target. In contrast, Figures 3b, 3c, and 3d show that when an irrelevant new object was presented, in many instances the eye went in the direction of the new object. Even when the new object appeared at a location opposite the singleton target (at 150°), the eye tended to start moving in the direction of the new object. Overall, the results indicate that in about half of the trials, the appearance of a new object disrupted the planning and execution of the goal-directed saccade toward the singleton target.² Irrespective of where the new

1. It might be argued that the initial capture of attention by the new object occurred not because of the sudden appearance of the new object but instead because the new object appeared at the center of a cluster, or group, of three closely spaced objects (see, e.g., the location of the new object in Figs. 2b, 2c, and 2d). We tested this hypothesis in a control study by including an additional circle in the display in the same positions in which the new object appeared in this study. However, in this control study, the extra circle appeared at the beginning of each trial along with all of the other circles. In this case, observers did not start moving their eyes in the direction of this additional circle. Therefore, it was the appearance of a new object and not a cluster of three closely spaced objects that disrupted saccades to the singleton target.

2. Two different 90° target-distractor separations were used in the study: The onset distractor could appear 90° away from the target in the same or in the different hemifield. Given that there was no difference in the eye movement and performance patterns for these two 90°-separation conditions, they were collapsed for the purpose of presentation.

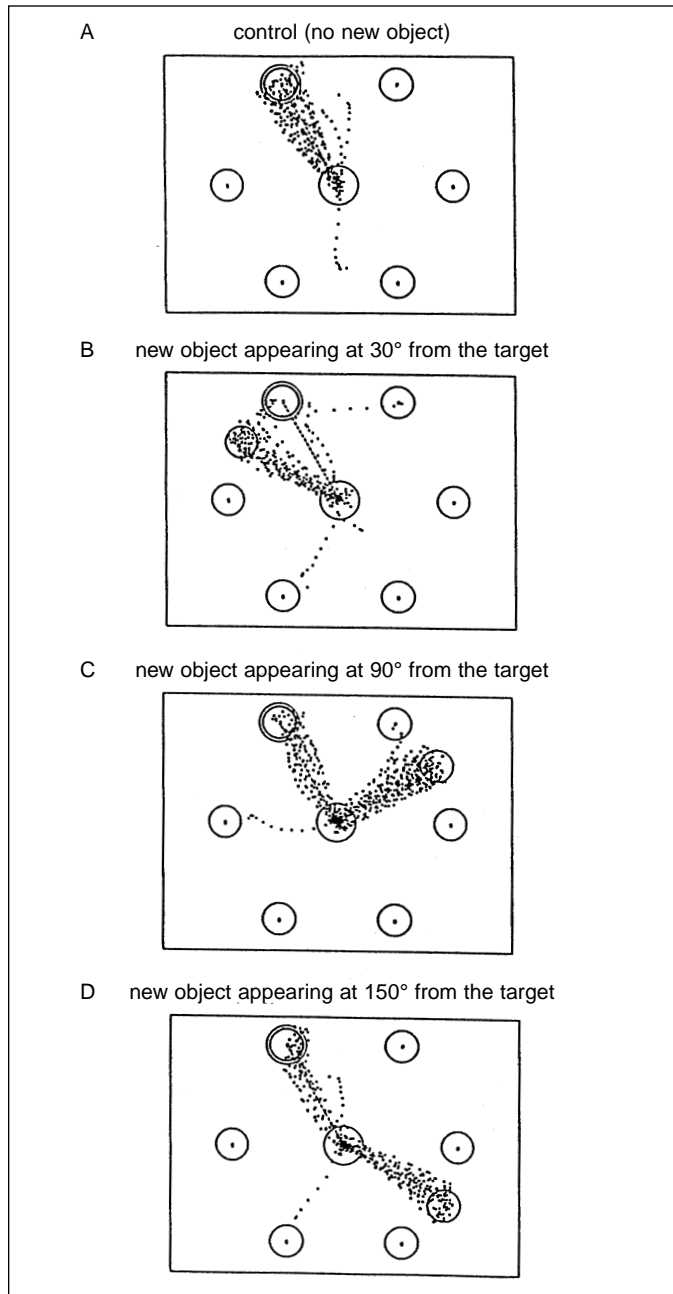


Fig. 2. Initial tracks that the eyes took as they left the fixation point until the first fixation near one of the colored circles. Eye position was digitized at 250 Hz. Thus, the points in the figure represent data points acquired every 4 ms during the initial eye movement. Eye movement behavior of an observer is shown for the control condition (a), in which no new object was presented, and for three onset conditions: when a new object was presented close to the singleton target (at 30° of arc, corresponding to a distance of 6.4° of visual angle) (b), when a new object was presented farther away from the singleton target (at 90° of arc, corresponding to a distance of 19.4° of visual angle) (c), and when a new object was presented at the opposite side of the visual field (at 150° of arc, corresponding to a distance of 25.4° of visual angle) (d). The results are collapsed and normalized with respect to the position of the target singleton (marked here with a double circle) and the position of the new object.

object appeared, the eyes tended to move in a direction that corresponded to the location of the new object.

When the eye started to move in the direction of the new object, in most cases the eye stopped for a brief period before it went on to the singleton target. Figure 4 shows the fixation durations after the first saccade for those saccades that went in the direction of the new object. For this analysis, we used only the 90° and 150° target-distractor separations because these separations made it easy to discriminate saccades toward the new object from those toward the target. Note that about 87% of the fixation durations were less than 150 ms, even though a complete change in the direction of the eye movement was required to redirect the eyes in the direction of the target.

We also explicitly asked observers after the experiment whether they were aware that the appearance of the new object affected their eye movements. Observers indicated that they were sure that their eye movements were not affected by the appearance of the new object.

On the basis of these results, we conclude that the appearance of a new object interferes with the planning and execution of a goal-directed eye movement to the color singleton. Earlier research has demonstrated that the appearance of a new object involuntarily captures attention (Theeuwes, 1994; Yantis & Jonides, 1984). The current results indicate that a new object not only captures attention, it also captures the eyes.

EXPERIMENT 2

The results of the first study suggest that both the goal-directed allocation of attention and the movement of the eyes to a clearly defined target can be disrupted by the appearance of a new but task-irrelevant object in the visual field, even when this object appears quite distant from the target. However, the data that we have reported thus far do not define the boundary conditions for this capture effect on attention and eye movements.

Previous studies of attentional capture have reported that the appearance of a new object does not influence performance when observers have a sufficient amount of time to attend to the location of a target prior to the appearance of the new object. For example, Yantis and Jonides (1990; see also Theeuwes, 1991) found that as long as a central arrow cue indicated the position of a target at least 200 ms before the appearance of an onset elsewhere in the visual field, the onset had no influence on the time it took subjects to identify the target letter.

In the present study, we examined whether precuing the location of the color-singleton target would eliminate or reduce the influence of the task-irrelevant onset on performance and eye movements. Given the previous literature, which suggested that attention is often shifted to an area of interest in advance of an eye movement (Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995), it was our expectation that providing subjects with sufficient time to attend to the location of the subsequent target and to program a goal-directed eye movement to this location would preclude the misdirection of the eyes to the task-irrelevant object.

Method

The stimuli and procedures were equivalent to those of Experiment 1 with the following exceptions. A centrally located arrow cue, which

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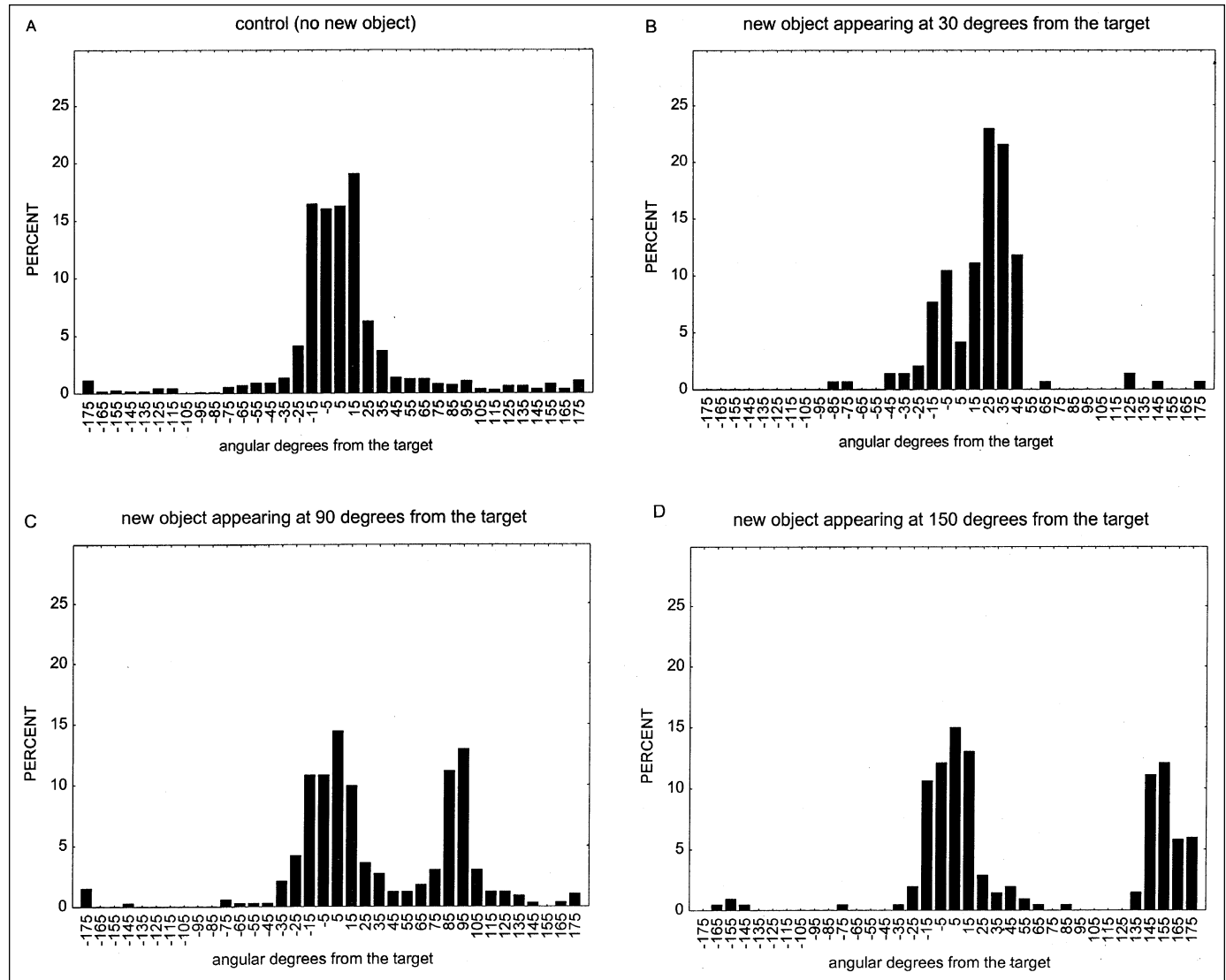


Fig. 3. Effect of the appearance of a new but task-irrelevant object on the scan path of the eye in Experiment 1. Shown here is the maximum angle deviation of the eye from a linear path between the fixation and the target object (in degrees of angle; positive values indicate that the eye moved in the direction of the new object, and negative values indicate that the eye went in the opposite direction). The panels show results for the control condition (a) and for onset conditions in which a new object appeared at 30° from the target (b), at 90° from the target (c), and at 150° from the target (d). Sample points were taken only from the first saccade on each trial.

pointed to the location of the subsequent color-singleton target, was presented on the display either 400, 500, or 600 ms prior to the color change, which defined the location of the target. Stimulus onset asynchrony (SOA) was varied to discourage anticipatory saccades. Each SOA was used on one third of the trials, and trials with different SOAs were randomly presented within blocks. The subjects were instructed that they should use the cue to shift their attention to the cued circle and to prepare to make an eye movement to this location as soon as the circle stimuli changed color. Subjects were cautioned against making anticipatory saccades to the cued object. Trials on which anticipatory saccades occurred were discarded prior to the analysis of the eye movement data.

In the present experiment, onset distractors were presented at 90° and 150° of arc separation from the target. The 30° separation was not

used because it was difficult to distinguish initial saccades to the onset from initial saccades to the target with such a close separation. Finally, we added an extra circle on the control trials in this study. This circle appeared simultaneously with the rest of the distractor circles at the beginning of each trial and underwent the same color change from gray to red when they did. It was included to equate the number of stimuli in the display on the onset and control trials. The extra circle was presented at either 90° or 150° of arc separation, as on the onset trials.

Seven subjects participated in two experimental sessions. Each session included 72 practice trials and 288 experimental trials. Given that none of the performance or eye movement effects differed across the two experimental sessions, all reported analyses were collapsed across sessions.

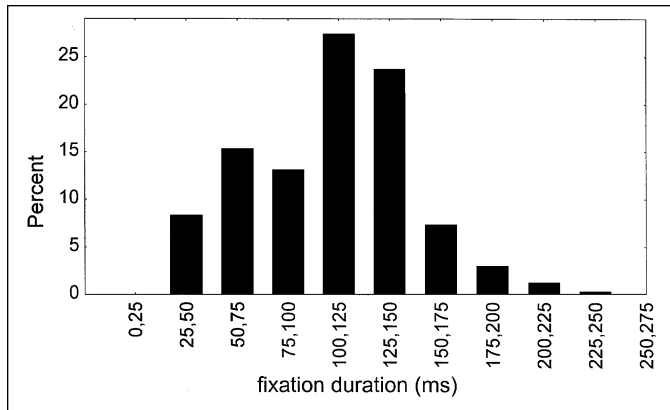


Fig. 4. Fixation durations after the first saccade for those saccades that went in the direction of the new object in Experiment 1. The results displayed here are from the conditions in which the new object appeared at 90° and 150° from the target and the eye started to move in the direction of the new object.

Results and Discussion

The main question addressed in this study was whether cuing the location of the color-singleton target would eliminate the influence of the task-irrelevant distractor on target identification and eye movements. Because there were no significant differences between results for the three SOAs, these results were combined for the analyses reported here. Figure 5 summarizes the effect of the appearance of the new but task-irrelevant object on the scan path of the eyes. The maximum angular deviation of the eyes from a linear path between fixation and the target object was calculated and collapsed across the 7 observers.

As can be seen in the figure, the distribution of trials is quite similar regardless of whether an onset distractor was present (bottom two panels) or absent (top two panels). These data suggest that onset distractors have little influence on the trajectory of eye movements when subjects are able to shift their attention to the target location in advance of the appearance of the onset. This observation was quantified by calculating the number of trials on which the eyes initially went in the direction of the onset (onset trials) or additional circle (control trials) and submitting these data to a two-way analysis of variance with target-distractor separation (90° vs. 150°) and condition (onset vs. control trials) as factors. Neither the main effects nor the interaction was statistically significant ($ps > .40$). The average proportion of onset trials on which the eyes initially went toward the onset circle was 2.3%; in comparison, on 1.7% of the control trials, the eyes initially went toward the nononset circle that appeared at a comparable spatial position.

An analysis of the RT data presents a similar picture. The RTs on the onset and control trials, collapsed across the three SOAs, were 617 and 607 ms, respectively. These RTs were not significantly different ($p > .30$).

In summary, the results of the present study establish an important boundary condition on the attentional and oculomotor capture effects observed in Experiment 1. Capture effects by the appearance of a task-irrelevant onset can be overcome when observers have sufficient time to attend and program an eye movement to the location of a subsequent target stimulus.

GENERAL DISCUSSION

The goal of the observers in our task was to make a saccade toward the color-singleton target. In order to execute such a saccade, attention first needs to be shifted to the location of the color singleton (Deubel & Schneider, 1996; Kowler et al., 1995). Furthermore, we assume that the shift of attention to the location initiated the programming of a saccade to the attended location (e.g., Deubel & Schneider, 1996; Morrison, 1984).³ In Experiment 1, simultaneously with the preparation of a goal-directed saccade to the color singleton, a new object appeared in the display, causing attention to be reflexively drawn to the location of the new object. We assume that the reflexive shift of attention to the new object also initiated the programming of a saccade, but to the location of the new object. In fact, the results suggest that there is parallel programming of two saccades, one to the singleton target and one to the new onset object. Depending on which eye movement program is ready first, the eyes will start moving in the direction of the onset or in the direction of the color singleton. If the eyes start moving in the direction of the onset, as soon as the program for a saccade to the color-singleton target is ready, inhibition of the reflexive saccade may occur, causing the eyes to stop somewhere along the trajectory between the initial center fixation point and the onset. Because the eye movement program toward the color-singleton target has been prepared, after the eyes stop for a brief period of time, they will move to the color singleton.⁴ This interpretation is in line with the very short fixation durations that we found after the first saccade (see Fig. 4). In fact, the majority of the fixations were too short to allow the programming of a completely new eye movement, which typically takes 150 to 200 ms (e.g., Becker, 1991; Findlay, 1997; Salthouse & Ellis, 1980).

Overall, these results suggest parallel programming of two saccades (see also McPeck, Skavenski, & Nakayama, 1996): one voluntary, goal-directed eye movement toward the color-singleton target and one stimulus-driven eye movement reflexively elicited by the appearance of the new object. The parallel programming of two saccades has been reported before in reading (Henderson & Ferreira, 1990; Morrison, 1984; Reichle, Pollatsek, Fisher, & Rayner, 1998): A reader may fixate a particular word for a very brief period and immediately move on to the next word. Parallel programming of two saccades has also been reported in the double-step paradigm (Becker & Jurgens, 1979), in which the position of a target changes just prior to a saccade.

Interestingly, shifting attention to the location of the target in advance of the appearance of the task-irrelevant onset effectively eliminated the misdirection of the eyes to the onset and the performance disruption observed in Experiment 1. Within the theoretical framework just described, the elimination of the effect of the onset would likely have resulted from the temporal advantage provided to the programming of the goal-directed saccade by the location precue. However, it is also conceivable that performance and eye movements (to the target)

3. We are not suggesting that the execution of the saccade necessarily followed saccade programming, only that the allocation of attention initiated saccade programming (Hoffman, in press; Klein & Pontefract, 1994). Indeed, on those trials on which the preparation of the goal-directed saccade was completed first, the reflexive saccade to the onset was prepared but not executed.

4. On many trials on which the eyes initially moved toward the onset, they did not reach its location. Indeed, on average, the saccades toward the onset traversed only 70% of the distance between fixation and the onset before stopping for a brief period of time and then moving to the location of the color-singleton target.

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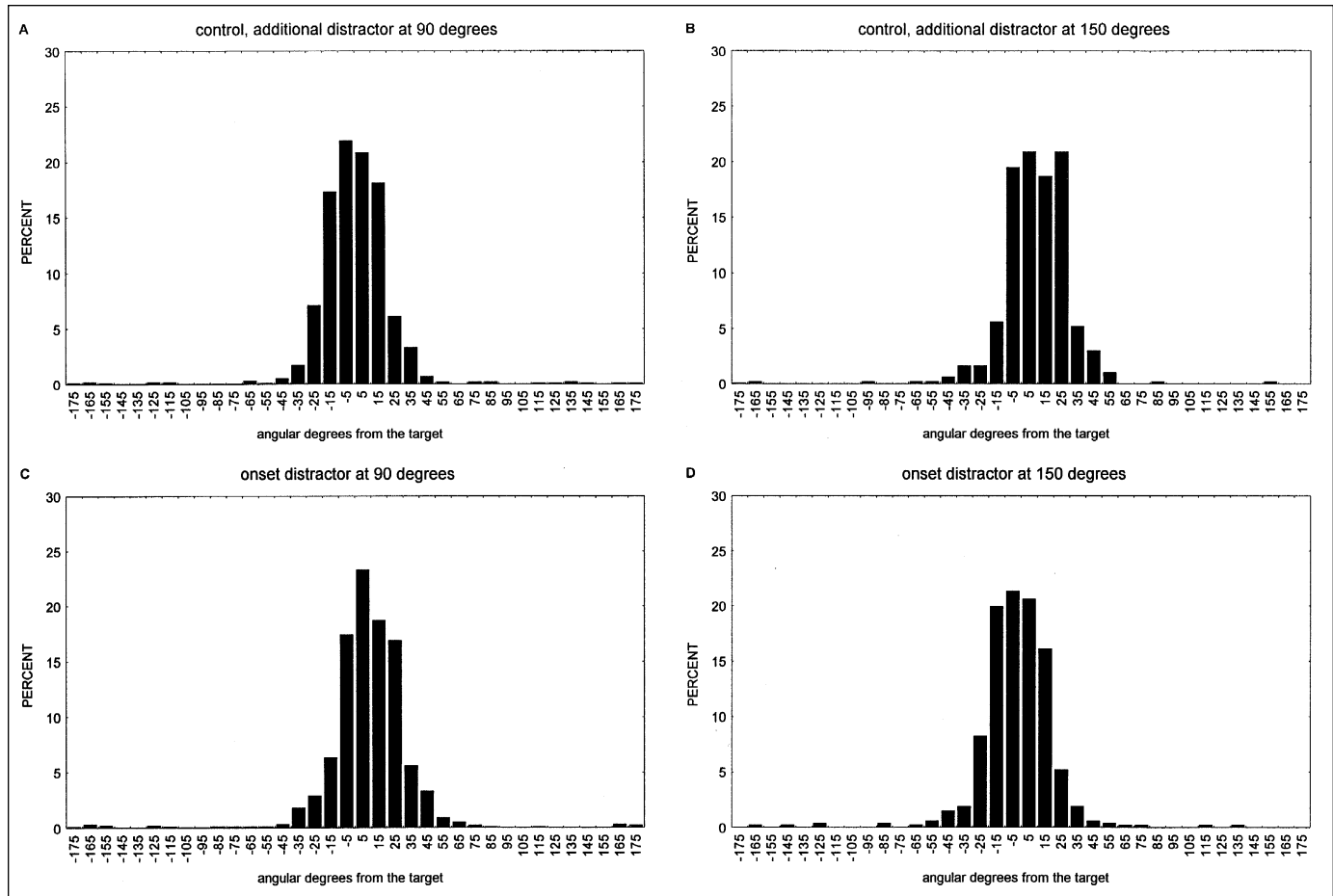


Fig. 5. Effect of the appearance of a new but task-irrelevant object on the scan path of the eye in Experiment 2. Shown here is the maximum angle deviation of the eye from a linear path between the fixation and the target object (in degrees of angle; positive values indicate that the eye moved in the direction of the new object, and negative values indicate that the eye went in the opposite direction). The panels graph eye position data in the control condition (i.e., on nononset trials) when the extra circle appeared 90° (a) and 150° (b) from the color-singleton target and in the onset condition when the onset distractor appeared 90° (c) and 150° (d) from the color-singleton target. Sample points were taken only from the first saccade on each trial.

might have benefited from an active inhibition of the distractor locations when the target location was precued. The determination of whether one or the other or both of these processes provide the most apt account of the data will need to await further research.

It has been suggested that different neuroanatomic structures are responsible for voluntary (goal-directed) and reflexive (stimulus-driven) saccades (LaBerge, 1995; Maunsell, 1995; Schall, 1995). In line with our claims regarding the parallel programming of two saccades, there is evidence that there are two parallel pathways involved in the generation of saccades: the subcortical pathway depending on the superior colliculus and the cortical pathway depending on the frontal eye fields, supplementary eye fields, and dorsolateral prefrontal cortex (Pierrot-Deseilligny, Rivaud, Gaymard, Muri, & Vermersch, 1995; Schall, 1995). Presumably, the superior colliculus is involved in producing the reflexive movements, whereas the frontal circuit is involved in the goal-directed eye movements. In order to inhibit reflexive saccades, the superior colliculus receives inhibition through the substantia nigra from the frontal eye fields. Research has shown that monkeys can still produce fast saccades to a flashed target

after lesions of the frontal eye fields, but not after lesions of the superior colliculus (Schiller, Sandell, & Maunsell, 1987). Also, patients with frontal lobe lesions have difficulty producing goal-directed saccades in the direction opposite to that of a flashed target (Guitton, Buchtel, & Douglas, 1985; Pierrot-Deseilligny et al., 1995; Rivaud, Muri, Gaymard, Vermersch, & Pierrot-Deseilligny, 1994).

In the present experiments, both pathways were likely active in parallel in generating saccades. When no new object was presented (control condition), the frontal control circuit was involved in generating a voluntary, goal-directed saccade toward the color-singleton target (Deubel, 1995; Schall & Hanes, 1993). However, when a new object appeared in the visual field and attention had not previously been shifted to the target location, attention was reflexively drawn to the location of the new object. Through the superior colliculus, a reflexive orienting saccade was made toward the location of the new object. Even though the new object was never relevant for the task, cortical inhibition from the frontal eye fields did not always prevent the execution of the reflexive saccade, causing the eyes to start moving in the direction of the new object. After inhibition through the

cortical pathways, the eyes stopped briefly and an additional saccade toward the color-singleton target was initiated.⁵ Because neurons in the frontal control circuit registering the color-singleton target were already active (Hanes, Thompson, & Schall, 1995), the threshold for generating a saccade was reached quickly, producing the short fixation durations before the additional saccade to the target.

Our results indicate that in everyday life, particular events or objects may catch a person's eyes even when they run counter to the person's intentions. When a new object appears in the scene, it can interrupt ongoing goal-directed eye movement behavior and elicit an eye movement to its location. Such a mechanism is ecologically beneficial because new objects are potentially important to the organism.

Acknowledgments—This work was supported by a U.S. Army Research Laboratory grant (DAAL01-96-2-0003). We thank Joseph Malpeli, Jeffrey Schall, and Steve Yantis for helpful comments on the manuscript and Roger Marsh for his technical help.

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(RECEIVED 8/22/97; REVISION ACCEPTED 3/27/98)