Journal of Experimental Psychology:
Human Perception and Performance
2005, Vol. 31, No. 5, 1061–1066

0096-1523/05/$12.00 DOI: 10.1037/0096-1523.31.5.1061

Attending to Eye Movements and Retinal Eccentricity: Evidence for the Activity Distribution Model of Attention Reconsidered

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When testing between spotlight and activity distribution models of visual attention, D. LaBerge, R. L. Carlson, J. K. Williams, and B. G. Bunney (1997) used an experimental paradigm in which targets are embedded in 3 brief displays. This paradigm, however, may be confounded by retinal eccentricity effects and saccadic eye movements. When the retinal eccentricities of the targets are equated and eye position is monitored, the pattern of results reported by LaBerge et al., which supported the activity distribution model, is not found. This result underscores the importance of considering targets' eccentricity and people's inclination to make saccadic eye movements in certain types of visual cognition tasks.

Keywords: attention, distribution, eye movements, eccentricity

One of the most fundamental issues in the study of visual cognition is how attention is allocated across the visual field. Over the years, researchers have offered several accounts as to how attention can be focused on certain regions of the visual field at the exclusion of other regions. In 1997, LaBerge, Carlson, Williams, & Bunney compared two such accounts: the "spotlight" model and the "activity distribution" model (ADM). Across a series of experiments, LaBerge et al. found evidence consistent with the ADM and inconsistent with the spotlight model. However, LaBerge et al.'s methodology could be sensitive to two confounds: (a) retinal eccentricity effects and (b) saccadic eye movements. We conducted the present study to examine this possibility.

Before expanding on how retinal eccentricity and saccadic eye movements may have affected LaBerge et al.'s (1997) results, we must first understand the method that they used and how it enabled the comparison between spotlight and activity distribution models of attention. During a brief time period, participants received a series of visual displays that researchers centered at the fixated location and separated by short delays. The first display consisted of "#####*#####" for 1,000 ms and was followed by three target displays. The first target display (T1) was the string "GQGQGOQGQGQ," presented for 116 ms and centered at the fixated location, with center character being O, C, or 0. After a 50-ms delay, the second target display (T2) was the string "VRV," presented for 167 ms and centered at one of three locations: two spaces to the left of fixation (−2), at fixation (0), and two spaces to the right of fixation (+2). The center letter of T2 was R, K, or P. The third target display (T3) was the string "GOQ," presented for 133 ms and centered at one of five locations: −4, −2, 0, +2, and +4. The center character of T3 was O, C, or 0. Researchers instructed participants to remain fixated throughout each trial and to make a key-press response as quickly as possible when the center letters of T1, T2, and T3 were O, R, and O, respectively. Reaction time (RT) was measured from the onset of T3. The critical comparison of the two models was whether T3 appeared on the same or on the opposite side of fixation as T2.

LaBerge and Brown (1986, 1989) developed the ADM to explore the notion that allocating attention is unlikely to be bounded within some sort of beam, leaving most of the visual field unattended. The ADM suggests that the visual field contains a series of attention channels (rather than a single beam of attention that moves from location to location). Opening a channel produces more attention in a certain area of the visual field; closing a channel does the opposite. Thus, attention activity is distributed across the visual field in the form of a "prolonged, spatially diffuse preparatory state" (LaBerge et al., 1997, p. 1381). According to the ADM, the appearance of a new object in the periphery will reflexively cause a corresponding attention channel to open, which in turn causes a change in overall distribution of attention.

All spotlight models would predict faster responses when T3 appears in the same location as T2, but they make different predictions about the other possible T3 locations. Distance-independent spotlight models (see, e.g., Remington & Pierce, 1984) predict that RTs to a T3 at any location other than T2 would be equal. Spotlight models that use a constant velocity (Shulman, Remington, & McLean, 1979; Tsal, 1983) predict that RTs to a T3 increase proportional to the distance from T2. We would expect a similar pattern of results from gradient models of attention (see, e.g., Downing & Pinker, 1985; Shulman, Wilson, & Sheehy, 1985). Unlike these models, the ADM predicts that RTs to the peripheral T3 will be slower than RTs to the medial T3 (the warning display and T1 produce a large gradient of activity tightly focused at the center location, and the appearance of T2 skews the gradient in its direction). Thus, when T3 arrives, considerable residual activity occurs at the central location and at the T2 location, but only baseline activity occurs on the other side of the display. LaBerge et al.'s (1997) findings support the ADM; with

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This research was supported by a Natural Sciences and Engineering Research Council grant and a Premier's Research Excellence Award to Jay Pratt.

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T2 either to the left or right of fixation, longer RTs occurred for T3 at more peripheral locations than the RTs that occurred for T3 at more medial locations (i.e., T2 at −2, longer RTs for T3 at −4 than at 0; T2 at +2, longer RTs for T3 at +4 than at 0).

As noted earlier, two confounds are possible in the experimental design used by LaBerge et al. (1997). Retinal eccentricity is a potential confound because researchers always presented the displays along a horizontal axis, with the most peripheral letters being some 2° from fixation. Given that the size of the fovea varies between 1.5° and 3.0°, depending on the individual, the most peripheral T3 locations were likely to be off the outer edge of the fovea. Because the proportion of cones to rods falls off quite rapidly outside the fovea, responses to peripheral T3s would be slower than to the medial T3s, especially for such a difficult task. LaBerge et al. found that the faster response to a T3 at position 0 versus −2 after a T2 at position −2 could be attributed to discrimination being easier at fixation than in the periphery (especially outside the fovea). More generally, the RT advantage for location 0 might be because it is located at fixation rather than at T1. Thus, previous results that supported the ADM may have been at least partially attributable to retinal eccentricity effects.

LaBerge et al. (1997) did attempt to address the eccentricity confound by citing previous studies in which researchers found flat slopes for peripheral targets (LaBerge, 1983; LaBerge & Brown, 1986, 1989). For example, in LaBerge and Brown (1989), a V-shaped curve was flattened when participants were instructed to attend to all of the letters (rather than just the center letter) in a five-letter word. LaBerge et al.'s (1997) Experiment 3 produced similar results; the first target (T1) was either a five-letter word or "V(R/K/P)V," and the second target (T2) was either another five-letter word or "Q(O/R/0)C." If RT to a target is determined by the location of the previous target—and not by eccentricity—then we should obtain a flat slope for all T2 locations when T1 is a word. The resulting data confirmed this prediction. However, the five-letter word encompassed all of the possible T1 locations; therefore, forward masking may have been responsible for the change in slopes. This issue was less of a concern in previous experiments because T2 was a three-letter string. The shorter duration of the five-letter T1 (117 ms) versus that of the three-letter T1 (167 ms) also may have contributed to forward masking. To reject the influence of eccentricity, researchers should equate latencies across all target locations.

Another possible confound in LaBerge et al.'s (1997) findings is that participants could have made saccadic eye movements in response to the various targets, despite researchers explicitly instructing them to maintain fixation. This possibility arose in pilot-testing experimental designs similar to those used by LaBerge et al. while watching eye movements with a closed-circuit TV camera. We found that more of the trials showed the pilot testers making saccades than remaining fixated, and the testers typically were unaware that they had moved their eyes. Other testers reported having to fixate the target strings to discriminate the center character. Two features of the paradigm make it especially conducive to eye movements: (a) the rapid serial presentation occurs in discrete spatial locations and (b) the discrimination task is difficult. The eye does not have sufficient time to land on the successive T2 and T3 locations; rather, people would often look at the T2 location while T3 appeared. Our main motivation in conducting the present study was to examine the likelihood that eye movements occurred and produced unknown effects on the results in LaBerge et al.'s research.

Experiment 1

Before examining the possible confounds of retinal eccentricity and eye movements, we must replicate the pattern of results typically found in the basic paradigm used to test the ADM (see, e.g., LaBerge & Brown, 1989; LaBerge et al., 1997; Pratt & Quilty, 2002). One key prediction of the ADM is that responses to a T3 at location −4 should be slower than responses to location 0 after a T2 of −2, because residual activity occurs at location 0 from T1. All three types of spotlight models (T1, T2, and T3) would predict equal RTs because the distances between −4 and −2, and between −2 and 0, are identical.

Method

Participants. Nine undergraduates at the University of Toronto participated in this experiment in exchange for course credit. All participants had normal or corrected-to-normal vision.

Apparatus. We tested participants individually, each in a single session. Each participant sat in a soundproof, electrically shielded chamber throughout the experiment. An experimental personal computer controlled the presentation of stimuli and recorded button-press responses. We presented stimuli on a Trinitron 19-in. (48 cm) monitor at a distance of 57 cm. Participants used an adjustable chin rest to maintain this distance. They made button-press responses using a Microsoft serial joystick.

Stimuli. Each trial consisted of four successive displays: a warning signal, T1, T2, and T3. All four displays were the same size and were centered on the screen. They consisted of a string of up to 11 white characters on a black background arranged along the horizontal axis and subtending 2.0° of visual angle. The characters subtended approximately 0.42° with a center-to-center distance of approximately 0.48°. The warning signal consisted of 11 symbols (i.e., #####*#####). We replaced the warning signal by T1—a string of Gs and Qs in which the central character of the series was determined using probability; O = 80%, C = 20% (i.e., "GQGQG[O/C]QGQGQ"). We then replaced T1 with T2—a three-character string of Vs, followed by either R (80%) or K (20%), followed by another V (i.e., "V[R/K]V"). T2 could be centered at one of three locations: left of center by two positions (−2), at center (0), or right of center by two positions (+2). Finally, we replaced T2 with T3—another three-character string of Gs, followed by either O (80%) or C (20%), followed by Q. T3 could be centered at five locations: left of center by four positions (−4), −2, 0, +2, or right of center by four positions (+4).

Procedure. To begin a trial, participants were instructed to fixate on the "*" and not to move their eyes during the course of each trial. However, similar to previous studies, we did not use an eye-tracking device to ensure fixation. We displayed the warning signal for 1,000 ms and then removed it. After 100 ms, we displayed T1 for 200 ms and then removed it. After another delay of 100 ms, we displayed T2 for 200 ms and then removed it. Finally, we displayed T3 for 200 ms and then removed it. At this point, participants had to decide whether the center characters in T1, T2, and T3 were O–R–O. If so, they should press the joystick button as quickly as possible, and they had 1,000 ms to do so. If they did not respond within the allotted time, a high-pitched error tone sounded. We instructed participants to ignore any other combination of center characters. A button press in these no-go trials also resulted in a high-pitched error tone. The intertrial interval was 1,000 ms. The timing and stimuli in this experiment, although different from those used by LaBerge et al. (1997), are based on Pratt and Quilty (2002), who obtained results consistent with those of LaBerge et al. (1997).

Participants completed 450 trials. We tested 15 conditions, T2 (−2, 0, +2) × T3 (−4, −2, 0, +2, +4), and thus allowed for 30 potential observations per condition. We randomized the trials across all conditions. Of these trials, 51.2% were appropriate for responses. The remaining 48.8% were no-go trials. Participants took self-paced breaks after 150 and 300 trials.

Results and Discussion

We presented the RT data in terms of within-subject 95% confidence intervals (Loftus & Masson, 1994; see Figure 1), and we used an omnibus error term to calculate the intervals by pooling the error terms for T2, T3, and T2 × T3 (Winer, 1971). This procedure is allowable because all three mean square errors are roughly equal—that is, within a 2:1 ratio (Masson & Loftus, 2003). Although confidence intervals are intended to discourage the use of null hypothesis statistical tests, they directly correspond to such tests: Two sample means are significantly different for $\alpha = .05$ if their difference is greater than one side of the 95% confidence interval by a factor of at least $\sqrt{2}$ (see proof in Appendix A3 of Loftus & Masson, 1994). If the intervals of two means overlap by less than one half of one side of the interval, then the means would be significantly different by analysis of variance (ANOVA) or *t* test (Masson & Loftus, 2003).

The results from Experiment 1, using a variant of LaBerge et al.'s (1997) paradigm, are consistent with predictions of the ADM. Responses to T3 location 0 were faster than those to location −4 following a T2 of −2, and responses to T3 location 0 were also faster than those to location +4 following a T2 of +2. These results are consistent with the buildup of attention at the central location, as predicted by the ADM. Accordingly, the V curve was symmetric around position 0 following a T2 at that location.

We defined participant response errors as a time-out on a go trial (miss) or as a key press on a no-go trial (false alarm [FA]) and analyzed these errors using an ANOVA of 2 (trial type: go vs. no-go) × 3 (T2) × 5 (T3) (see Table 1). There was a marginal main effect of trial type, $F(1, 8) = 4.48$, $MSE = 1{,}451.39$, $p = .07$, with fewer misses than FAs. There was also a main effect for the T2 location, $F(2, 16) = 10.19$, $MSE = 762.72$, $p < .01$, with the fewest errors at the T2 0 location. In addition, there was a main effect for the T3 location, $F(4, 32) = 3.40$, $MSE = 466.30$, $p < .03$, with the fewest errors at the center and the most errors at the periphery. There was an interaction between trial type and the T2 location, $F(2, 16) = 4.09$, $MSE = 459.54$, $p < .05$, with more FAs than misses at peripheral locations. Finally, there was an interaction between trial type and the T3 location, $F(4, 32) = 4.91$, $MSE = 600.96$, $p < .01$, with fewer misses than FAs at T3 locations −2, 0, and +2. No other interactions reached significance, *p*s > .29.

Experiment 2

In Experiment 1, we replicated the basic pattern of results that other researchers used to support the ADM. In Experiment 2, we addressed two potential confounds:

1. To control for eccentricity, we arranged the display characters on a semicircle around a fixation point so that they were all equally eccentric from the fixation (see D'Aloisio & Klein, 1990).
2. To eliminate the possibility of eye movements, we used an eye tracker to ensure fixation at center. If retinal eccentricity and eye movements did not play a role in the results produced by LaBerge et al. (1997), then we expected to obtain results similar to those of Experiment 1.

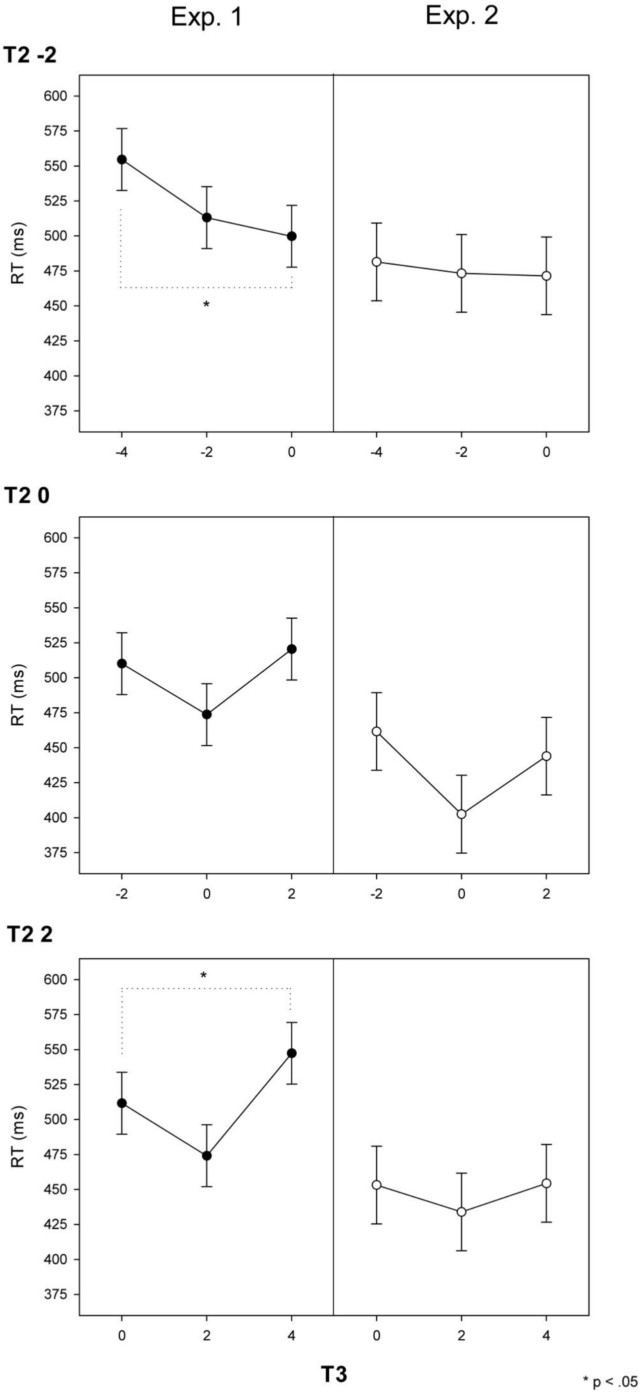

Figure 1. Mean reaction times for the three T3 locations centered around the T2 −2, 0, and +2 locations (error bars are 95% confidence intervals; see Loftus & Masson, 1994). Asterisks indicate significant difference between the left and right T3 locations. Exp. = experiment; T3 = third target display; T2 = second target display; RT = reaction time.

Table 1
Mean Error Rates, Experiment 1

	T3									
	−4		−2		0		2		4	
T2	Miss	FA	Miss	FA	Miss	FA	Miss	FA	Miss	FA
−2	21.8	16.3	0.9	17.4	4.2	19.9	8.0	23.6	14.8	19.3
0	19.2	5.8	4.7	8.1	2.1	3.9	5.9	13.0	11.3	14.3
2	10.2	10.9	8.7	14.2	6.9	11.8	5.7	15.0	14.1	14.4

Note. T2 = Target 2 display; T3 = Target 3 display; Miss = a time-out on a go trial; FA = false alarm, a keypress on a no-go trial.

Method

Participants. Twelve undergraduates at the University of Toronto participated in this experiment in exchange for course credit. All participants had normal or corrected-to-normal vision.

Apparatus. We used the same apparatus that we used in Experiment 1, except that we added an EyeLink II (SR Research, Toronto, Ontario, Canada) head-mounted eye tracker, which interfaced in real time with the experimental personal computer. We calibrated the eye tracker using a nine-dot pattern at the beginning of the experiment, and we drift corrected at the beginning of each trial. The eye-tracking PC used proprietary software that comes with the EyeLink II system to track pupil position at a rate of 500 Hz.

Stimuli. We used stimuli similar to those from Experiment 1 except that we arranged the characters into a semicircle of 1.50° of visual angle radius and the warning signal consisted of 11 symbols (i.e., ###########). We placed a yellow fixation cross directly below the middle warning signal character (see Figure 2). Contrary to previous experiments, all target positions were equidistant from fixation.

Procedure. We used a procedure similar to that used in Experiment 1, except for the eye-tracking controls (see Figure 2). To begin a trial, participants were instructed to fixate on the yellow fixation cross and press a button. If they pressed the button while they were fixated, the cross became white, the calibration was drift corrected, and the warning signal appeared. As before, we instructed the participants to remain fixated

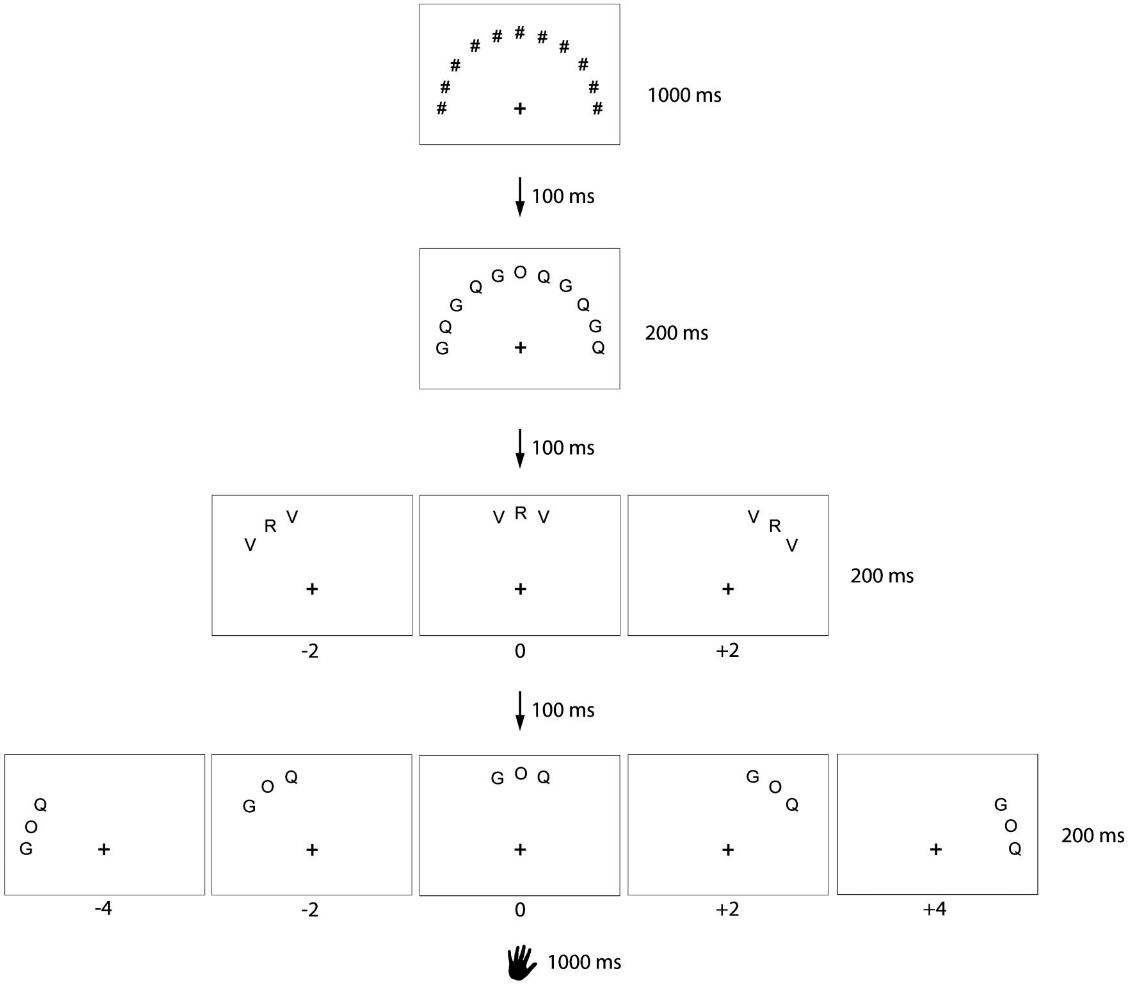

Figure 2. Sample trial sequence for Experiment 2, based on Pratt and Quilty (2002) and LaBerge et al. (1997). The trial shown is a "go" trial because the central characters of the target displays form the string "O-R-O." The trial sequence for Experiment 1 was identical, except that all characters were displayed in a horizontal line at fixation. The cross represents the point of fixation, and the hand represents the manual keypress responses to the targets.

throughout each trial. To ensure fixation, if at any point in the trial the bilateral gaze exceeded a region of 1° radius around fixation, the trial would end and a low-pitched error tone would sound. We did not re-present the trial later because of limited time. We selected a 1° threshold to filter out eye jitter that did not indicate a break of fixation. The experimenter remained outside and monitored the accuracy of the eye tracking. On occasion, the eye tracker needed to be recalibrated because of being knocked by the participant. Although the timing and stimuli are slightly different from those used by LaBerge et al. (1997), our results from Experiment 1 are consistent with the predictions of the ADM.

Results and Discussion

The RT data are presented using within-subject confidence intervals (see Figure 1). We pooled the error terms for T2, T3, and their interaction on the basis of the same criterion that we used in Experiment 1. After controlling for eccentricity and eye movements, we observed that the difference between T3 locations on either side of the T2 -2 and T2 $+2$ locations disappeared. Responses to T3 -4 were no longer slower than responses to T3 0 after T2 -2; likewise, responses to T3 $+4$ were no longer slower than responses to T3 0 after T2 $+2$. Our findings indicate that eccentricity and/or eye movements can account for some of LaBerge et al.'s (1997) results.

We again analyzed participant response errors using an ANOVA of 2 (trial type: go vs. no-go) × 3 (T2) × 5 (T3) (see Table 2). There was a main effect of trial type, $F(1, 11) = 40.93$, $MSE = 90{,}376.71$, $p < .01$, with fewer misses than FAs. No other main effects were significant, *p*s $>.2$. There was an interaction between trial type and the T2 location, $F(2, 22) = 4.10$, $MSE = 1{,}311.74$, $p < .05$, with the fewest misses and the most FAs at the T2 0 location. No other interactions reached significance, *p*s $>.57$. Because eye movements caused the early termination of a trial, we added them across conditions. The percentage of eye movement errors per participant was high ($M = 31.4\%$, $SE = 3.6$), indicating the difficulty of remaining fixated. Roughly twice as many eye movements occurred during the initial target presentation (T1) than during subsequent target displays (T2 and T3).

A notable difference between Experiments 1 and 2 was the increase in FA rates across conditions. One possible explanation is that participants divided their attention between maintaining fixation and discriminating the targets. In addition, because we presented no stimuli within fixation, participants may have found the discrimination task more difficult. However, we would then expect a decrease in the overall hit rate, which did not occur. To further ensure that participants could adequately discriminate between go and no-go trials, we calculated d' scores for each participant and condition (see Table 2). None of our conclusions based on the RT data were challenged by the d's, which were all substantially above chance. Finally, it is unlikely that the high FA rate and reduced RT latencies were responsible for flattening the V curves in Experiment 2, because we closely replicated our results at T2 0 and neither the FA rates nor the RTs were different at that location than at the others.

General Discussion

The two experiments reported here demonstrate the dramatic effects of eye movements and retinal eccentricity on performance in visual attention tasks. In this case, we attenuated results from the multiple display task used by LaBerge et al. (1997) by equating the retinal eccentricity of targets and by preventing eye movements. Therefore, the task performed by LaBerge and colleagues does not adequately test the activity distribution and spotlight models of attention, as was intended, and the conclusions that favor the ADM are unsupported. Further, the experiments presented here highlight the need to control for potential confounds when examining the allocation of attention across the visual field.

What are the possible consequences of the present findings for the ADM and other models of attention? First, one could argue that although the current task is confounded, the ADM remains a powerful and parsimonious theory of visual attention; a new task is needed to demonstrate that the ADM captures the nature of attention better than spotlight models. One class of tasks involves the splitability of attention—that is, attention can be split between multiple locations that are noncontiguous and spatial (see, e.g., Awh & Pashler, 2000; Bichot, Cave, & Pashler, 1999; Castiello & Umiltà, 1992; Eimer, 2000; Kramer & Hahn, 1995). The fact that attention need not be a contiguous unitary beam is a key feature of the ADM and, by definition, contradicts spotlight models of attention.

Second, these findings represent direct evidence against the ADM and in favor of spotlight models. This is a reasonable position to take, given that the confounded results from LaBerge et al. (1997) served as the empirical foundation of the ADM. In addition, many researchers (see, e.g., Kiefer & Siple, 1987; McCormick & Klein, 1990; Posner, Snyder, & Davidson, 1980) have challenged the notion of attention splitability, often used to support the ADM above. McCormick, Klein, and Johnston (1998) demonstrated that in one of the first reports of splitability (Castiello &

Table 2
Mean Error Rates and d' Scores, Experiment 2

	T3														
	-4			-2			0			2			4		
T2	Miss	FA	d'	Miss	FA	d'	Miss	FA	d'	Miss	FA	d'	Miss	FA	d'
-2	9.2	35.9	1.82	14.0	40.3	1.54	11.8	33.7	1.78	12.8	35.6	1.67	7.3	32.6	1.97
0	4.9	47.9	1.68	6.8	46.3	1.66	10.3	39.7	1.67	9.4	45.8	1.48	3.7	43.6	1.88
2	5.5	39.3	1.89	12.4	39.6	1.61	7.9	44.5	1.62	11.1	42.1	1.54	8.8	44.5	1.57

Note. T2 = Target 2 display; T3 = Target 3 display; Miss = a time-out on a go trial; FA = false alarm, a keypress on a no-go trial.

Umiltà, 1992), attention was spread diffusely across the display rather than split into noncontiguous locations.

Finally, the present findings highlight an important realization: Searching for a single metaphor to capture all aspects of visual attention may be too simplistic. Rather, in light of the discrepant findings in the literature (and the vastly different paradigms researchers used to produce them), a better strategy may be to study the conditions under which certain models best characterize attention. This approach could prove to be more fruitful in understanding the nature of attention by elaborating some of its ubiquitous and subtle complexities that overgeneralization has obscured.

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Received February 5, 2004
Revision received March 31, 2005
Accepted March 31, 2005 ■