



# Saccades require focal attention and are facilitated by a short-term memory system

Robert M. McPeck<sup>a,\*</sup>, Vera Maljkovic<sup>b</sup>, Ken Nakayama<sup>a,1</sup>

<sup>a</sup> *Vision Sciences Laboratory, Department of Psychology, Harvard University, Cambridge, MA, USA*

<sup>b</sup> *Department of Psychology, University of Chicago, Chicago, IL, USA*

Received 23 April 1997; received in revised form 7 April 1998

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## Abstract

We performed two sets of experiments in which observers were instructed to make saccades to an odd colored target embedded in an array of distractors. First, we found that when the colors of the target and distractors switched unpredictably from trial to trial (the mixed condition), saccadic latencies decreased with increasing numbers of distractors. In contrast, saccadic latencies were independent of the number of distractors when the color of the target and distractors remained the same on each trial (the blocked condition). This pattern of results mirrors visual search tasks in which focal rather than distributed attention is required (Bravo, M.J., Nakayama, K. (1992). The role of attention in different visual search tasks. *Perception and Psychophysics*, 51, 465–472.). Second, we found that saccades to an odd target were made more quickly and accurately when the target was the same color as on previous trials than when it changed color. This priming of the target color accumulates across five to seven trials over a period of approximately 30 s. A similar priming effect has been previously shown for the deployment of focal attention (Maljkovic, V., Nakayama, K. (1994). Priming of popout: III. Role of features. *Memory and Cognition*, 22(6), 657–672.). Thus, we show a close congruence between the pattern of saccadic eye movement latencies and the deployment of focal attention. This supports the view that (1) the execution of saccades requires focal as opposed to distributed attention and that (2) this focal attention is guided by a short term memory system which facilitates the rapid refixation of gaze to recently foveated targets. © 1999 Elsevier Science Ltd. All rights reserved.

*Keywords:* Visual search; Saccade; Attention; Priming

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## 1. Introduction

Humans typically make many eye movements when examining a scene or even when performing fairly simple visuo-motor tasks that do not seem to require much scrutiny (Ballard, Hayhoe, Li & Whitehead, 1992). Indeed, it has been estimated that we make more than three saccades per second, in every second of our waking lives (O'Regan, 1992). Clearly, then, an important part of understanding vision is to understand how we are able to move our eyes to the right place at the right time so efficiently and seemingly effortlessly.

Given that the visual scene is often crowded with many different stimuli, there must be a mechanism which selects one particular stimulus as the target for a saccade. One long-debated hypothesis is that the saccade target is chosen by allocating attention to it. A growing number of studies have supported this view (Shepherd, Findlay & Hockey, 1986; Hoffman & Subramanian, 1995; Kowler, Anderson, Doshier & Blaser, 1995; Deubel & Schneider, 1996). In the current study, we use visual search tasks not only to confirm the results of these previous studies, but also to address the question of whether saccades require a spatially focused pattern of attention, or whether a distributed pattern of attention is sufficient for their generation. We begin by briefly reviewing the evidence for an obligatory link between saccades and attention. Next, we turn to the distinction between focal and distributed spatial patterns of attention. Following this, in the first experi-

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\* Corresponding author. Present address: Smith-Kettlewell Eye Research Institute, 2232 Webster Street, San Francisco, CA 94115, USA. Tel.: +1 415 5611639; fax: +1 415 5611610; e-mail: rmm@skivis.ski.org.

<sup>1</sup> To whom reprint requests should be addressed.

ment, we show that an unusual pattern of set-size effects, selectively seen for tasks requiring focal attention (Bravo & Nakayama, 1992), is also seen for a simple saccade task. In the second experiment, we find that a short-term memory system which facilitates shifts of focal attention (Maljkovic & Nakayama, 1994) also facilitates the generation of saccades. The results of these two experiments support the view that a focal (rather than distributed) pattern of attention is required for saccades. Finally, we discuss how the unusual characteristics of this memory system could allow it to improve the efficiency of the saccadic system in many situations.

### 1.1. *The coupling of saccades and attention*

Neurophysiologists have identified neurons in several regions of the brain which respond both to eye movements and to movements of attention such as the pulvinar (Robinson & McClurkin, 1989; Petersen, Robinson & Morris, 1987); parietal cortex (Bushnell, Goldberg & Robinson, 1981); and area V4 (Fischer & Boch, 1985). Along similar lines, behavioral studies have shown that attention is shifted to a target before a saccade to the target is made (Henderson, 1992). While these results indicate that there does tend to be an association between attention and saccades, they do not establish an obligatory or functional link.

This question was recently addressed by Hoffman and Subramanian (1995), Kowler et al. (1995), and Deubel and Schneider (1996), who all found that saccades do in fact require a shift of attention to the target location. These three studies used dual-task paradigms, requiring subjects to perform an attentionally demanding shape-discrimination task at a peripheral location while simultaneously programming a saccade, either to the same location, or to a different location. They found that when attention was directed away from the location of the saccade target, the latency of saccades increased, and the saccades tended to be less accurate. Furthermore, Kowler et al. (1995) measured the 'attention operating characteristic' (Sperling & Doshier, 1986) in order to determine the amount of attention required to make a saccade, relative to the amount required to perform a letter discrimination task. Interestingly, they found that only a small amount of attention is required for a saccade. This may explain the conflicting results of prior dual-task studies, some of which concluded that saccades do not require attention (Klein, 1980; Posner, 1980; Remington, 1980; but also see Shepherd et al., 1986). These earlier studies all used luminance detection tasks, which are less attentionally demanding than the shape discrimination tasks used in the later studies. Since the attentional requirements of saccades are fairly modest, it is plausible that when programming a saccade, enough attentional resources may re-

main to simultaneously perform other reasonably undemanding tasks, such as luminance detection. Dual-task interference will only be found when testing with a task which sufficiently taxes attentional resources (Nakayama & Joseph, 1998).

More indirect evidence for the coupling of attention and saccades has been revealed by Fischer (1987) and colleagues, who demonstrated the role of attention in short-latency 'express saccades' (Mayfrank, Mobashery, Kimmig & Fischer, 1986)<sup>2</sup>. Mackeben and Nakayama (1993) strengthened the argument that attention is responsible for shortening saccadic latencies, by directly showing that the conditions favoring express saccades also allow attention to be allocated to peripheral locations more rapidly. Using a different paradigm, Sheliga, Riggio, Craighero and Rizzolatti (1995) demonstrated that the locus of attention can affect the trajectory of saccades, thus providing additional indirect evidence for a functional link between attention and saccades (also see Kustov and Robinson (1996) for similar results in monkey).

### 1.2. *Focal versus distributed attention*

The emerging view is that attention is necessary for the production of a saccade, but that the amount of attention required is rather modest (Kowler et al., 1995). Thus, we felt it important to clarify the attentional demands of saccades, particularly whether a spatially focused pattern of attention is necessary for the execution of a saccade, or whether distributed attention will suffice. Much early work investigating control of the spatial scope of attention was done by LaBerge and colleagues (LaBerge, 1983). More recently, Bravo and Nakayama (1992) have provided evidence for a distinction between visual search tasks which require attention to be focused on the target and those which can be performed with attention distributed across the field. In their scheme, a spatial narrowing or focusing of attention is required for perceptual tasks involving discriminations made on a fine scale, such as determining the shape of a small detail of a stimulus element. In contrast, attention is distributed across the field when a pattern recognition task at a more global scale is performed, such as detecting the presence of an orientation or color oddball in an array of distractors. While the importance of focal attention has been recognized for many years, the necessity of distributed attention for perception has only become fully recognized recently. Indeed, many tasks which were once classified as 'pre-attentive' have, in fact, been found to require small

<sup>2</sup> Kingstone and Klein (1993) provided evidence against Fischer's attentional hypothesis. However, their experiments focused on the oculomotor gap effect, a general reduction in saccade latency, rather than on express saccades, per se.

amounts of distributed attention (Joseph, Chun & Nakayama, 1997; Nakayama & Joseph, 1998).

This distinction between focal and distributed attention has not been directly addressed with regard to saccades. For example, Kowler et al. (1995) found that when attention is focused away from the target of a saccade, the execution of the saccade is impeded. This indicates that when attention is focused elsewhere, insufficient attentional resources remain to program a saccade, but it does not indicate whether the pattern of attentional deployment required for a saccade is focal or distributed. Kowler and colleagues also found that when attention is focused on the saccade target, the execution of the saccade can proceed unhindered. This shows that focal attention is sufficient for the execution of a saccade, however, the question of whether distributed attention is also sufficient is not addressed. Particularly in light of the finding that saccades have relatively modest attentional requirements, it is possible that focal attention may not be necessary for the production of a saccade.

### *1.3. Using visual search to investigate focal and distributed attention*

In order to address the question of whether saccades require focal attention or merely distributed attention, we examined eye movements in visual search, as this allowed us to draw upon a large body of research on attention and visual search for comparison. In particular, we employed a diagnostic originated by Bravo and Nakayama (1992), which delineates the patterns of attentional deployment required for various visual search tasks. They argued, somewhat unconventionally, that when there are salient perceptual differences between the target and distractors, the broad scope of distributed attention allows observers to detect the presence or absence of the odd target using a global pattern matching process on the entire stimulus array at once. As a result, the time needed to make such a present versus absent response does not depend on the time required to focus attention on the target. Thus, reaction times to perform this detection task should not vary appreciably even for large differences in the number of distractors. Bravo and Nakayama produced this well-known constant or flat search function in an experiment in which observers maintained fixation at the center of the screen, and detected the presence or absence of an odd-colored target presented with a variable number of distractors. Furthermore, they showed that this flat search function persists when the color of the target remains the same from trial to trial (the blocked condition) and when it varies (mixed condition).

In order to measure the amount of time required to allocate focal attention to the target, Bravo and

Nakayama employed the same configuration of distractors and targets, but added a further requirement to the task: they instructed the observers to discriminate a subtle aspect of the odd colored target's shape, asking which side of the diamond shaped target was cut off. In order to perform this fine shape discrimination task, observers would presumably be required to focus attention on the target before responding. This seemingly small manipulation had a dramatic effect, yielding a characteristic signature of reaction times across conditions. Least surprising was the overall lengthening of reaction times, reflecting the well known difference between detection and discrimination tasks. More interesting and significant were the differences seen between the blocked and mixed trial conditions: (1) reaction times (RTs) for the blocked condition were shorter overall than for the mixed condition. (2) RTs for the blocked condition did not vary with the number of distractors. (3) RTs for the mixed case decreased for increasing numbers of distractors. These same results were confirmed in a subsequent replication (Maljkovic & Nakayama, 1994).

Bravo and Nakayama accounted for these findings by arguing that when the distinctive feature of the target does not change from trial to trial (the 'blocked' case), attention can be rapidly guided by top-down mechanisms which take advantage of the predictable features of the target to draw attention quickly to the target's location, regardless of the number of distractors. (Maljkovic and Nakayama (1994) subsequently provided evidence that an implicit short-term visual memory system mediates this function.) This results in shorter overall RTs for the blocked condition, as well as its flat search slopes. On the other hand, when the distinctive feature of the target changes from trial to trial (the 'mixed' case), it is necessary to use slower bottom-up mechanisms, such as Gestalt grouping processes, to guide attention to the odd target. Several theories of bottom-up attentional guidance (Koch & Ullman, 1985; Julesz, 1986), predict that these grouping processes become more efficient as the density of homogeneous distractors increases, and consequently, that the time required to shift attention to the target should decrease as the number of distractors increases. Bravo and Nakayama's results show precisely this pattern: in the mixed condition, the time required to shift focal attention to the target decreases with increasing numbers of distractors, while in the blocked condition, it is independent of the number of distractors. Thus, these results provide a diagnostic to distinguish between tasks which require attention to be focused on the target, such as a high-acuity shape discrimination, and those which can be performed with attention distributed across the field, such as the detection of an odd target.

#### 1.4. Do saccades require focal or distributed attention?

In the present study, we apply this method to determine if saccades in a visual search task require focal attention. Specifically, we ask subjects simply to make a saccade to an odd-colored target, and measure saccade latency as a function of the number of distractors in the mixed and blocked conditions. On the surface, this saccade task seems more similar to Bravo and Nakayama's detection task than to their discrimination task. However, one might argue that making a saccade to the target presumably involves localizing it, while detecting its presence or absence may not. But does the act of localizing a target require the deployment of focal attention to it? In other words, if we are able to determine where a target is (sufficient to make a saccade there), do we necessarily have to shift focal attention to it or is it sufficient to allocate attention more diffusely?

The results of Sagi and Julesz (1985) suggest that there is no obligatory connection between localization and focal attention. They examined performance in tasks requiring detection and localization of odd targets in search arrays. Localization was assessed by asking the subject to discriminate the global shape of three odd stimuli that formed a triangle. Their results indicated that this localization task did not require focal attention—it was performed in the same time as detection and the subjects did not encode the tiny local shapes of the odd stimuli which defined the global shape. However, this localization task could also be regarded as global shape recognition task, since it simply required subjects to discriminate the global shape formed by the three odd tokens. Thus, although their study indicated that this task did not require attention to be focused on any of the vertices of the implicit triangle, it leaves open the possibility that other localization tasks, particularly motor tasks, such as saccadic programming, might be different.

To determine whether saccades require focal or distributed attention, we used Bravo and Nakayama's diagnostic for assessing attentional requirements. If distributed attention were all that would be required, we should see a flat latency function with increasing numbers of distractors in both the mixed and blocked cases for the saccade task, just as Bravo and Nakayama found for the manual reaction time detection task. This would indicate that although the execution of a saccade does require some attentional resources, as shown by Kowler et al. (1995), it does not require attention to be focused at the target, but rather, like the detection task, can be performed with attention distributed across the field. On the other hand, if saccades do require focal attention, a very different pattern should emerge: (1) an overall faster pattern of saccadic reaction times (SRTs) in the blocked case as compared to the mixed case; (2)

SRTs which are independent of the number of distractors in the blocked case, and finally; (3) a decrease in SRTs with increasing number of distractors in the mixed case. If this unusual pattern could be revealed for saccadic eye movements, it would indicate that a spatial focusing of attention on the target is, in fact, required for the production of a saccade.

## 2. Experiment 1: variable number of distractors

### 2.1. Method

#### 2.1.1. Stimuli

The stimuli and displays are schematized in Fig. 1. The search displays consisted of between three and twelve stimulus elements. The stimulus elements were solid, red or green colored diamond-shaped figures subtending  $1.4^\circ$  vertically and horizontally, with a small (15 min arc) black dot in the center. The luminance of the red diamond was  $4.71 \text{ cd/m}^2$ , and the green was  $5.06 \text{ cd/m}^2$ , against a  $10 \text{ cd/m}^2$  background. The red and green used were chosen to be approximately equiluminant using heterochromatic flicker photometry.

The stimuli were arranged uniformly around an ellipse subtending  $14.8^\circ$  horizontally and  $11.7^\circ$  vertically. The ellipse was used only to position the stimuli, and was not visible during the experiments. The target stimulus was always distinguished by a difference in color from the distractor stimuli. In the blocked condition, the color of the target stayed constant for the entire block of trials. In the mixed condition, the color of the target was randomly selected to be red or green with equal probability on each trial. On each trial, if the target was red then the distractors were green, and vice-versa.

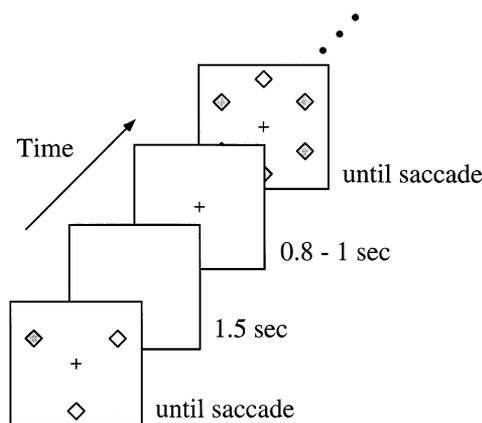


Fig. 1. Schematic illustration of the stimuli used in Experiment 1. On each trial, the target was the odd-colored diamond (either a red element among green distractors, or a green element among red distractors). The task of subjects was to make a saccade to the target.

The target was positioned randomly from trial to trial at one of six possible positions, corresponding to 1, 3, 5, 7, 9, and 11 o'clock. The number of distractors displayed was randomly varied among 2, 3, 5, and 11 distractors. The distractors and target were always positioned so as to be equidistant around the ellipse.

### 2.1.2. Procedure

Subjects were seated 50 cm in front of a color monitor on which the stimuli were presented. At the beginning of each block of 100 experimental trials, calibration stimuli were presented sequentially at 12 positions around the clock. Subjects were urged to accurately fixate each calibration stimulus in turn, and to press a key when they felt confident that they had centered their gaze over the mark at the center of each stimulus. After calibration was complete, the subjects pressed a key, and after ten practice trials, the experimental trials commenced.

At the beginning of each trial, subjects fixated the central fixation point. After a variable delay ranging from 800–1000 ms, the search array was presented. Subjects were instructed to make a saccade to the odd target as quickly and accurately as possible. After performing the saccade, the subjects pressed the space bar to go on to the next trial. At this point, the search array was removed, and after a 1.5 s pause the next trial was initiated by the appearance of the fixation point.

### 2.1.3. Subjects

Three experienced subjects each performed 400 trials in the mixed condition and 400 trials in the blocked condition over a period of 4 days. Subject RM was an author, while subjects PT and SS were naive with regard to the purpose of the experiment.

### 2.1.4. Apparatus

The subject's head was stabilized using a combination chin-rest and head-support device. Vertical and horizontal positions of both eyes were recorded using the Ober2 infrared reflection system. Eye position was sampled at 240 Hz. In our hands, the Ober2 system was fairly sensitive, picking up saccadic movements of less than  $0.3^\circ$  reliably. However, the system showed a slow drift in DC level over time, and thus, eye position was re-zeroed at the start of each trial when the subject fixated the central fixation point. Within the  $\pm 8^\circ$  range used in these experiments, we found the responses of the Ober2 system to be approximately linear with eye position.

### 2.1.5. Data analysis

The eye position records were analyzed using an interactive computer program which used a velocity criterion to detect saccades. A saccade was identified when eye velocity exceeded a threshold of approxi-

mately  $30^\circ/\text{s}$ . After identification, more precise onset and ending times for saccades were determined using a lower threshold which was chosen individually for each subject by examining a large number of saccades. The analysis for each trial was carefully inspected by hand to verify, and correct, if necessary, the program's analysis. The latency, duration, start-, and end-point of each saccade were recorded. The calibration data obtained at the beginning of each block of 100 trials were used to determine the stimulus position toward which each saccade was directed. Occasionally, we observed saccades with a latency of less than 80 ms. These saccades tended to be very hypometric and were often not directed toward any of the stimuli. Such saccades were classified as anticipatory and trials containing them were rejected from further analysis. Trials were also occasionally rejected because of blinks. In total, however, less than 3% of the trials were rejected.

For large upward movements, the records produced by the Ober2 were occasionally affected by movements of the subjects' eyelids. Since all our trials began with the eyes in the central position, when this artifact was present, it affected the end of large upward movements, resulting in an apparent decrease in velocity and increase in duration of the movements. It is unlikely that this artifact affected our latency measurements, because the affected saccades showed slowing only in the later part of the movement. This results from the fact that the latency of eyelid movements is longer than the latency of the saccades which they accompany (Becker & Fuchs, 1988). When determining the vertical end-points of saccades in which the eyelid artifact was present, we were careful to measure the steady-state eye position at the end of the slowed vertical movement.

## 2.2. Results

The results for the three subjects are shown in Fig. 2. Trials in which the initial saccade landed within  $2^\circ$  of the target were coded as 'correct' trials, while all other trials were coded as 'errors.' Saccadic latencies were analyzed for correct trials only. Across all distractor set sizes, latencies in the blocked condition were significantly shorter than those in the mixed condition. Accordingly, in a two-way analysis of variance performed separately for each subject (using condition (mixed vs. blocked) and number of distractors (2, 3, 5, or 11) as the factors), the main effect of condition was significant,  $P < 0.001$  for all subjects, with overall longer latencies in the mixed condition. Furthermore, there was a significant interaction between condition and number of distractors ( $P < 0.015$  for all subjects): in the mixed condition, the saccadic latencies of all three subjects showed a decline as the number of distractors increased (linear contrasts yielded  $P < 0.01$  for all subjects), while in the blocked condition, saccadic latencies

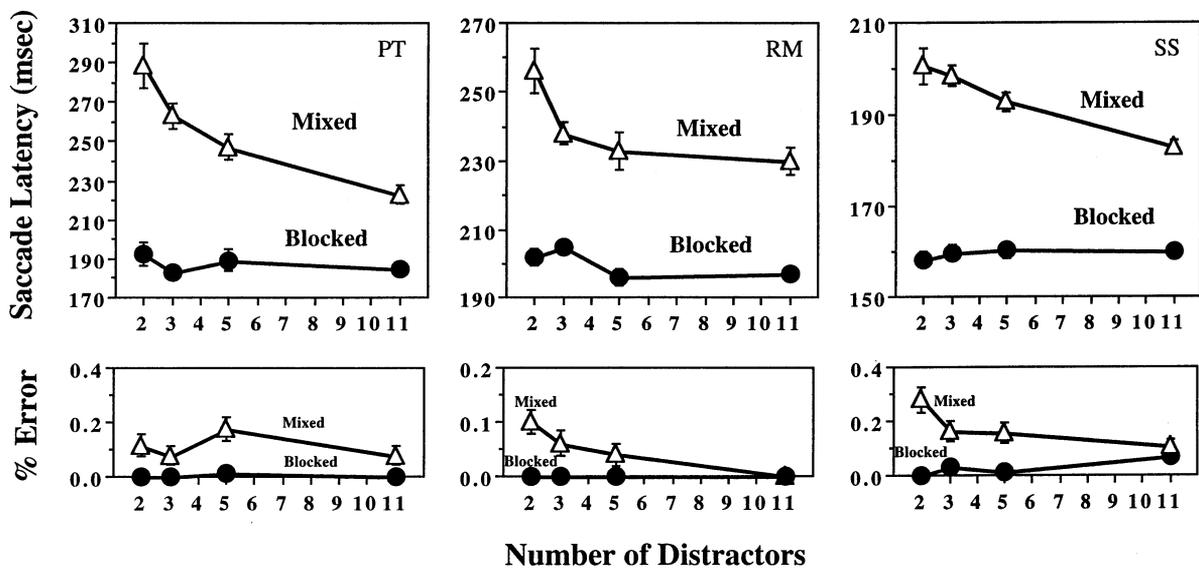


Fig. 2. Experiment 1. Mean saccadic latency for each subject decreases as the number of distractors increases in the mixed condition, but not in the blocked condition. The error rate, defined as the percentage of inaccurate saccades (see text for details), follows the same trends as the latencies. Note that the latency data exclude all inaccurate saccades. Error bars for this and all subsequent figures denote standard error of the mean.

remained relatively constant with increasing numbers of distractors (linear contrasts were not significant,  $P > 0.10$  for all subjects).

Although the frequency of errors made by the different subjects varied, in general the error rates (Fig. 2, lower panels) showed trends similar to those of the latencies. For each subject a two-way analysis of variance for error rates (using the same factors and levels as in the analysis of latencies) showed a significant main effect of mixed versus blocked condition ( $P < 0.001$  for all subjects), with a greater number of errors occurring in the mixed condition. In addition, subject SS showed a significant interaction of condition and number of distractors ( $P < 0.01$ ), with a stronger effect of the number of distractors in the mixed condition than in the blocked condition. Finally, linear contrasts showed that in the mixed condition, errors significantly decreased with increasing number of distractors for subjects SS and RM ( $P < 0.01$ ), while in the blocked condition, there was no linear trend ( $P > 0.10$  for all subjects).

### 2.3. Discussion of Experiment 1

If saccades can be executed with attention distributed across the field, we would expect to find flat search slopes in both the mixed and blocked conditions of our saccade task like those found in the detection task of Bravo and Nakayama (1992). However, despite the apparent similarity of detecting the presence or absence of a salient odd target and making a saccade to it, the results of our saccade task differ significantly from those of the detection task.

Instead, our results are remarkably similar to those found in the high-acuity shape discrimination task of Bravo and Nakayama (1992): saccade latencies decrease with increasing numbers of distractors in the mixed, but not in the blocked condition. These effects are echoed in the error rate data, indicating that subjects have not achieved the shorter latencies by sacrificing accuracy. This set of results is precisely the pattern predicted for tasks requiring focal attention. As Bravo and Nakayama argued, in the mixed condition, tasks which require focal attention must use bottom-up grouping processes to allocate attention to an odd-colored target. Models of focal attention predict that such grouping processes allow attention to be shifted to the target more quickly when the density of distractors is greater (Koch & Ullman, 1985; Julesz, 1986). Accordingly, we find that saccade latencies decrease with increasing numbers of distractors in the mixed condition. On the other hand, in the blocked condition, the colors of the target and distractors remain the same from trial to trial, and so tasks which require focal attention can make use of more rapid top-down mechanisms to direct attention directly to the target, regardless of the number of distractors. Consistent with this, we find that saccade latencies in the blocked condition are independent of the number of distractors.

As argued before, the saccade task is superficially similar to Bravo and Nakayama's detection task, which can be performed with distributed attention. However, the saccade task has the added requirement that subjects make a spatially precise response, rather than simply a keypress. Although Sagi and Julesz (1985) found that perceptual localization in a pop-out display

does not require focal attention, their task required only relative localization of stimuli in an array, and could be regarded as a global shape recognition task, as discussed in the introduction. Our results indicate that programming a saccade, a motor localization task, does require focal attention. Thus, although the saccade task has no explicit requirement for focal attention, these results indicate that focusing attention on the target is an implicit, and necessary, step in the process of making a saccade. This finding not only strengthens the hypothesis of a functional link between attention and saccades, but also indicates that focal attention, rather than distributed attention, is required for the production of a saccade.

### 3. Experiment 2: priming of saccade target features

In Bravo and Nakayama's shape-discrimination task, reaction times in the blocked condition are consistently shorter than in the mixed condition. One might be tempted to assume that this advantage stems from the ability of subjects to predict the color of the target on each trial in the blocked condition. However, Maljkovic and Nakayama (1994) determined that this difference does not depend on the predictability of the target, but rather, results from a cumulative, automatic, and unconscious priming of its distinguishing feature (in this case, color). They showed that this 'priming of pop-out' allows subjects to deploy focal attention to the target more quickly when the target color repeats. The strength of the priming increases with more repetitions of the target color, but does not depend on the cognitive predictability of the target color (Maljkovic & Nakayama, 1994). The priming also seems to passively decay over a period of seconds or minutes (Maljkovic & Nakayama, 1993), rather than hours or weeks, as with several other forms of unconscious (implicit) memory (Schacter, Chiu & Ochsner, 1993). When the color of the target is unchanging, this priming allows subjects to rapidly deploy attention directly to the target, regardless of the number of distractors, resulting in the flat search slopes seen in the blocked condition. This provides a means of supporting our initial findings: if saccades do indeed require attention to be focused on the target, the manipulation of focal attention through priming should affect saccade latencies. In addition, if the priming of focal attention were found to affect saccades, it would suggest that a possible function for this memory system is to improve the efficiency the saccadic system by priming objects of recent interest.

In their study of the priming of focal attention, Maljkovic and Nakayama employed a shape-discrimination task with two distractors, in the same spatial configuration as we used in Experiment 1. Using this same configuration of target and distractors in the

present experiment, we asked subjects simply to make a saccade to the odd-colored target. If saccadic eye movements require focal attention at the target, we would expect the priming of attentional deployment to affect the latency of saccades in a manner similar to that observed in Maljkovic and Nakayama's task.

#### 3.1. Method

The apparatus and data analysis methods used in this experiment were virtually identical to those used in Experiment 1. The stimuli and task were also quite similar, with the exception that the number of distractors was held constant at two, and that the stimuli were located around the circumference of an imaginary circle (rather than an ellipse) of radius  $7^\circ$ . On each trial, the target was either red or green with equal probability, and was located randomly in one of six positions around the clock. The distractors were always of the opposite color, and were equidistant from each other and the target.

Each of the three experienced subjects performed 700 trials total, over a period of several days. Subjects RM and VM were authors, and subject SS, who participated in Experiment 1, was naive. Trials were run in blocks of 100, with 12 calibration and ten practice trials preceding each block of 100 experimental trials. Each subject's head was stabilized using a rigid, deep-impression dental bite-bar and a chest support bar. One block of subject SS's data could not be analyzed due to an unacceptable calibration.

#### 3.2. Results

##### 3.2.1. Cumulative priming of saccades

If color repetition has an effect on saccades, as it does on the deployment of focal attention, then it should be most evident when the target color happens to repeat on several consecutive trials. Thus, we first grouped the data according to the number of immediately-preceding trials in which the target color was the same as on the current trial (the 'run-length'). Specifically, all the trials in which the target color was different from its color on the previous trial were assigned a run-length of one. Trials in which the target color was the same as on the previous trial, but different from its color two trials ago, were assigned a run-length of two, and so on. In Fig. 3, data showing this cumulative priming effect are presented for three observers. At the top, the latency of correct saccades is plotted as a function of the run-length. As is evident, for all observers, the latency of saccades to the target decreased as the number of previous same-color trials in a row increased. We performed a one-way analysis of variance individually for each subject, using run-length as a factor with five levels (run-lengths higher than five were

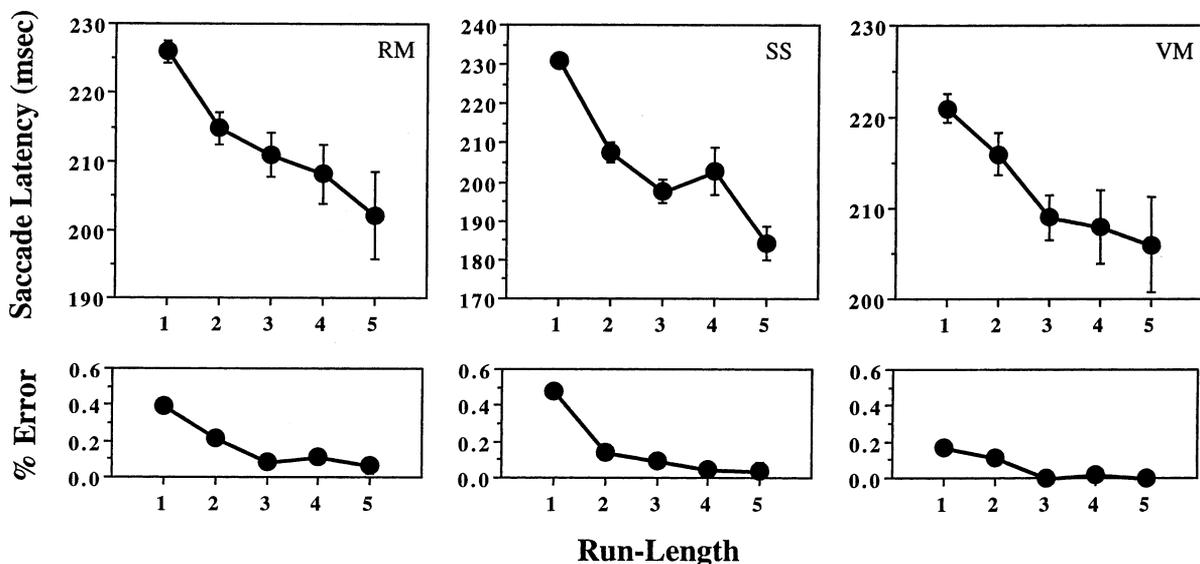


Fig. 3. Experiment 2. Cumulative effects of color repetition on saccade latency and accuracy. Both saccade latency and the percentage of inaccurate saccades decrease as the number of prior same-color trials increases. Note that the latency data exclude all inaccurate saccades. The error bars for some points in the lower panels are smaller than the plotting symbols.

not analyzed, given the very small number of cases in which the color remained the same for more than five trials in a row). In accordance with the graphs, we found a significant effect of run-length on saccade latencies ( $P < 0.001$  for all subjects), and linear contrasts confirmed significant linear trends ( $P < 0.005$ ) for all subjects.

Trials on which the initial saccade did not land within  $2^\circ$  of the target stimulus were defined as errors. For the latency data presented above, all error trials were omitted. Error rate as a function of the run-length is plotted in the lower panels of Fig. 3. In general, the error rates followed the same trend as the latencies. A one-way analysis of variance for each subject (with run-length as the factor with five levels) showed a significant effect of run-length ( $P < 0.001$  for all subjects) on error rates, with errors decreasing as the number of previous same-color trials increased (linear contrasts showed  $P < 0.015$  for all subjects). The majority of the errors (88% overall) consisted of saccades in the direction of one of the distractor stimuli. Using a similar color pop-out task, but with a larger number of distractors, Findlay (1997) has observed that incorrect saccades are often directed to the stimuli which are adjacent to the target stimulus. In a separate study, we examine the characteristics of the error saccades in our task, as well as the short-latency corrective saccades to the target which frequently followed them (McPeck, Skavenski & Nakayama, 1996).

### 3.2.2. Memory kernel analysis

In the previous section, we examined the cumulative effects of priming on saccade latency and accuracy. To

better understand the time-course of the priming, Maljkovic and Nakayama (1994, 1996) developed a technique, called memory kernel analysis, which allowed them to determine the influence on the current trial of the color of the target on a single trial some time in the past. This method can be regarded as a simplification of the sequential dependency analysis of Falmagne, Cohen and Dwivedi (1975). To illustrate Maljkovic and Nakayama's adaptation of this technique, consider how one might determine the influence of the color of the target  $i$  trials in the past: For each trial  $n$ , the color of the target on trial  $n - i$  can either be the same as or different from its color on trial  $n$ . Over a large number of trials, there will be equal numbers of same and different color trials between trial  $n$  and trial  $n - i$ , so the influence of these intervening trials is averaged out. A measure of the influence of the target color  $i$  trials in the past can then be made by comparing performance in trials in which the target color on trial  $n - i$  was the same to those in which it was different from its color on trial  $n$ . The influence of future trials on the present trial can also be calculated. Since one would expect future trials to have no effect, this provides a measure of the variability inherent in this analysis.

We applied memory kernel analysis to our latency and error rate data in order to determine the time-course of the priming of saccades and to compare it to the priming found by Maljkovic and Nakayama. In Fig. 4, the amount of priming is plotted for up to ten trials in the past and four trials in the future. We defined the amount of priming as the difference in latency (or error rate) between the same-color trials and

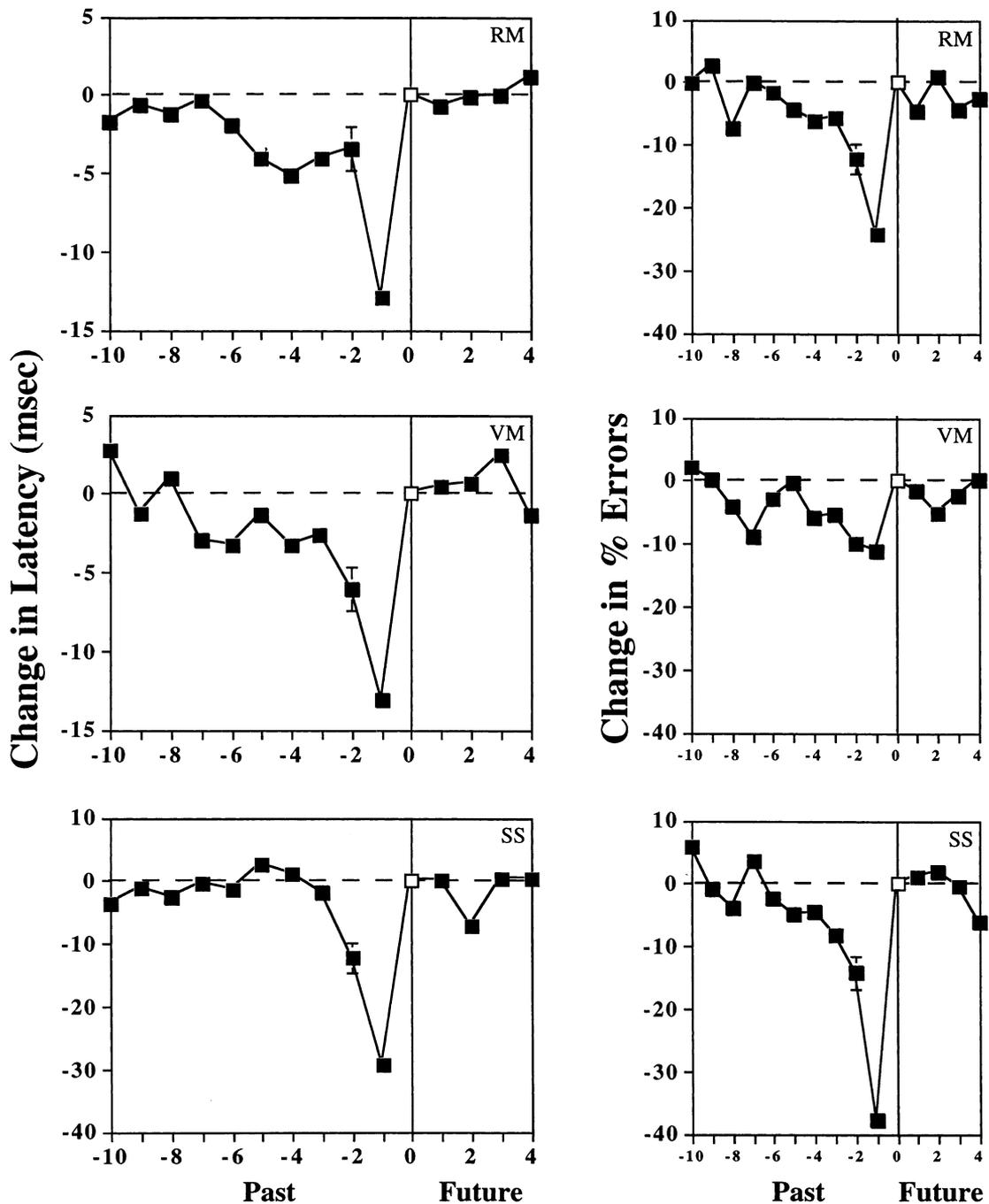


Fig. 4. Memory kernel analysis, showing the effect (as measured by a decrease in latency and error rate) of a single same-color trial in the past versus a different-color trial in the past. Points further to the left of the open square represent the influence of trials further in the past, while points to the right of the open square show the influence of future trials on performance in the current trial, providing a measure of the baseline variability of the data. The error bar indicates the mean standard error.

the different-color trials, for each step in the past (or future). Clearly, for all subjects, priming from the previous trial exerted the greatest effect, and priming decayed as the number of intervening trials increased. We calculated 95% confidence intervals for each point in the priming decay functions in order to determine the number of consecutive trials in the past exerting significant priming effects. We found some interesting inter-

subject differences: although subject VM had the lowest error rate, she showed significant priming of both latencies and error rates from trials as far back as four trials in the past. On the other hand, subject SS had a high overall error rate, and showed a robust priming effect on error rates from trials as far back as five trials in the past. However, he showed significant latency priming across only two trials in the past. Finally, subject RM

showed a moderate error rate, and had a significant priming effect for both latencies and error rates from trials as far back as five trials in the past. Thus, when both latencies and error rates are considered, it is evident that priming persists over approximately five subsequent trials. This is within the range found by Maljkovic and Nakayama for their shape discrimination task.

However, to remove any lingering doubts about the duration of the priming, we decided to intensively train a single subject (RM) on the saccade task until his error rate fell to approximately 10%. This error rate is comparable to that of the subjects in Maljkovic and Nakayama's study, and would presumably allow most of the priming effect to become evident in the latency of the saccades. The task remained the same as before, but the subject made a concerted effort to keep errors at a minimum. RM performed four blocks of 80 trials each day for 3 days, until his error rates were below 10%. At this point, data from nine blocks (over 3 days) were collected and analyzed.

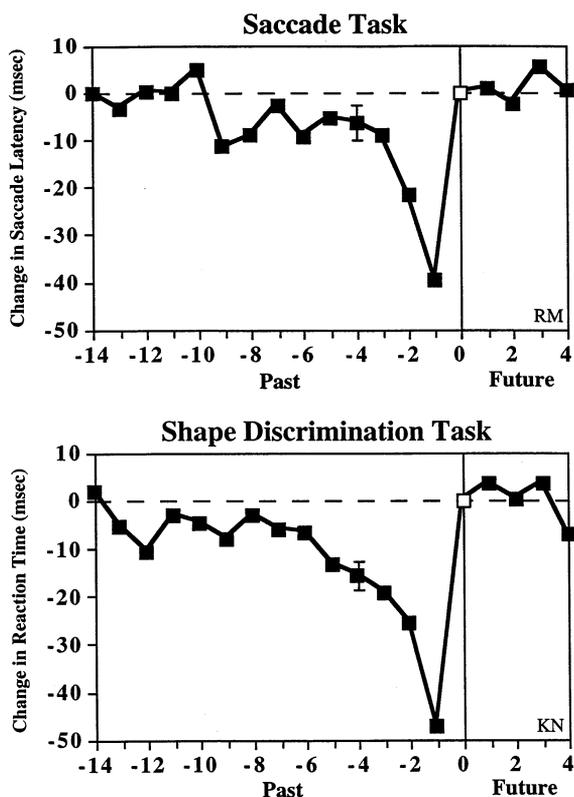


Fig. 5. The upper panel shows the results of a memory kernel analysis of saccade latencies in a task in which the subject (RM) made an additional effort to keep the number of errors low. As a result, the saccade latencies show a greater priming effect, presumably because the effect is no longer split between latencies and error rate, as in Fig. 4. For comparison, in the lower panel, we have reproduced a figure from Maljkovic and Nakayama (1994), showing the priming function for their shape discrimination task.

In Fig. 5 (upper panel), the amount of priming in this task is plotted for up to 14 trials in the past and four trials in the future. As before, we defined the amount of priming as the difference in latency between the same-color trials and the different-color trials, for each step in the past (or future). Overall, the magnitude of the priming effect on saccade latencies was larger than that seen in the previous data for this subject. This was to be expected, because in the previous experiment the priming effect was presumably split between the latencies and error rates, while in this experiment almost the entire effect is reflected in the latencies. As before, the priming from a single trial gradually decays across subsequent trials; overall, the priming lasts approximately five to seven trials. This is in accord with the duration observed by Maljkovic and Nakayama (1994) in their shape discrimination task. For comparison, a sample of their results (from a different subject) is shown in Fig. 5 (lower panel).

### 3.3. Discussion of Experiment 2

In this experiment, we again find a remarkable similarity between the pattern of performance in a saccade task and in an attentionally-demanding shape discrimination task. Previously, Maljkovic and Nakayama (1994) demonstrated that shifts of focal attention are facilitated by a repetition of the color of the target. If saccades require focal attention, we would expect the priming of focal attention to similarly affect saccade latencies. The present experiment confirms this prediction: when the target color repeats, presumably priming focal attention, saccade latencies show a concomitant decrease. Indeed, there is a close congruence between the priming functions for focal attention and for saccades (Fig. 5), supporting the view that saccades require a shift of focal attention to the target. This linkage is reinforced by the error rate findings: when the color of the distractors on the current trial is the same as the color of the target on previous trials, presumably resulting in the priming of attention toward the distractors, subjects tend to make saccades toward a distractor, rather than to the target. This finding raises the possibility that even in tasks in which eye movements are not required (such as in Maljkovic and Nakayama's task), the longer response times observed when the distractor color is primed may result in part from focal attention being erroneously drawn to the distractors.

The priming of saccades shown here differs from, and is complementary to, previous work by Kowler, Martins and Pavel (1984). They found that the latency of saccades to repeated target locations is shortened, and that this priming accumulates over several trials in the past. In our study, we found priming for saccades to a repeated target color, regardless of the position of the target on previous trials.

### 3.4. On the functional role of priming for saccades

In a series of experiments, Maljkovic and Nakayama revealed several notable characteristics of the priming of focal attention. First, they found that the priming is not limited to color. It is also seen for shape, when shape features are used to draw attention to the target (Maljkovic & Nakayama, 1994). Second, they showed that the priming of pop-out is similar to other types of priming in that it occurs automatically and without subjects' awareness (Maljkovic & Nakayama, 1994, 1996), but differs significantly from conventional priming (Schacter et al., 1993) in that it persists only for short durations (Maljkovic & Nakayama, 1993). Here, we have presented data indicating that the priming of focal attention facilitates saccades.

In speculating on the functional significance of this priming, it is instructive to consider that humans normally make approximately two hundred thousand saccades every day, and that the quality and immediacy of our visual perception of the world depends in part on our ability to make these gaze shifts quickly and accurately. In light of this, it would not be surprising if there were a dedicated memory system which uses stored information to assist the saccadic system. We propose that the priming of focal attention and saccades may represent the workings of just such a system. By priming the distinguishing color or shape features of saccade targets, this memory system would make it easier to re-visit previously-viewed objects. Since intrinsic object features, such as color or shape, are likely to remain invariant across time, this priming could help the saccadic system to efficiently access objects of interest even in the face of self-motion or object motion.

Given the sheer number of saccades that we typically make in a day, the automatic, unconscious nature of the priming of focal attention, make it well-suited to the task of assisting the saccadic system not only for reasons of speed, but also because these properties would allow priming to function without imposing an additional cognitive load for every saccade. Furthermore, the short persistence of the priming would work to ensure that the memory representations are being constantly tuned to the changing conditions of the environment and to the task currently being performed.

The trade-off is that this memory system lacks some flexibility. For example, in Experiment 2, in which the target color is randomly varied from trial to trial, the automatic build-up of priming often causes subjects to make errors. The real world is not random, however, and we suggest that in many situations, automatic priming of the distinguishing features of previously-viewed objects would be advantageous. Without intruding on our awareness, this simple memory mechanism could provide the saccadic system with valuable temporary representations which are automatically and appropriately updated.

It seems likely that there may be other forms of memory which also facilitate saccades. Interestingly, Chun and Jiang (1998) have recently described an implicit memory system which uses information about the spatial configuration of targets and distractors in a display (i.e. the visual context) to facilitate shifts of attention. Since we have shown here that manipulations of focal attention affect saccades, it is likely that this unconscious memory for the spatial layout of scenes would also affect saccades, and may, in fact, work alongside the feature-based memory system we have described here.

## 4. Conclusion

Previous work using dual-task paradigms indicated that attention is required for the execution of saccades (Hoffman & Subramanian, 1995; Kowler et al 1995; Deubel & Schneider, 1996). In the present study, we not only confirmed the generality of these results using an independent experimental paradigm, but also addressed the question of the spatial pattern of attention (focal vs. distributed) required for saccades. Specifically, by drawing comparisons between our results with saccades in visual search tasks and previous work on attention and visual search, we have uncovered a broad and varied set of correlations indicating that saccades require focal attention at the saccade target:

(1) The latency of saccades to an odd-colored target decreases with increasing numbers of distractors when the color of the target and distractors can change from trial to trial, but not when the target and distractor colors remain constant. This pattern differs from the flat search slopes found in detection tasks, which can be performed with distributed attention. However, it fits the predictions made by models of attention-focusing processes, and is very similar to the pattern of reaction times found by Bravo and Nakayama (1992) in a task requiring focal attention. These findings support the idea that a spatial focusing of attention is necessary to produce accurate saccadic eye movements.

(2) We have shown that the 'priming of pop-out,' which speeds the deployment of focal attention to a target (Maljkovic & Nakayama, 1994), also shortens saccade latency and improves accuracy. This provides further evidence of a functional link between focal attention and saccades.

Thus, our findings both add weight to a growing body of evidence indicating an obligatory link between attention and saccades, and more specifically, indicate that focal attention, rather than distributed attention, is necessary for the execution of an accurate saccade. Finally, these experiments also suggest a use for the automatic priming of target features, such as color. It has been shown that even simple tasks elicit numerous

saccades which often repeatedly visit the same objects (Ballard et al., 1992). Given this fact, we would expect the priming of relevant target features to allow this type of eye movement behavior to proceed much more rapidly and efficiently than would otherwise be possible.

## Acknowledgements

Thanks to Alex Skavenski for his contributions to this project. This work was supported by AFOSR Grant F49620-92-J-0016 to K. Nakayama and by an NDSEG graduate fellowship to R.M. McPeck.

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