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Inhibiting Reflexive Saccades to Peripheral Targets:
Effects of Fixation Offset on the Gap Effect

by

Gregory Craig, B.A., M.A.

A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfilment of
the requirements for the degree of
Doctor of Philosophy

Department of Psychology

Carleton University
Ottawa, Ontario
September, 1997

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acceptance of the thesis

**Inhibiting Reflexive Saccades to Peripheral Targets: Effects of
Fixation Offset on the Gap Effect**

Submitted by

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in Partial Fulfilment of the requirements for
the degree of Doctor of Philosophy

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September 1997

Abstract

Four experiments were conducted to examine whether the "gap effect" depends on the presence of reflexive eye movements. The "gap effect" refers to the decrease in saccadic latencies associated with removing a fixation stimulus before the onset of a peripheral saccadic target. The first experiment examined saccadic latencies under conditions where the subject could execute a reflexive saccade to the target stimulus. The remaining experiments attempted to prevent reflexive saccades to the target stimulus by requiring saccades in the direction opposite to the location of a peripheral stimulus or by requiring a saccadic response to a specific target stimulus presented randomly among distractor stimuli. In all experiments, saccadic latencies were shorter when a central fixation stimulus was extinguished prior to target onset than when it was extinguished after target onset. This replicates the classic "gap effect" in conditions where reflexive saccades were permitted and in conditions where reflexive saccades were not permitted. It is concluded that the "gap effect" depends on the offset of fixation prior to the initiation of a saccadic eye movement. Several explanations of the "gap effect" are discussed including ocular disengagement, attentional disengagement, warning and Fischer and Weber's (1992) neural model of saccadic eye movements.

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TABLE OF CONTENTS

	Page
Abstract	ii
Acknowledgements.....	iii
List of Figures	vi
List of Appendices	vii
INTRODUCTION	1
A Model of the Saccadic Controlling System	2
Neurological Evidence for the Three-Loop Model	4
Psychophysical/Behavioral Evidence for the Three-Loop Model	6
Express Saccades as Anticipatory Responses	12
Reflexive and Voluntary Saccades in the Gap Effect	17
Reflexive Saccades and the Gap Effect	20
Disengagement From Fixation	24
Methodological Considerations	29
EXPERIMENT 1: Unilateral Detection	32
METHOD	32
Subjects.....	33
Apparatus and Stimuli	33
Procedure.....	34
RESULTS AND DISCUSSION	36
EXPERIMENT 2: Anti-saccades	38

METHOD	39
Stimuli and Procedure	39
RESULTS AND DISCUSSION	39
EXPERIMENT 3: Unilateral Search	44
METHOD	45
Apparatus and Stimuli	45
Procedure	46
RESULTS AND DISCUSSION	46
EXPERIMENT 4: Bilateral Search	50
METHOD	51
Apparatus and Stimuli	51
Procedure	51
RESULTS AND DISCUSSION	52
GENERAL DISCUSSION	54
Reflexive Saccades and the Gap Effect	55
Attentional Disengagement and the Gap Effect	61
Alternative Explanations for the Gap Effect	62
Facilitated Target Detection	62
Effects of Warning	63
Alternative Explanations: Summary	64
Ocular Disengagement Hypothesis	65
GENERAL CONCLUSIONS	66
REFERENCES	68

LIST OF FIGURES

Figure 1	Three-loop Model of Saccadic Control (Adapted from Weber et al., 1992).....	3
Figure 2	Timing of Warning Tone, Fixation Offset and Target Onset in the Gap Paradigm.....	8
Figure 3	Sample Displays used in Experiments 1-4.....	23
Figure 4	Saccadic Latencies and Errors Across Inter-Stimulus Intervals for Experiment 1 (Unilateral Detection).....	37
Figure 5	Saccadic Latencies and Errors Across Inter-Stimulus Intervals for Experiment 2 (Anti-Saccades).....	40
Figure 6	Saccadic Latencies and Errors Across Inter-Stimulus Intervals for Experiment 3 (Unilateral Search).....	47
Figure 7	Saccadic Latencies and Errors Across Inter-Stimulus Intervals for Experiment 4 (Bilateral Search).....	53

LIST OF APPENDICES

Appendix A , Footnotes	72
Appendix B , Reaction Times to Search Stimuli: Pilot Research.....	73
Appendix C , Summary of the Overall Analysis of Variance of Mean Saccadic Latencies and Error Rates for Experiment 1 (Unilateral Detection).....	77
Appendix D , Summary of the Overall Analysis of Variance of Mean Saccadic Latencies and Error Rates for Experiment 2 (Anti-saccades).....	78
Appendix E , Summary of the Overall Analysis of Variance of Mean Saccadic Latencies and Error Rates for Experiment 3 (Unilateral Search).....	79
Appendix F , Summary of the Overall Analysis of Variance of Mean Saccadic Latencies and Error Rates for Experiment 4 (Bilateral Search).....	80
Appendix G , Summary of the One-Way Analyses of Variance of Mean Saccadic Latencies for Serial and Parallel Search Tasks for Experiment 4 (Bilateral Search).....	81

INTRODUCTION

The human eye is constantly in motion. Movements of the eye can be classified into several different categories including saccades, pursuit tracking, vergence, nystagmus, and cyclotorsion. This thesis will focus on saccadic eye movements, which are ballistic, fast movements that carry the eye from one position to another, permitting the visual system to sample the scene with the fovea.

Specifically, this thesis examined the control of saccadic eye movements using a technique called the gap paradigm. The research will focus on differences in saccadic latencies to a target, brought about by the presence or absence of a fixation stimulus during the programming and initiation of the saccade. The difference in saccadic latencies generated by the presence or absence of a fixation stimulus is known as the *gap effect* (Kingstone & Klein, 1993b; Reuter-Lorenz, Hughes, & Fendrich, 1991; Ross & Ross, 1980; Tam & Ono, 1994; Tam & Stelmach, 1993). Two hypotheses concerning the generation of the gap effect are examined in detail. The primary hypothesis being examined is that the gap effect can be generated without the presence of automatic or *reflexive* saccades. The secondary hypothesis concerns the possible role of attention in the generation of the gap effect. The following sections provide a rudimentary background on the neurological control of saccades and examine the relevant behavioral/psychophysical research on saccadic eye movements and the gap effect. More generally, the goal of the current research was to discover whether reflexive

and voluntary saccades shared a common control system.

A Model of the Saccadic Controlling System

One model of the neural system controlling the generation of saccades is shown in Figure 1 (adapted from Weber, Aiple, Fischer, & Latanov, 1992). The symbols in the model refer to the superior colliculus (SC), the striate visual cortex (V1), the prestriate cortex (Pre), the parietal cortex (Par), the frontal eye fields (FEF) and the efferent eye movement structures in the brain stem (EM). According to this model, the superior colliculus, the frontal eye fields, the prestriate cortex and the parietal cortex play important roles in saccadic eye movements.

The model consists of three loops. The first loop, indicated in single lines, involves the eyes, the striate visual cortex (V1), the superior colliculus and the brainstem eye movement centers. The second loop (double lines in fig. 1) involves the eyes, V1, the prestriate cortex, and the frontal eye fields. The third loop (triple lines in fig. 1) involves the eyes, V1, the prestriate cortex and the parietal cortex.

This model is supported by a range of behavioral/psychophysical and neurological research (Fischer & Ramsperger, 1986; Fischer & Weber, 1992; Fischer & Weber, 1993; Guitton, Buchtel, & Douglas, 1985; Kingstone & Klein, 1993a; Kingstone & Klein, 1993b; Munoz & Wurtz, 1992; Munoz & Wurtz,

Figure 1

Figure 1. Schematic drawing of the Weber et al. (1992) three-loop model of the anatomical structures involved in generating reflexive and non-reflexive saccades. Single lines indicate the reflexive saccade loop, involving V1, the superior colliculus (SC), the efferent eye movement structures (EM) and the eye. The non-reflexive loop responsible for fast, regular saccades is indicated by the double lines, whereas the loop responsible for slow, regular saccades is indicated by the triple lines. The structures involved in the generation of regular saccades include the prestriate cortex (Pre), the parietal cortex (Par) and the frontal eye fields (FEF). Figure adapted from Weber et al. (1992).

1993; Reuter-Lorenz et al., 1991; Schiller, Sandell, & Maunsell, 1987; Weber et al., 1992).

Neurological Evidence for the Three-Loop Model

Neurological studies indicate that ablation of the superior colliculus in monkeys results in the elimination of reflexive saccades (Munoz & Wurtz, 1992). The term *reflexive saccades* refers to involuntary, short-latency saccades occurring in response to sudden and substantial changes in the peripheral visual environment, such as the sudden appearance of a stimulus (Fischer & Ramsperger, 1984; Fischer & Ramsperger, 1986; Kingstone & Klein, 1993b; Klein, Kingstone & Pontefract, 1992; Posner, 1980). Elimination of the superior colliculus means that the monkey is no longer able to execute reflexive saccades to a target appearing in the visual field. Yet, voluntary saccadic eye movements are not eliminated by ablation of the superior colliculus (Schiller, Sandell, & Maunsell, 1987). Several researchers have regarded this as evidence that the superior colliculus is vital to the generation of reflexive saccades (Fischer & Ramsperger, 1986; Fischer & Weber, 1993; Kingstone & Klein, 1993b; Reuter-Lorenz et al., 1991) which is represented by the first loop of the three-loop model. When the first loop is destroyed by ablation of the superior colliculus, voluntary saccades are still possible.

In terms of the loops in the model that are responsible for voluntary saccades, most of the neurological work has involved the second loop and the

contribution of the frontal eye fields to the generation of saccades. *Voluntary* or controlled saccades are planned eye movements based on examination of the visual environment and/or task requirements (Forman, Cohen & Johnson, 1993; Klein et al., 1992). It has been found that ablation of the frontal eye fields does not eliminate reflexive saccades. However, monkeys with frontal eye field lesions seem not to have any voluntary control over saccades. That is, the monkey will execute reflexive saccades to any stimulus in the visual field, regardless of training to do otherwise (Schiller et al., 1987). Studies of humans with similar lesions in the frontal lobe (including the frontal eye field, but not the superior colliculus) have shown that participants cannot inhibit execution of reflexive saccades (Guitton, Buchtel, & Douglas, 1985). These results lend support to the three-loop model because they suggest that reflexive saccades are controlled by a separate loop. As expected, ablation of the superior colliculus *and* the frontal eye fields virtually eliminates saccadic eye movements (Schiller, True, & Conway, 1980).

Overall, these results lend support for two loops of the three-loop model that Weber et al. (1992) proposed. Specifically, evidence indicates that reflexive saccades are primarily controlled by the superior colliculus, since removal of the superior colliculus eliminated reflexive saccades. Voluntary saccades are considered to be at least partially controlled by the frontal eye fields, since removal of the frontal eye fields results in increased numbers of reflexive saccades to stimuli and in the apparent loss of control over voluntary saccades. Thus,

evidence obtained from studies of monkeys and humans suggests that there is a neurophysiological basis for two loops of the three-loop model. The important distinction in this work has been between a system that generates reflexive saccades (loop 1) and a system that generates voluntary, non-reflexive saccades (second and third loops). Neurological investigation of the third loop is somewhat difficult because ablation of the structures involved (parietal cortex) can potentially affect many more structures than just the saccadic eye movement system. In the present work, no distinction will be made between the secondary and tertiary loops of the three-loop model.

Psychophysical/Behavioral Evidence for the Three-Loop Model

Weber et al. (1992) and others (Fischer & Weber, 1992; Fischer & Weber, 1993; Kingstone & Klein, 1993a; Kingstone & Klein, 1993b; Reuter-Lorenz et al., 1991) have proposed that the time to generate a saccade depends on the neural structures involved. For example, Weber et al. (1992) proposed that all short latency (100-150 ms) saccades to a visual stimulus occurred via the loop indicated in single lines in Figure 1. In this loop, the stimulus is detected by the eye, the retinal location is registered in V1 and the activity in the saccade cells in the superior colliculus increases as the saccade is generated. This system is generally implicated in the generation of reflexive (Kingstone & Klein, 1993b; Reuter-Lorenz et al., 1991) or express saccades¹ (Fischer, 1987; Fischer & Ramsperger, 1984; Fischer & Ramsperger, 1986) and fast, regular saccades (Weber et al.,

1992) to visual stimuli and will be referred to as the *reflexive saccade loop*.

However, this reflexive saccade loop is only available when the participant is *not actively maintaining fixation*. When the participant is fixating a stimulus, the saccade cells in the superior colliculus are inhibited so that the reflexive saccade loop is unavailable (Fischer & Weber, 1993; Munoz & Wurtz, 1992; Weber et al., 1992). In order for a saccade to be generated, the frontal eye fields (and/or the parietal cortex via the frontal eye fields) must disinhibit the superior colliculus. Weber et al. (1992) has argued that the loop involving the prestriate cortex, frontal eye fields and the brainstem eye movement structures (indicated by double lines in Fig. 1) and/or the loop involving the prestriate cortex, parietal cortex, frontal eye fields, and the brainstem eye movement structures (triple lines) are responsible for slow, regular saccades (200 ms). The primary difference between the different loops (routes) for reflexive or slow regular saccades is in the number of structures and the amount of processing involved in generating the saccade.

A powerful technique for studying control and generation of saccades is the gap paradigm, developed by Saslow (1967). In this paradigm, participants are required to fixate a central stimulus and make a saccade to a target stimulus that appears in the periphery. In the *gap condition* (see Fig. 2a), the fixation stimulus is removed prior to the onset of the saccadic target. In the control condition, known as the *overlap condition* (see Fig. 2b), the fixation stimulus is not removed

Figure 2

Figure 2. a) In the gap condition, the offset of fixation precedes the target onset by 100 ms (100 ms ISI), while b) in the overlap condition, fixation offset follows target onset by about 100 ms (-100 ms ISI). In the current experiments, a 100 ms warning tone is always presented 400 ms after the beginning of the trial, the offset of the tone occurring 500 ms before the onset of the target.

until after the onset of the saccadic target. Typically, the time required to initiate a saccade (saccadic reaction time, or SRT) to the peripheral saccadic target is greater in the overlap condition (200-250 ms) than in the gap condition (100-150 ms). This reduction in latency caused by removing the fixation stimulus prior to the onset of the saccadic target is known as the *gap effect* (Kingstone & Klein, 1993b; Reuter-Lorenz et al., 1991; Ross & Ross, 1980; Tam & Ono, 1994; Tam & Stelmach, 1993).

In terms of the three-loop model several researchers have argued that the stimulus configuration in the gap condition (fixation offset precedes target onset) allows the reflexive saccade loop to be active (Fischer & Ramsperger, 1986; Fischer & Weber, 1993; Reuter-Lorenz et al., 1991). Specifically, since no fixation stimulus is present, the reflexive saccade loop can be used and participants can immediately execute a reflexive saccade to the target stimulus. Some researchers have claimed that the occurrence of short-latency, reflexive saccades in the gap condition causes the difference in latencies between gap and overlap conditions that gives rise to gap effect (Fendrich et al., 1991; Reuter-Lorenz et al., 1991; Reuter-Lorenz, Oonk, Barnes, & Hughes, 1995).

In the overlap condition, the fixation stimulus remains present until after the target is presented. Due to the presence of the fixation stimulus, the superior colliculus, and hence the reflexive saccade loop, remains inhibited. In terms of the three-loop model, non-reflexive saccades have a longer latency because the

secondary (or tertiary) loop must disinhibit the superior colliculus before a saccade to the target stimulus can occur. Since the secondary loop is longer and involves more structures and in some instances, extended processing (Schiller et al., 1987), the additional processing overhead results in longer saccadic reaction times in the overlap condition relative to the gap condition (Reuter-Lorenz et al., 1991).

Research on reflexive eye movements has centered on the occurrence of reflexive saccades and whether reflexive saccade latencies form a separate distribution (or mode) of saccadic latencies known as *express saccades* (Fischer & Boch, 1983). Fischer and Boch (1983) noted that in monkeys, there occurred a separate distribution of saccades with extremely short latencies (70 ms) in the gap condition.

Fischer and Ramsperger (1984, 1986) were the first to examine the possibility that express saccades occurred in human observers. Previous research in monkeys (Fischer & Boch, 1983) had indicated that express saccades were most likely to occur when the fixation offset preceded target onset by 200 ms (interstimulus interval or *ISI*). Thus, Fischer and Ramsperger examined saccadic latencies when the ISI was 200 ms versus when the ISI was 0 ms (simultaneous fixation offset- target onset). In the 0 ms ISI condition, only one distribution of saccadic latencies was revealed, centered around a SRT of 180 ms. However, in the 200 ms ISI condition, two distributions of saccadic reaction times were apparent. A bimodal distribution of saccadic latencies was found with the first

peak centered around SRT's of 100 ms, while the second peak was centered around 150 ms.

Fischer and Ramsperger (1984) argued that the first peak of the distribution of saccadic latencies represented a population of express saccades. They noted that the existence of an express saccade population might not have been discovered prior to their study since many studies might have discarded the short latency saccades assuming that they were anticipatory. Thus Fischer and Ramsperger (1984, 1986) argued that the express saccades were a separate population of reflexive saccades initiated by the onset of a peripheral target, in the absence of a central fixation stimulus.

Several researchers (Fischer & Ramsperger, 1984, 1986; Fischer & Weber, 1992, 1993; Weber, Biscaldi, & Fischer, 1995) have found similar distributions of short latency saccades in humans and have argued that these short latency, express saccades contribute to the gap effect. While others agree that short-latency, reflexive saccades may contribute to the gap effect (Fendrich et al., 1991; Juttner & Wolf, 1992; Kingstone & Klein, 1993b; Tam & Stelmach, 1993; Weban-Smith & Findlay, 1991) or even cause the gap effect (Reuter-Lorenz et al., 1991; Reuter-Lorenz et al., 1995), not all researchers have been successful in finding a separate population of express saccades.

Fischer and colleagues (1987; Fischer & Ramsperger, 1986; Fischer & Weber, 1992, 1993; Weber et al., 1992) have proposed that express saccades

result from removal of the fixation stimulus. When the fixation stimulus is removed before target onset, the participant can immediately execute a saccade to the target. In contrast, when the fixation marker is present, the participant has to terminate the oculomotor processes that maintain fixation before a saccade can be executed. Fischer and Weber (1993; Weber et al., 1995) have implicated the superior colliculus in the execution of express saccades. They note that express saccades are not found when the superior colliculus is ablated in monkeys. Converging evidence of this finding came from Munoz and Wurtz (1992, 1993) who observed that the superior colliculus has been found to contain groups of cells activated during fixation while other cells are active during the preparation of a saccade. Munoz and Wurtz (1993) found that activation of the fixation cells inhibited the "saccade" cells in the superior colliculus. When the fixation stimulus was removed, activity in the superior colliculus "fixation" cells decayed while activity in the "saccade" cells increased. In terms of the three-loop model, Fischer and Weber (1993; Weber et al., 1992; Weber et al., 1995) argued that the disinhibition of the saccade cells in the superior colliculus in the gap condition allowed the participant to make express saccades to the target, which contributed to the lower SRT's in the gap condition.

Express Saccades as Anticipatory Responses

Several researchers have argued that express saccades are the result of participants anticipating when and where the target would appear (Jüttner & Wolf,

1992; Kingstone & Klein, 1993b). Saslow (1967) noted that the offset of fixation might be used as a warning of the impending target onset in the gap condition, such that saccades could be initiated in anticipation of the target onset. Fischer and Ramsperger (1984) noted that when participants could not anticipate where the target would appear (left or right of fixation), the number of express saccades was reduced. In a follow-up study Fischer and Ramsperger (1986) found that participants executed a saccade (in the absence of a target) as soon as the fixation stimulus was removed. They argued that if participants were using the fixation offset to anticipate target onset, saccadic latencies to fixation offset should be similar to latencies found for express saccades. Instead these researchers observed that saccadic latencies in response to fixation offset were 30 ms faster than those found for express saccades.

Kalesnykas and Hallett (1987) replicated the results of Fischer and Ramsperger (1984, 1986) and provided a means of identifying anticipatory versus express saccades. They argued that if participants were anticipating target onset, there should be a greater number of directional errors for anticipatory saccades than for visually-guided (reflexive) saccades. Kalesnykas and Hallett found the greatest number of directional errors were associated with saccades of 70-100 ms. They maintained that the minimum latency for a visually-guided saccade would be between 100-120 ms (depending on the error rate).

Weban-Smith and Findlay (1991) studied this problem by randomly varying

the time of target onset and its spatial location (right or left). in order to prevent anticipatory responses. Although a reliable gap effect was observed and latencies similar to those of express saccades were produced, no distribution of express saccades was found. Weban-Smith and Findlay argued that express saccades did not represent a separate system of eye-movements. Rather, express saccades represented the minimum time required to generate a saccade under favourable conditions (i.e., gap condition and an optimal state of readiness) (Weban-Smith & Findlay, 1991).

Juttner and Wolf (1992) maintained that the occurrence of express saccades depended on the anticipation of the target onset. In their experiment, catch trials (i.e., where a target stimulus did not appear) were presented in addition to regular trials. Participants were required to maintain fixation on catch trials. Juttner and Wolf found that evidence for express saccades decreased as the proportion of catch trials increased. They asserted that increasing the percentage of catch trials decreased the participant's ability to predict when the target would occur. That is, if express saccades were stimulus based (in response to the onset of a saccadic target), the ability to anticipate the onset of a target should not affect the generation of express saccades and participants should be able to generate express saccades on any trial where a target appeared. Juttner and Wolf (1992) argued that the decrease in the percentage of express saccades as the number of catch trials increased indicated that participants were generating "express" saccades when

they could predict the target onset and regular saccades when they could not anticipate target onset.

Kingstone and Klein (1993b) also argued that the ability to generate express saccades depended on the participant's ability to anticipate target onset. They noted that most of Fischer and colleagues' (1987; Fischer & Ramsperger, 1984, 1986; Fischer & Weber, 1992, 1993) attempts to find express saccades only examined the gap condition and only used a single target position within a block of trials. They proposed that these conditions would facilitate anticipation of the target onset which would allow the participant to prepare, in advance, a saccade timed to occur shortly after target onset. In order to make it more difficult for participants to anticipate target onset, Kingstone and Klein tested the following conditions: (a) target position was fixed and catch trials were used, (b) target position was randomized and no catch trials were used, and (c) target position was randomized and catch trials were used. In addition, a baseline condition was run where target position was fixed and no catch trials were presented to attempt to generate a population of express saccades. No evidence of express saccades was found in any condition. There was evidence of saccades with latencies similar to that of express saccades, but no evidence of a separate population of express saccades. Kingstone and Klein (1993b) proposed that the short latency saccades generated under conditions of random target position and catch trials were stimulus controlled, since it would be difficult for participants to anticipate target onset in

these conditions. However, they argued that, without the randomization and catch trials, that short- latency, stimulus controlled saccades could not be differentiated from anticipatory saccades.

In summary, Fischer and others (1987; Fischer & Ramsperger, 1984, 1986; Fischer & Weber, 1992, 1993; Weber et al., 1995) had little difficulty in finding populations of express saccades. Weber et al. (1995) noted a reduction (but not elimination) in the number of express saccades when test conditions such as target position, duration of fixation foreperiod, and the number of ISI's were independently randomized. Other researchers, however, were unable to find a separate population of express saccades even under conditions that should elicit maximum number of express saccades (Fendrich, et al., 1991; Juttner & Wolf, 1992; Kingstone & Klein, 1993b; Weban-Smith & Findlay, 1991). Indeed, many researchers have claimed that express saccades cannot be reliably differentiated from any other type of reflexive or non-reflexive saccade (Kingstone & Klein, 1993b; Kowler, 1990; Weban-Smith & Findlay, 1991). This is not to say that reflexive saccades, or saccades with latencies similar to those for express saccades, do not occur at all. As Kingstone and Klein (1993b) note, participants can produce short latency or reflexive saccades in response to the onset of a saccadic target, under conditions where anticipatory saccadic responses are improbable. The problem with express saccades as defined by Fischer (1987; Fischer & Boch, 1983; Fischer & Ramsperger, 1984, 1986) is in finding the separate population of

express or reflexive saccades.

Reflexive and Voluntary Saccades in the Gap Effect

Neurophysiological and psychophysical research provide compelling evidence that reflexive, short latency saccades (involving the reflexive (first) loop of the model in Figure 1) play an important role in producing the gap effect originally observed by Saslow (1967). That is, extinguishing the fixation point prior to target onset disinhibits the superior colliculus and enables the reflexive saccade loop. While the existence of express saccades as a distinct population can sometimes be observed under certain conditions, this finding is not reliable. The important point arising from this work is that fast latency saccades (90-120 ms) are needed for the gap effect. This argument has been advanced most effectively by Reuter-Lorenz et al. (1991, 1995), who claimed that the gap effect was observed only in conditions where reflexive saccades were possible.

Reuter-Lorenz et al. (1991) had participants perform either a reflexive or a controlled eye-movement task in conjunction with the gap paradigm. In the reflexive saccade task, the participant was required to make an eye movement to the target stimulus as soon as it appeared, known as the pro-saccade task. In the controlled saccade task, the participant was required to make a saccade to the location *opposite* to where the target appeared, known as the anti-saccade task (Hallett & Adams, 1980). In both conditions, the fixation stimulus could be removed before target onset (gap) or after target onset (overlap). Reuter-Lorenz

et al. argued that in order for participants to perform the anti-saccade task, they would have to *inhibit* reflexive saccades to the target location in order to generate a saccade to a position opposite to the location of the target. According to this argument, no gap effect should occur in the anti-saccade condition because the generation of saccades is under voluntary control. Accordingly, Reuter-Lorenz et al. found no evidence of a gap effect in the anti-saccade task where voluntary saccades were required and reflexive saccades were inhibited. Evidence of a gap effect was found only in the pro-saccade task where reflexive saccades were possible. Reuter-Lorenz et al. took this as support for their argument that the gap effect results from execution of reflexive saccades which is made possible by the removal of the fixation stimulus in the gap condition.

The argument set forth in the present thesis is that the view advanced by Reuter-Lorenz et al. (1991) is too restrictive and limiting. Their explanation of the gap effect is valid only in situations where a reflexive saccade is possible; that is, when a single target is presented for the saccade, providing an unambiguous neural representation of the saccade target in the visual field map of the superior colliculus. One implication of Reuter-Lorenz et al.'s position is that the gap effect should not be present when reflexive saccades are prevented.

Reuter-Lorenz et al. (1991) emphasized the necessity of a reflexive trigger for the gap effect to be observed. In the current thesis, a more general view is advocated wherein the critical factor for the presence of a gap effect is not the

reflexive trigger but instead is the disinhibition of the superior colliculus (Fisher & Weber, 1992). This is a more general position because it admits the possibility that the gap effect will occur in a variety of stimulus conditions, provided that the necessary conditions for disinhibition are met. Specifically, a gap effect should be observed whenever the fixation stimulus is removed near the point in time that a saccade is being programmed, because fixation removal causes disinhibition (Munoz & Wurtz, 1992, 1993). In this view, inhibition of the superior colliculus should prevent or delay *all* saccade types, reflexive and voluntary. That is, both voluntary and reflexive saccades will be inhibited when a fixation stimulus is present at the time of the saccade.

It is noteworthy that the original Reuter-Lorenz et al. (1991) results have been questioned by Fisher and Weber (1992). Fischer and Weber (1992) *did* find evidence of a gap effect in the anti-saccade task. Their paradigm was similar to the one used by Reuter-Lorenz et al. (1991), in which the participant was required to make pro- or anti- saccades within a given block of trials. Their goal was to determine whether or not express saccades would be found in the anti-saccade task, where the onset of the stimulus could only serve as a cue to begin a saccade. They found that there were few, if any express saccades in the anti-saccade task, *but there was a 30-40 ms gap effect*. Thus, even though reflexive or express saccades did not occur, a gap effect was still found, contrary to the findings of Reuter-Lorenz et al. (1991; c.f., Reuter-Lorenz et al., 1995). Fischer and Weber

(1992) explained their results in terms of disinhibition of the superior colliculus that occurs on overlap but not on gap trials.

The results of Reuter-Lorenz et al. (1991) imply that fixation offset is not sufficient to release the oculomotor system from inhibition because saccadic latencies were the same in gap and overlap conditions. This implies that the saccade system was being tonically inhibited during the anti-saccade task. Possibly, the second or third loop of the three-loop model was tonically inhibiting the superior colliculus and the brainstem eye movement centers, thereby preventing unwanted reflexive saccades to the stimulus. Any disinhibition that might have been caused by the offset of the fixation point was counteracted by the tonic inhibition of the saccade system. In contrast, the results of Fischer and Weber (1992) imply that fixation offset is sufficient to release the oculomotor system (specifically, the superior colliculus) from inhibition.

The conflicting findings of Reuter-Lorenz et al. (1991) and Fischer and Weber (1992) with respect to the presence of a gap effect in the anti-saccade task have created some confusion regarding the inhibitory control of saccades and the contribution of voluntary and reflexive saccades to the gap effect. The goal of the current research was to clarify these issues using convergent methodology.

Reflexive Saccades and the Gap Effect

Does the gap effect depend on the execution of reflexive saccades, as Reuter-Lorenz et al. (1991) suggest? Or, is the gap effect merely enhanced by the

presence of reflexive saccades, as Fischer and Weber (1992) suggest? The anti-saccade experiments are important in that they represent some of the first attempts to examine the gap effect under conditions where reflexive saccades were not permitted in the gap condition. Most of the previous research on the gap effect used tasks where voluntary saccades occurred in the overlap condition and reflexive saccades occurred in the gap condition. As saccadic responses in the gap condition are largely reflexive, the traditional gap paradigm does not lend itself to the examination of the role of *voluntary saccades* in the gap condition. Thus, one could not determine whether the gap effect resulted from reflexive saccades alone (Reuter-Lorenz et al., 1991), or some combination of reflexive and voluntary saccades (Fischer & Weber, 1992).

Use of the anti-saccade task has led to different results for Reuter-Lorenz et al. (1991) and Fischer and Weber (1992), perhaps due to the requirement of executing a saccade in response to an empty visual field. In the anti-saccade task, participants, a) inhibit a saccade to a stimulus that appears on one side of fixation, and b) make a saccade to the opposite location. While the anti-saccade task does place saccades under voluntary control, it is somewhat unusual. A more naturalistic task would be to have the participant identify a specific stimulus and direct a saccade to that stimulus. In this task, saccades are under voluntary control because the participant has to inhibit a saccade until the stimulus has been identified. For example, if the stimuli consist of digits, the participant could be

instructed to make a saccade only if an even numbered digit is presented. If a "2" is presented, the participant executes a saccade to the "2". The voluntary nature of the task could be increased by presenting distractors (e.g. "5") with the target digit (see Figure 3b). If only 5's are presented, the participant maintains fixation.

The voluntary component of the task could be further increased by presenting more than one stimulus and having the participant execute a saccade to the correct stimulus. Reuter-Lorenz et al. (1991) suggested that reflexive saccades were most likely to occur when a single target is presented for the saccade and an unambiguous neural representation of the saccade target is available in the visual field map of the superior colliculus. Reflexive saccades should be prevented when stimuli are presented at multiple locations in the visual field because an unambiguous neural representation of the saccadic target would be unavailable (Schiller et al., 1987). In the current task, participants are required to search for and identify the target stimulus among one or more distractors. For example, if a "2" is presented on the left side of fixation and a "5" is presented on the right side of fixation, the participant would make a saccade to the "2" (see Figure 3d). This should prevent participants from executing a reflexive saccade to the target when it appeared. These conditions provide a way of evaluating the inhibitory control of saccades and the contribution of reflexive and voluntary saccades to the gap effect. If a gap effect is absent under these conditions, it would support Reuter-Lorenz et al.'s (1991) argument that the gap effect depends

Figure 3

Figure 3. Sample displays used in Experiments 1-4. In Experiments 1-3, all stimulus displays were unilateral (a & b), while in Experiment 4, all stimulus displays were bilateral (c & d). In Experiment 1 the subject was instructed to make a saccade to any stimulus that appeared. In Experiment 2, the subject was instructed to make a saccade to the side of the display opposite to where the stimulus appeared (anti-saccade). In Experiment 3, the subject only made a saccade to the stimulus array if the target digit was present. In Experiment 4, the task was the same, but distractors were presented on both sides of the display. Examples of overlap trials are presented in a) and d), while examples of gap trials are presented in b) and c).

on reflexive eye movements. Alternatively, evidence of a gap effect when reflexive saccades are inhibited would support Fischer and Weber's (1992) view that fixation offset, and not reflexive saccades, is the critical factor in the generation of the gap effect. More generally, the results would clarify the inhibitory role of the fixation point in generating saccades.

Disengagement From Fixation

A subsidiary goal of the current thesis was to examine the role of attention in the gap effect. Fischer and Ramsperger (1986) and Fischer (1987) have described two different mechanisms to explain the gap effect that were independent of the explanation for the occurrence of express saccades. Both mechanisms rest on the claim that the participant has to disengage from the fixation marker in the overlap condition. Initially, Fischer and Ramsperger (1986) claimed that the participant had to disengage the *ocular mechanisms* responsible for maintaining fixation (e.g., fixation cells in the superior colliculus, frontal eye fields) before executing a saccade. However, Fischer (1987) later claimed that the participant had to cease *attending* to the fixation marker before executing a saccade. Both of these explanations will be examined briefly in the following section.

As noted above, the attentional disengagement hypothesis proposed that attentional processing of fixation had to cease before an eye movement could be made (Braun & Breitmeyer, 1988; Fischer, 1987). When fixation is removed before target onset, attention becomes disengaged such that a saccade could occur

immediately. When the fixation stimulus remained present, attention had to be disengaged before the saccade could occur. The attentional disengagement hypothesis emphasized that it was the disengagement of attentional processing, not the ocular system per se, that resulted in reduced saccadic latencies in gap conditions.

Alternatively, the ocular disengagement hypothesis proposed that an ocular mechanism exists which disengages the eye from the fixation point before the eye moves to the target (Fischer & Ramsperger, 1986; Tam, 1989; Tam & Stelmach, 1993). According to Weber et al. (1992), the disengagement from fixation may involve the frontal eye fields (or the parietal cortex via the frontal eye fields) disinhibiting the "saccade cells" and inhibiting the "fixation cells" in the superior colliculus (Munoz & Wurtz, 1992; Munoz & Wurtz, 1993). In the gap condition the fixation stimulus is removed before the onset of the saccadic target, disinhibiting the saccade cells. Consequently, a saccade can be executed sooner in the gap condition than in the overlap condition. The ocular disengagement hypothesis holds that the reduction in saccadic reaction times is strictly the result of ocular processes.

Evidence suggesting an attentional disengagement mechanism emerged from paradigms where the focus of attention and the point of ocular fixation were dissociated. Braun and Breitmeyer (1988) had participants fixate centrally while attending to a peripheral stimulus. The attended stimulus was extinguished before

or after onset of a peripheral target. Saccadic reaction times were reduced when the offset of the attended stimulus preceded target onset (Braun & Breitmeyer, 1988). Such results suggest that attention, rather than ocular fixation, has to be disengaged to reduce saccadic latencies.

One problem with Braun and Breitmeyer's (1988) account is that only the attended stimulus was extinguished. They did not compare the results of removing the attended stimulus *and* the foveal stimulus. A second difficulty with their experiment is that they did not attempt to assess whether or not attention actually was directed to the peripheral stimulus.

In an attempt to rectify these difficulties, Tam and Stelmach (1993) varied whether a peripheral or a fixated stimulus was attended to and which of these stimuli were turned off. It was found that offset of the fixated stimulus reduced saccadic latencies, irrespective of the direction of attention. However, attention modulated this effect. Specifically, offset of the attended stimulus did have a slight facilitory effect on saccadic latencies. Tam and Stelmach concluded that an explanation emphasizing ocular disengagement provided the best account of the results.

A similar experiment was conducted by Kingstone and Klein (1993a) where they examined both endogenous and exogenous attentional allocation to peripheral stimuli, in conjunction with the gap paradigm. In the endogenous task (Exp. 1), Kingstone and Klein had participants fixate on a central stimulus (crosshair) while

attending to another crosshair stimuli above or below the central fixation marker. On half of the trials the participants were required to make a manual reaction time response to the attended or the unattended crosshair above/below the fixation crosshair (to confirm that attention was directed to these stimuli). On the remaining trials, the participants were required to make a saccade to a stimulus (dot) appearing to the left or right of the fixation stimulus. In the exogenous task, one of the three crosshairs (central, above or below) was brightened briefly to draw attention to the stimulus. On half of the trials, the participant was required to identify a change in one of the three markers from a crosshair to a "T". On the remaining trials, the dot appeared to the right or left of the centrally fixated crosshair and the participant was required to make a saccade to the peripheral dot.

Kingstone and Klein (1993a) confirmed that participants were attending to the appropriate locations in both the endogenous task and the exogenous task on the trials where manual reaction times were collected. In terms of saccadic reaction time, the largest gap effect (50 ms) was associated with the offset of the central fixation crosshair. In the endogenous attentional allocation task, the offset of the attended stimulus had no effect on saccadic latencies. However, in the exogenous attentional allocation task there was a modest effect (33 ms) of the offset of the attended crosshair in comparison to the saccadic reaction times for the overlap condition in which none of the crosshairs was extinguished. However, the offset of the *unattended* crosshair also produced a significant reduction in saccadic

latencies. Kingstone and Klein claimed that the offset of the peripheral stimulus (attended or unattended) provided a warning that the target was about to appear and that in the usual gap paradigm, the offset of the fixated stimulus would likewise provide an element of warning as to the onset of the saccadic target. The further reduction in saccadic latencies produced by the offset of the fixated stimulus were the result of ocular disengagement mechanisms. Kingstone and Klein therefore maintained that their results supported the ocular disengagement hypothesis.

The current research also examined the role of attention in the gap paradigm. The participant was required to *search for (and identify) the target before making a saccade*. Specifically, the task required the participant to make a saccade to a peripheral stimulus array (Fig. 3) only if the stimulus array contained a predesignated target. If the peripheral stimulus array did not contain a target, the participant maintained fixation. Identification tasks are generally regarded as attentionally demanding. If attention was initially engaged at fixation (c.f., Fischer, 1987), the participant would have to direct attention to the peripheral stimulus in order to identify whether or not the stimulus was a target. The participant would be required to disengage attention in order to identify the target in both the overlap and gap conditions. Thus, in terms of the attentional disengagement hypothesis, the overlap and gap conditions should functionally be identical, potentially eliminating the gap effect. Alternatively, if the gap effect

depended only on ocular disengagement from the fixation stimulus and not the allocation of attention, reduced saccadic latencies should be observed in gap conditions even when participants were required to identify the peripheral stimulus.

Methodological Considerations

The proposed research implemented a set of sophisticated methodological controls to address the issues of attentional allocation, warning and anticipatory saccades. Treisman (1982, 1988) argued that some stimuli can be differentiated (rather than identified) pre-attentively, if the stimuli can be differentiated based on a single, unique feature. For example, the target stimulus in Figure 3a and 3d, a vertical line, can be distinguished from the distractors on the basis of orientation alone and should not require attention (Treisman, 1982). If, in the experiment described above, the different peripheral targets could be distinguished pre-attentively, then attention might remain engaged on the fixation stimulus until the time of the saccade. In this case, a gap effect might still be expected as predicted by the attentional (and ocular) disengagement hypothesis.

In contrast, the feature conjunction search task is known to consistently require attentional processing (Treisman, 1982, 1988). When a target cannot be identified by a single unique feature which distinguishes the target from the distractors, the participant is required to examine each item in the display (serial search). Specifically, if the target and the distractors share one or more features, Treisman (1982, 1988) has argued that attention is required to combine the

elementary features of the stimulus to identify the stimulus. Thus, in the current experiments, participants performed a serial *search* of a stimulus array for a specific stimulus prior to the execution of a saccade (see Figure 3b and 3c). The target (the digit "2") and distractor (the digit "5") stimuli (Figure 3b and 3c) cannot be distinguished on the basis of a single feature, and therefore attention should be required to find the target. If attention was directed to the stimulus array before a saccade was executed, the participant's attention should have been disengaged from the fixation stimulus.

A second, more general problem was that the gap effect might be caused by warning. Saslow (1967) noted that in the gap condition, the offset of the fixation stimulus might serve to warn participants of the onset of the saccadic target. In the overlap condition, no such warning occurred, since the fixation stimulus was not removed until after the target appears.

As noted earlier, Kingstone and Klein (1993a) found that warning did play a role in the gap effect. They found that the offset of any stimulus in the visual field prior to target onset resulted in a reduction of saccadic latencies as compared to the overlap condition, although not as great a reduction as when the stimulus being fixated was removed. Kingstone and Klein (1993a) argued that the reduction in SRT arising from the removal of the attended stimulus prior to target onset was the result of warning. That is, the offset of the fixation stimulus would serve as warning of the target's onset, while simultaneously freeing the participant's ocular

fixation mechanism so that the participant could immediately execute a saccade to the target when it appears.

In the current experiments, a warning tone was presented 400 ms prior to target onset on both gap and overlap trials to equate possible warning effects across all overlap and gap conditions. Participants were able to predict precisely when the target stimuli would appear in all conditions of the experiment. Thus, any differences that were observed between conditions could be attributed to factors other than warning. Similar controls for warning have been used by Saslow, (1967) and Reuter-Lorenz et al. (1991).

A final problem was that by increasing the predictability of target onset participants could actually increase the frequency of anticipatory saccades (Juttner & Wolf, 1992; Kalesnykas & Hallett, 1987; Kingstone & Klein, 1993b). These saccades should be executed before the target/distractor stimuli were processed. In order to ensure that saccades were stimulus driven, and not anticipatory, participants were required to process the target/distractor stimuli on each trial by including catch trials. On these trials, no target was presented and participants were required to withhold saccade execution. The purpose of the catch trials was to force the participant to process the target/distractor stimuli on each trial before making a saccade. In this way, anticipatory saccades should have been prevented.

The experiments discussed in this thesis addressed two issues. The primary issue was whether or not reflexive saccades were required to generate the gap

effect. The secondary issue was whether or not the gap effect depended on attentional disengagement.

EXPERIMENT 1: Unilateral Detection

The purpose of the first experiment was to replicate the basic gap effect using stimuli that were to be used in later experiments. The results of Experiment 1 served as a basis for comparison with the tasks where the participants were required to search for the target. Target/distractor stimuli were presented only on one side of fixation. The participant's task in this experiment was to make a saccade to any stimulus array (3 items) that appeared to the left or right of the center of the screen. Because a stimulus was presented on only one side of fixation, it was theoretically possible to execute reflexive saccades. Two methodological controls were implemented. First, a warning tone consistently preceded the onset of the peripheral stimulus to equate warning events in the gap condition to warning in the overlap condition (Saslow, 1967; Kingstone & Klein, 1993b). Secondly, in order to reduce the frequency of anticipatory saccades, catch trials were presented where no target was displayed. On the catch trials (Juttner & Wolf, 1992; Kingstone & Klein, 1993b) the participant was asked to maintain central fixation until the end of the trial. In overlap trials, the fixation stimulus remained present until after target onset. On gap trials, the fixation stimulus was removed prior to the onset of the target array.

Method

Subjects. The participants consisted of seven individuals from Carleton university and one individual from the Communications Research Centre. One participant had some familiarity with the gap paradigm whereas the remaining participants were naive observers. Each participant participated in all the experiments in random order.

Apparatus and Stimuli. All displays were presented on a Tektronix 608 oscilloscope equipped with a P15 phosphor and controlled by an Interactive Electronic Systems controller (Finley, 1985). The P15 phosphor has an extremely short persistence and decays to 10% of its original value in 2 microseconds. The background luminance of the display was 50 cd/m² and the luminance of the stimuli was 400 cd/m².

To ensure that participants' fixation mechanisms were fully engaged on the fixation stimulus, a fixation dot was changed to a fixation cross when participants pressed the start button to initiate a trial. The target stimuli consisted of an array (1.2° wide by 1.7° high) of three items. The array was centered 2° to the left or right of a central fixation stimulus. The individual items in the stimulus display consisted of a "2" and two "5"'s or of a vertical line and two horizontal lines in another block of trials (See Fig. 3). These stimulus arrays were used in this and in the subsequent experiments. The alphanumeric stimuli subtended .6° of visual angle vertically and .4° horizontally, whereas the line stimuli subtended .6° of visual angle in length and .08° in width.

A headrest was used to maintain a steady head position. Eye position was sampled at a rate of 60 Hz with an ISCAN RK-426 pupil tracking system. The 60 Hz sampling rate ensured that detection of saccades was accurate to within 16.7 ms. The spatial resolution of the eye tracker is better than $.25^\circ$. All equipment was controlled by an 80486-based computer.

Procedure. The participant viewed the oscilloscope display from a distance of 46 cm. Each session began with a brief calibration of the eye tracker. Experimental trials began immediately after calibration.

Participants initiated each trial by pressing a button on a button box. Four hundred milliseconds after pressing the button, a 100 ms warning tone was presented (see Fig. 2). Participants were informed that the warning tone offset always preceded the target onset by 500 ms. At the point determined by the ISI, the fixation cross disappeared. The ISI (-500, -100, 0, 100, 150, 200, 300 and 500 ms), refers to the temporal interval between the offset of fixation and the onset of the target. Negative ISI's indicate trials where the onset of the target preceded the offset of fixation. Positive ISI's indicate trials where the onset of the target followed the offset of fixation. At the 0 ISI, offset of fixation and onset of the target coincided. One second after the start button was pressed, the target appeared. Participants were instructed to make a saccade to the center of the target array when it appeared. Findlay (1982) and Fischer and Weber (1992) have noted that participants can effortlessly execute a saccade to the location which

corresponds to the center of a multi-element display.

Catch trials were included in this and the following experiments. Approximately 15 catch trials were added to each session. These trials differed from real trials in two major respects, (a) no target appeared and (b) participants were instructed not to move their eyes from the location of the fixation cross. In the current experiment, where the task was to detect the presence of a stimulus, the catch trial consisted of the presentation of no stimulus. The purpose of these trials was to eliminate anticipatory saccades to the target. Trials were rejected if saccades (a) were too fast (below 85 ms, based on Fischer & Ramsperger, 1984, 1986) or too slow (above 600 ms), (b) too small (less than 1.5°; the minimum edge to edge distance from the fixation stimulus to the target stimulus), (c) if no saccade was made when a target was presented and (d) if a saccade was made in the wrong direction. Rejected trials were replaced at random within the same session. On catch trials, a rejection was recorded if the participant made a saccade (catch trials were not replaced, however). Two criteria existed for replacing a session. Sessions were repeated if the error rate (not including catch trials) for the session exceeded 10%, or if the error rate on catch trials was more than 50%. Replaced sessions were excluded from the overall analyses.

For this experiment and the following experiments, a minimum of one practice session was given to each participant. The maximum number of practice sessions (for more difficult experiments) was five sessions. Each session consisted

of 32 target-present trials, 4 trials for each of 8 ISI's. The target stimulus appeared on the left side of the display on half of the trials and on the right side of the display for the remaining trials. The participants participated in six sessions each, repeating a session if they made an eye movement on more than half of the catch trials or if they had an error rate of greater than 10%.

Results and Discussion

Saccadic latencies were examined with a 2 X 8 within-participants analysis of variance (ANOVA). The two factors were target type (numbers or lines) and ISI (-500, -100, 0, 100, 150, 200, 300 and 500 ms), referring to the temporal interval between the offset of fixation and the onset of the target. The negative ISI indicates overlap trials whereas positive ISI's indicate gap trials. The dependent variable was saccadic latency. In terms of the saccadic latencies, it was expected that the latencies would be longer in the overlap conditions than in the gap conditions. Examination of Figure 4 reveals that overlap latencies were longer than gap latencies. This difference in saccadic latencies between overlap and gap trials was significant, $F(7,49) = 17.61$, $MSe = 392.14$, $p < 0.0001$ (See Appendix C). Post-hoc analysis (Tukey's) revealed that saccadic latencies for the -500 ms and -100 ms (overlap) ISI's were significantly different from all of other ISI's ($p < .05$). As expected, there was no difference in detection time for the parallel and serial stimulus arrays ($F < 1$). The parallel and serial search stimulus arrays were apparently equally capable of eliciting short-latency saccades. No other

Figure 4

Figure 4. Saccadic Latencies and Errors Across Inter-Stimulus Intervals for Experiment 1 (Unilateral Detection).

effects were significant for SRT.

The mean number of errors per session for this experiment was low, with participants typically making only one or two errors per session, usually due to poor fixation. Analysis of the error rate revealed only a marginally significant effect of target type, $F(1,7) = 5.49$, $MSe = 0.029$, $p < 0.05$. Participants made slightly more errors with the line stimuli (2.28%) than with the digit stimuli (3.97%). No other effects of error rate were significant.

The pattern of results for the ISI's in Experiment 1 (Fig. 4) represent the typical configuration of saccadic latencies in the gap effect (Kingstone & Klein, 1993b; Reuter-Lorenz et al., 1991; Ross & Ross, 1980; Saslow, 1967; Tam & Ono, 1994; Tam & Stelmach, 1993). In this simple detection task, the participant was able to move to the target stimulus as soon as it appeared. In the gap condition, since the fixation was removed, the participant should be able to reflexively saccade to the target. The saccadic latencies for *some* gap trials for some participants were within the range of saccadic latencies for express saccades². It is possible that some of these short latency saccades were in fact reflexive saccades (c.f., Kalesnykas & Hallett, 1987; Weban-Smith & Findlay, 1991). According to Reuter-Lorenz et al. (1991) and Fischer and Weber (1992; Weber & Fischer, 1994) reflexive saccades should be present in the gap condition when the participant has only to detect and execute a saccade to the target stimulus.

EXPERIMENT 2: Anti-saccades

In the anti-saccade task, a stimulus array appeared on one side of the display and the participants looked to the opposite side of the display (Hallett & Adams, 1987). For example, if the participant saw the stimulus display on the right as shown in Figure 3a or 3b, the participant would make a saccade to a similar position on the left side of the display. In this task, the participant was implicitly compelled to suppress the reflexive saccade to the stimulus that was displayed. Reuter-Lorenz et al. (1991) argued that reflexive saccades were a necessary component of the gap effect, while Fischer and Weber (1992) found a gap effect with the anti-saccade task. The current experiment provided an additional examination of the anti-saccade paradigm using different stimuli.

Method

Stimuli and Procedure. The current experiment was identical to Experiment 1, with only one difference. Participants were asked to execute a saccade to the side of the display *opposite* where the stimulus array appeared. In this experiment, as in Experiment 1, catch trials consisted of presenting no stimulus array.

Results and Discussion

The data for Experiment 2 were analyzed using the same design as Experiment 1: target type and ISI were analyzed with a 2X8 within-subjects ANOVA. Examination of Figure 5 reveals a difference between saccadic latencies for overlap and gap conditions, although this difference is somewhat smaller than

Figure 5

Figure 5. Saccadic Latencies and Errors Across Inter-Stimulus Intervals for Experiment 2 (Anti-Saccade).

the difference found in Experiment 1. However, the overlap/gap difference was significant, $F(7,49) = 12.41$, $MSe = 184.63$, $p < 0.0001$ (See Appendix D). Post-hoc analysis revealed that SRT's for the overlap ISI's were significantly longer than SRT's for all of the gap ISI's except the 0 and 500 ms ISI's ($p < 0.05$). No other effects were significant.

As in Experiment 1, participants made very few errors in this experiment, typically making than two to three errors per session, again from poor fixation maintenance. Analysis of the error rate revealed an effect of ISI, $F(7,49) = 2.62$, $MSe = 0.056$, $p < 0.02$. Due to the conservative criterion of the Tukey's post-hoc analysis, no differences between the levels of ISI were revealed. No other effects were significant. Although the gap effect in this experiment was somewhat smaller than has been found in typical gap paradigms (e.g., Experiment 1), a gap effect was present, in agreement with the findings of Fischer & Weber (1992) but contradictory to the findings of Reuter-Lorenz et al. (1991). The results of the current experiment, combined with the results of Fischer & Weber (1992), suggest that the gap effect can occur when reflexive saccades are restricted.

Recently, Reuter-Lorenz et al. (1995) claimed that Fischer and Weber (1992) found a gap effect with the anti-saccade task because Fischer and Weber did not include a warning tone to equate overlap and gap conditions. That is, the offset of fixation in the gap condition may have served to warn participants that target presentation was imminent. Presenting a tone before target onset in the

overlap condition may have served to equalize warning between overlap and gap trials. Reuter-Lorenz et al. (1995) found gap effects for pro- and anti-saccades (65 ms and 32 ms) when a warning tone was not present. When a warning tone was present, gap effects were found only for pro-saccades (43 ms) but not for anti-saccades (14 ms). Yet, in the current experiment a gap effect was found for anti-saccades when a warning tone was present.

The current research suggests that the gap effect does not depend on the presence of reflexive saccades. However, the anti-saccade task does not seem to be particularly reliable, because it produced no gap effect for Reuter-Lorenz et al. (1991, 1995), a minimal effect in the current experiment, and a larger effect in Fischer and Weber (1992). Given the variability in the findings, verification with a convergent task is warranted. The nature of the anti-saccade task, as discussed in the introduction, is somewhat unnatural in that the participant is essentially asked to look at nothing as quickly as possible.

A different task could be used to inhibit reflexive saccades, such as the tasks employed by Weber and Fischer (1994). They required the participant to identify or search for the vertical-line target that was presented with oblique-line distractors. In the baseline condition, no distractors were presented and the participant executed a saccade as soon as a target stimulus was detected. In the baseline condition, express saccades and short latency saccades were much in evidence. A large decrease in the number of express saccades occurred when

distractor stimuli were presented on the opposite side of the display from the target. When distractor stimuli were presented on both sides of the display, express saccades were virtually eliminated. However, Weber and Fischer (1994) did not examine the effects of these voluntary eye movement tasks on the gap effect³.

Therefore, the third and fourth experiments used tasks which included identification and search components to try to eliminate the occurrence of reflexive saccades. In these experiments, participants were required to either: a) identify whether or not a target stimulus was present in a single, unilateral stimulus array or b) search two, bilateral stimulus arrays for a target presented among distractors. Participants executed a saccade only if the target was present. Since the search for the target in this type of task is generally processing intensive (as compared to a simple detection task), it was highly improbable that reflexive saccades would occur without a concomitant increase in the error rate. The requirement to search for the target would also minimize the usefulness of warning of the onset of the target. The search task required that the participant respond as soon as the target stimulus had been found and not to the onset of the stimulus, as is the case in the typical pro- and anti-saccade paradigms.

The search paradigm also allowed for the examination of the secondary issue of the role of attention in the gap effect. The attentional disengagement hypothesis proposed that attentional processing of fixation had to cease before an

eye movement could be made (Braun & Breitmeyer, 1988; Fischer, 1987). If this was the case, a task which required the participant to attend to the target before a saccade would effectively prime the participant to execute a saccade immediately after confirmation of the presence of the target. That is, the participant should be equally prepared to execute a saccade whether the fixation stimulus is present or not. Two search tasks were employed in experiments three and four; an attentionally demanding serial search and a less demanding parallel search. If the attentional disengagement hypothesis (Braun & Breitmeyer, 1988; Fischer, 1987) is correct, there would not be any difference between saccadic latencies for overlap and gap conditions in the serial search condition; attention should be disengaged from fixation on both overlap and gap trials. In contrast, a gap effect would be expected with the parallel search, as it is less attentionally demanding.

EXPERIMENT 3: Unilateral Search

In this experiment, the participant was required to locate the target among distractors in a stimulus array appearing on the left or right of the fixation point. The requirement to locate the target before executing a saccade should help to prevent reflexive saccades to the stimulus array. The methodology of this experiment was based on an extensive series of pilot experiments where various design factors were independently manipulated (Craig, Stelmach & Tam, 1994). The participant was required to execute a voluntary saccade to the center of the array that contained the target stimulus. If the gap effect depends on the

occurrence of reflexive saccades (Reuter-Lorenz et al., 1991), a gap effect should not be evident in the current experiment where the execution of reflexive saccades is unlikely. However, if the critical event in the generation of the gap effect was the offset of fixation, then a gap effect should be evident in the current experiment (Fischer & Weber, 1992).

A subsidiary goal of the present experiment was to contrast an attentional disengagement and an ocular disengagement explanation of the gap effect. In terms of these two hypotheses, two tasks were run, one of which did not require the participant to attend to the stimulus array prior to the execution of a saccade (parallel search; fig. 3c), and the other which did require the participant to attend to the stimulus array to find the target stimulus (serial search; fig. 3d). The purpose of adding these two conditions was to determine if there was a difference between conditions where attention was directed to the stimulus arrays (serial search task) and conditions where attention was not required to find the target.

Method

Apparatus and Stimuli. The apparatus and stimuli in this experiment were identical to those used in the first two experiments. In the parallel search condition, the target consisted of a vertical line and the distractors were horizontal lines. In the serial search, the target consisted of the digit 2 and the distractors were 5's. Participants were instructed to locate the target stimulus *before* executing a saccade.

Procedure. There were two major differences between the current experiment and the previous experiments. The first difference was that the catch trials in this experiment consisted of presenting only distractor stimuli as opposed to no stimulus array. This forced the participant to actively search for a target on each trial, to ensure that a target was present before they executed or withheld a saccade. The requirement to search for a target was the second major difference between this experiment and the previous experiments. The search task was added to this experiment to prevent the execution of immediate, reflexive saccades to the stimulus array. All other aspects of the experiment were identical to those employed in Experiment 1.

Results and Discussion

Two important aspects of the results are apparent from the graph in Figure 6. The first is that there was an effect of ISI for the gap conditions (positive ISI's) as compared to the overlap conditions (negative ISI's). The second aspect of the data that is noteworthy is there were differences in latency arising from the attentional manipulation (serial vs. parallel). These differences in search tasks and ISI's were examined using a 2x8 within-subjects ANOVA (See Appendix E). In terms of the primary focus of the work, a significant gap effect was found ($F[7,49] = 9.64$, $MSe = 417.27$, $p < 0.0001$), despite the prevention of reflexive saccades by requiring participants to search for the target before making a saccade. Post-hoc analysis (Tukey's) confirmed that the sole difference in ISI lay between

Figure 6

Figure 6. Saccadic Latencies and Errors Across Inter-Stimulus Intervals for Experiment 3 (Unilateral Search).

the -500 ms ISI and all other ISIs. It is noteworthy that the SRT for the -100 ms ISI was not different from the SRT's for any of the gap ISIs. This can be readily explained in that participants required 317-368 ms to initiate a saccade from target onset. By the time the participant initiated a saccade, the fixation marker had been removed from the screen for at least 200 ms. Thus, the -100 ms ISI, given the prolonged search times in the present experiment, effectively "becomes" a gap condition.

In terms of attentional search task, the participants required more time (51 ms) to execute a saccade in the serial search task (369.32 ms) than in the parallel search task (317.86 ms), $F(1,7) = 70.66$, $MSe = 1199.38$, $p < 0.0001$. They also tended to make more errors in the serial condition (16.67%) than in the parallel condition (9.7%), $F(1,7) = 14.43$, $MSe = 0.192$, $p < 0.007$ (this was the only effect of error rate that was significant). This suggests that additional processing time was required for the serial search as compared to the parallel search because the serial search required more attentional resources than the parallel search (Treisman, 1982, 1988). This factor was important with respect to the secondary issue of this thesis, namely, ocular versus attentional disengagement. The importance of contrasting the parallel versus the serial search was to first show that attention was allocated to the stimulus array in the serial search task. Attentional disengagement hypothesis predicts that there should be an interaction between search and ISI. Specifically, there should be a gap effect for the parallel

search where attention does not have to be disengaged from fixation to identify the target, but no effect for the serial search where attention has to be disengaged from fixation to identify the target. However, the interaction between search task and ISI was not significant ($F < 1$). These results suggest that the gap effect is not produced by attentional disengagement from fixation. Instead, the gap effect appears to be related to the offset of fixation.

The results of this experiment combined with the results of Experiment 2, and those of Fischer and Weber (1992) support the proposition that reflexive saccades are not a prerequisite for the occurrence of the gap effect. Similar results have been obtained in a series of pilot studies (Craig et al., 1994), with slightly different methodology. On each trial, one of four objects was presented. Two of the four objects were designated as targets while the remaining stimuli were designated as distractors. Thus, participants were required to identify the stimulus on each trial to determine whether or not a saccade was required. Having the participants identify the target, in all likelihood, decreased the probability that a reflexive saccade was executed. In these pilot experiments, as in the present experiment, gap effects were present.

Two aspects of Experiment 3 warrant further examination. First, it was possible that participants were not actively searching for the target but instead were executing saccades to the stimulus array, regardless of which stimuli were presented. Given the prolonged SRT's arising from Experiment 3 as compared to

Experiment 1 where reflexive saccades were not inhibited, this seems unlikely. However, the increased error rate for this experiment as compared to the first two experiments suggests that further examination is warranted. An analysis of the error data suggested that there were a larger number of catch trial errors than any other type of error⁴. Secondly, in both Experiment 2 and Experiment 3, participants had to actively suppress reflexive saccades to the stimulus arrays. Would the results differ if the reflex was repressed by the arrangement of the stimuli, in which the stimuli were presented bilaterally, for example. According to Reuter-Lorenz et al. (1991) conditions for reflexive saccades are most optimal when a single target is presented for the saccade, and an unambiguous neural representation of the saccade target is available in the visual field map of the superior colliculus. Thus, if more than one stimulus array is present in the visual field, the likelihood of a reflexive saccade occurring is diminished. Accordingly, a bilateral stimulus display was used in the final experiment to prevent or minimize the occurrence of reflexive saccades.

EXPERIMENT 4: Bilateral Search

In this experiment, the participant was required to locate the target on the left or right of the fixation point before executing a saccade. Stimulus arrays were presented on both sides of fixation to help eliminate reflexive saccades to the target. One side of the display consisted of distractors only while the other side of the display consisted of distractors and a target. The presence of a gap effect

under these conditions would suggest that the emergence of the gap effect does not depend on the presence of reflexive saccades, as suggested by Reuter-Lorenz et al. (1991, 1995). An additional advantage of this design was that the increased number of distractors should increase the difficulty of the serial search task (Treisman, 1982, 1988), providing a stronger test of the attentional disengagement hypothesis.

Method

Apparatus and Stimuli. The apparatus and stimuli in this experiment were identical to those used in the previous experiment with one exception. In this experiment, stimulus arrays appeared simultaneously on both sides of the location of the central fixation marker. One array (on the right or left) consisted of a target and two distractors, while the array on the opposite side of fixation consisted of three distractors. In the parallel search condition, the target consisted of a vertical line and the distractors were horizontal lines (e.g., Figure 3c). In the serial search, the target consisted of the digit 2 and the distractors were 5s (e.g., Figure 3d).

Procedure. The basic procedure was identical to the that of the previous experiments. The participant was required to fixate the central stimulus at the beginning of the trial. The central fixation stimulus was removed before or after the onset of the search array (using the same ISIs as the previous experiments). The participant was told to maintain central fixation until they detected the target.

regardless of whether the fixation stimulus was still present or not. Unlike previous experiments, participants had to search both sides of fixation to determine whether or not a target was present. The participant was told to make a saccade to the array containing the target as soon as they detected the target. If no target was found (on catch trials), the participant was instructed maintain central fixation until the target array disappeared.

Results and Discussion

Inspection of Figure 7 reveals a difference between gap and overlap ISI's. As in Experiment 3, this difference appears to lie between the -500 ms overlap ISI and the other ISIs⁵. A 2x8 ANOVA confirmed that there was an effect of ISI, $F(7,49) = 12.48$, $MSe = 449.5$, $p < 0.0001$ (See Appendix F). Post-hoc analysis (Tukey's) confirmed that the difference in ISI lay between the -500 ms overlap ISI and the remaining ISI's, while the -100 ms overlap ISI was significantly different from only the 100 ms and 300 ms gap ISI's ($p < 0.05$). The fact that the gap effect was present here supports the hypothesis that reflexive eye movements are unnecessary in the generation of the gap effect.

There was also an effect of search task ($F[1,7] = 54.84$, $MSe = 3296.81$, $p < 0.0001$) with participants requiring 75 ms more to find the target in the serial search task (371.54 ms) than in the parallel search task (296.38 ms). Participants typically made more errors in the serial search task (26.04%) than in the parallel search task (7.42), $F(1,7) = 53.48$, $MSe = 0.318$, $p < 0.0002$. The importance

Figure 7

Figure 7. Saccadic Latencies and Errors Across Inter-Stimulus Intervals for Experiment 4 (Bilateral Search).

of contrasting the parallel versus the serial search was to show that attention was allocated to the stimulus array in the serial search task. Attentional disengagement hypothesis predicts an interaction between search and ISI. Specifically, there should have been a gap effect in the parallel search condition, but no gap effect in the serial search condition. While there was a search task X ISI interaction ($F[7,49] = 2.93$, $MSe = 97.44$, $p < 0.012$), one-way analyses of search revealed significant gap effects (ISI) for both serial ($F[7,49] = 8.05$, $p < 0.0001$) and parallel ($F[7,49] = 14.18$, $p < 0.0001$) search tasks⁶ (See Appendix G). The finding of gap effects in both serial and parallel search tasks is contrary to the predictions of the attentional disengagement hypothesis. The alternative, ocular disengagement hypothesis (Fischer & Ramsperger, 1986; Kingstone & Klein, 1993a; Tam, 1989; Tam & Stelmach, 1993), holds that the gap effect is solely due to the removal of the fixation stimulus in gap conditions, regardless of the allocation of attention. Since the gap effect appeared in all of the experimental conditions in the present experiment, the results of this and the previous experiments indicate that the ocular disengagement hypothesis is a more feasible explanation for the gap effect.

GENERAL DISCUSSION

The present thesis studied the programming and execution of saccades. Two classes of saccades were examined: reflexive and voluntary saccades, with particular emphasis on the latter. The goal was to discover whether reflexive and

voluntary saccades shared a common fixation disengagement stage. One possibility is that only reflexive saccades have a fixation disengagement stage (Reuter-Lorenz et al., 1991, 1995). Another possibility is that the fixation disengagement stage is a common aspect of all saccades (Forbes & Klein, 1996; Tam & Ono, 1994).

Two specific issues were examined in this research, the role of reflexive saccades and the role of attentional disengagement in the generation of the gap effect. Experiment 1 demonstrated that the gap effect could be obtained under conditions where participants produced reflexive saccades to eccentric targets, using the experimental set-up and techniques employed in this thesis. Experiments 2-4 studied saccadic latencies under conditions where participants were required to execute voluntary saccades. In Experiment 2 a gap effect was obtained under conditions where an anti-saccadic response was required. In Experiments 3 and 4, a gap effect was produced under conditions where participants had to search a stimulus array for a particular target before executing a saccade. In all four experiments a gap effect was found, suggesting that both reflexive and voluntary saccades share a common stage, referred to as the ocular disengagement stage.

In the following sections, some possible explanations for the gap effect are discussed.

Reflexive Saccades and the Gap Effect

One explanation of the gap effect is that it results from the execution of reflexive saccades, made possible by the removal of the fixation stimulus in the

gap condition (Reuter-Lorenz et al., 1991). According to this view, a gap effect would only be found if conditions permitted the execution of reflexive saccades on gap trials. Specifically, reflexive saccades may occur if no fixation stimulus is present, and a single, unambiguous stimulus appears in the peripheral visual field (Fischer & Weber, 1993; Weber et al., 1992). Since the stimulus configuration of gap trials facilitates the execution of short-latency, reflexive saccades, more low-latency saccades would occur in the gap condition than in the overlap condition. This view is supported by the majority of research on the gap effect, which has typically employed stimulus conditions conducive to the generation of reflexive saccades on gap trials (e.g., Braun & Breitmeyer, 1988; Fischer, 1987; Fischer & Ramsperger, 1986; Fischer & Weber, 1993; Kingstone & Klein, 1993a, 1993b; Reuter-Lorenz et al., 1991, 1995; Saslow, 1967; Tam & Ono, 1994; Tam & Stelmach, 1993; Weban-Smith & Findlay, 1991; Weber et al., 1995). An alternative explanation is that removal of the fixation stimulus causes disinhibition of saccade cells in the caudal superior colliculus in advance of a saccade, which allows for immediate execution of the saccade (Fisher & Weber, 1992; Forbes & Klein, 1996). This latter explanation is more general because it acknowledges that the gap effect will occur in a variety of situations, provided that the necessary conditions for disinhibition are met. Specifically, a gap effect should be observed whenever the fixation stimulus is removed immediately preceding the moment in time that a saccade is programmed; fixation removal causes disinhibition of the

superior colliculus (Munoz & Wurtz, 1992, 1993). In this view, the presence of a fixation point should delay all saccade types, reflexive and voluntary. This hypothesis was studied in the present research.

It was found that the gap effect could be obtained with reflexive or voluntary saccades. The implication of these results is that reflexive saccades are not necessary in the generation of the gap effect. This appears to be true in a variety of tasks, such as the anti-saccade task (Experiment 2; Fisher & Weber, 1992; Forbes & Klein, 1996), identification tasks (Craig et al., 1994), and in search tasks (Experiments 3 & 4), where task requirements and/or stimulus conditions required voluntary saccades and effectively inhibited the generation of reflexive saccades. It is possible that reflexive saccades may contribute to the gap effect, but they are not key to the generation/emergence of the gap effect.

Recently, Forbes and Klein (1996) have found gap effects with reflexive and voluntary saccades. In addition to the normal pro- and anti-saccades tasks, Forbes and Klein used a verbal cue to direct saccades to location markers presented to the left and to the right of fixation. A warning tone was presented on gap and overlap trials in all conditions. Gap effects were found for all three tasks, including the anti-saccade task. Since gap effects were found in all conditions, Forbes and Klein (1996) concluded that both reflexive and voluntary saccades were inhibited by the presence of a fixation stimulus.

Forbes and Klein (1996) described saccade generation in the gap paradigm

in terms of three control systems. The *exo* (exogenous) system, which is based on the superior colliculus (SC), is responsible for programming of reflexive saccades to visual targets. The *endo* (endogenous) system, which is based on the frontal eye fields (FEF) and the prefrontal cortex (Pre), is responsible for planned or voluntary saccades. Both the *exo* and the *endo* control systems send input to a common control system, the *sac* (saccade) system, which is responsible for the actual execution of the saccade. According to Forbes and Klein, the typical gap paradigm is largely controlled by the *exo* system. If a fixation stimulus is present, fixation cells in the rostral pole of the SC inhibit the saccade cells in the caudal SC and excite the inhibitory cells (omnipause neurons) in the *sac* system. Without the fixation stimulus, these systems are disinhibited, which reduces saccadic latencies. For voluntary saccade tasks, information from the *endo* system is transmitted in parallel to the *exo* and *sac* systems. Inhibition of saccades by a fixation stimulus in the *endo* system occurs via the inhibitory controls of the *exo* system. With respect to the anti-saccade task, Forbes and Klein maintain that the *endo* system continually inhibits the *exo* system until the visual stimulus has been processed and the saccade to the opposite side of fixation is prepared. Once the saccade has been programmed, information from the *endo* system is transmitted in parallel to the *exo* and *sac* systems (Forbes & Klein, 1996).

The findings of the current research concurs with that of Forbes and Klein (1996) on all but one point. They noted that the gap effect for the anti-saccade

task was smaller in magnitude (21 ms) than the gap effect associated with the pro-saccade task (43 ms) and the verbal task (43 ms). Likewise in the current work, the magnitude of the gap effect for the anti-saccade task (Exp 2) was reduced (28 ms) compared to the magnitude of the gap effects for the unilateral detection task (Exp. 1, 42 ms), the unilateral search task (Exp. 3, 50 ms) and the bilateral search task (Exp. 4, 52 ms). That the reduction in the magnitude of the gap effect occurs with the anti-saccade task, but not with other voluntary saccade tasks suggests that the reduced gap effect is not associated with the requirement to execute voluntary saccades (Forbes & Klein, 1996). Forbes and Klein proposed that the reduced magnitude of the gap effect in the anti-saccade task was due to the *inhibition* of a reflexive saccade to the visual stimulus. In the current research, participants had to inhibit reflexive saccade to the visual stimulus in the anti-saccade task (Exp. 2) and a reduced gap effect was found. But, participants also had to inhibit reflexive saccades to the stimulus array in the unilateral search task (Exp. 3) until a target stimulus had been found. Yet, the magnitude of the gap effect in the unilateral search task was not reduced (50 ms). Since reflexive saccades had to be inhibited in both experiments, but only the anti-saccade task showed a reduction in the size of the gap effect, the inhibition reflexive saccades can not adequately explain the reduced gap effect associated with the anti-saccade task. Forbes and Klein (1996) note that in the anti-saccade task, once the reflexive saccade to the visual stimulus is inhibited, a voluntary saccade in the opposite

direction be programmed. This need to reprogram the saccade, to transform the voluntary anti-saccade into a reflexive pro-saccade, may explain the reduced magnitude of the gap effect associated with the anti-saccade task. In all the experiments discussed in the present work (and in Forbes & Klein), the direction of the saccade does not have to be reprogrammed once the target is located, except in the anti-saccade task. Perhaps the reduction in the magnitude of the gap effect in the anti-saccade task is related to the requirement to reprogram the direction of the saccade, rather than the inhibition of reflexive saccades. Although this issue requires further examination, the central conclusion of Forbes and Klein (1996) and the current thesis is that reflexive and voluntary saccades share a common requirement for disengagement in the gap paradigm.

In terms of the three-loop model, Fischer and Weber (1993)'s explanation of the gap effect is similar to that of Reuter-Lorenz et al. (1991). That is, a large proportion of short-latency reflexive saccades occur in the gap condition, while longer latency, voluntary saccades occur in the overlap condition. The difference in the average latencies between the reflexive saccades in the gap condition and the voluntary saccades in the overlap condition gives rise to the gap effect. In terms of their three-loop model (Fischer & Weber, 1993), Fischer and Weber proposed that gap latencies are composed of express and fast regular saccades (80-150 ms) generated by the first and second loops of the model. Overlap latencies are composed of slow regular saccades (200 ms) generated by the third loop. In their

model, only the third loop is responsible for the generation of long-latency, voluntary saccades. In the search tasks used in Experiments 3 and 4 of the current work, saccadic responses consisted almost entirely of long-latency voluntary saccades. Yet, a gap effect was found in both experiments, despite the large proportion of voluntary saccades. Since control of voluntary saccades is located in the third loop, Fisher and Weber (1993)'s explanation of the gap effect based on the execution of reflexive and voluntary saccades clearly fails to explain how a gap effect was obtained in Experiments 3 and 4, where only voluntary saccades were permitted.

Clearly explanations of the gap effect presupposing a key role for reflexive saccades are untenable (Reuter-Lorenz et al., 1991, 1995; Fischer & Weber, 1993). Other explanations will be examined in the following sections.

Attentional Disengagement and the Gap Effect

A secondary issue in the current work was whether attentional disengagement is a viable explanation of the gap effect. The premise of attentional disengagement is that attention has to be disengaged *from fixation* prior to a saccade (Braun & Breitmeyer, 1988; Fischer, 1987). In Experiments 3 and 4, attention was disengaged from fixation on all trials in the serial search condition. According to attentional disengagement, this should have lead to participants having equally short SRT's in overlap and gap conditions. This was not the case. Previous research (Kingstone & Klein, 1993a; Tam & Stelmach, 1993) has shown

that the *offset of fixation* reduces saccadic latencies, regardless of the direction of attention. The results of Experiments 3 and 4 provide additional support for these findings, contrary to the predictions arising from attentional disengagement.

A different interpretation of attentional disengagement is that attention cannot be engaged at any point in visual space prior to the initiation of a saccade. In Experiments 3 and 4, attention was not engaged at fixation, but it was (presumably) engaged in examining the stimulus array(s). Thus, attentional disengagement may still have been required in Experiments 3 and 4. Yet, if this were the case, attentional disengagement would be required in overlap and gap conditions. Therefore, latencies should have been *elevated* but *equal* in gap and overlap conditions. Yet, gap effects were evident in Experiments 3 and 4. Thus, even a more general version of attentional disengagement fails to account for the results of the previous and current research.

Alternative Explanations for the Gap Effect

If reflexive saccades and attentional disengagement cannot account for the gap effect, what alternative explanations exist? The following sections examine two proposals that might account for the gap effect.

Facilitated Target Detection

One possible explanation of the gap effect is that the gap condition facilitates target detection (Reulen, 1984). In the traditional gap paradigm, the target is the only stimulus visible on gap trials. Target detection might be faster

on gap trials than on trials where other stimuli are present (Fischer & Weber, 1993). Weber and Fischer (1994) found that the presentation of distractors with the saccadic target did increase saccadic latencies on gap trials. Although unlikely, it may be possible that the presence of the fixation marker on overlap trials decreases the speed of target detection, which results in increased saccadic latencies. Weber and Fischer (1994) did not examine this issue. Being primarily interested in the effects of distractors on express saccades, they only used gap presentations.

The facilitation of target detection is an unlikely explanation of the gap effect. This proposal is based on the premise that target detection is easier in the gap condition since the target is the only stimulus present. In contrast, both the target and the fixation stimulus are present in the overlap condition. However, a gap effect was present in Experiments 3 and 4, even though multiple distractors were presented. This is especially true of the serial search task, where the target and distractors were highly similar in appearance. The proposal that the gap effect results from the increased ease of target detection in gap conditions compared to overlap conditions seems untenable in light of these results.

Effects of Warning

Reuter-Lorenz et al. (1995) has claimed that gap effects can occur or can be augmented by the lack of a warning tone on gap *and* overlap trials. In the absence of a warning tone, fixation offset in the gap condition serves to warn the

participant of the impending onset of the target. The participant is able to prepare a saccadic response earlier in this condition than in the overlap condition where no such warning is available. While warning may prove beneficial in the typical gap paradigm or in the anti-saccade paradigm, it would be of less use in the current experiments. In these experiments, a warning tone was always presented prior to the onset of the target. Additionally, warning of the onset of the stimulus would have been of less use in Experiments 3 and 4, where the participants had to first find the target placed among distractors. Participants could not use the onset of the target as a cue to initiate a saccadic response. Thus, warning would have played a minimal role in Experiments 3 and 4.

Warning, as some have suggested (Fischer & Ramsperger, 1986; Kingstone & Klein, 1993a; Reuter-Lorenz et al., 1995; Saslow, 1967) can contribute to the size of the gap effect. In some instances (Fischer & Weber, 1992), the lack of a tone to equate warning in gap and overlap conditions may have led to spurious gap effects (Reuter-Lorenz et al., 1995). However, gap effects occur even when warning is equalized across gap and overlap conditions (Kingstone & Klein, 1993a; Reuter-Lorenz et al., 1991; Reuter-Lorenz et al., 1995), suggesting that warning alone cannot explain the gap effect.

Alternative Explanations: A Summary

Both facilitated target detection and warning fail to adequately explain the results of the present research. In the present studies, gap effects were found

when target detection was easy and when target detection was difficult. Gap effects were found even when warning was equalized across gap and overlap conditions. This eliminates explanations of the gap effect in terms of reflexive saccades, attentional disengagement, warning and ease of target detection. Therefore, I would like to present an explanation in terms of ocular disengagement.

Ocular Disengagement Hypothesis

Under the ocular disengagement hypothesis, an ocular mechanism exists which disengages the eye from the fixation point before the eye moves to the target (Fischer & Ramsperger, 1986; Tam, 1989; Tam & Stelmach, 1993). According to Weber et al. (1992), disengagement from fixation may involve the frontal eye fields (or the parietal cortex via the frontal eye fields) disinhibiting the "saccade cells" (Dias & Bruce, 1994; Munoz & Wurtz, 1993) and inhibiting the "fixation cells" in the superior colliculus (Dorris & Munoz, 1995). In the gap condition the fixation stimulus is removed before the onset of the saccadic target, disinhibiting the saccade cells and inhibiting the fixation cells. Consequently, a saccade can be executed earlier in the gap condition than in the overlap condition. The ocular disengagement hypothesis holds that the reduction in saccadic reaction times is strictly the result of these processes.

The results of the current experiments are best explained by ocular disengagement. This hypothesis holds that a fixation stimulus drives the

oculomotor fixation mechanisms. If a saccade is required in the presence of a fixation stimulus, the maintenance of fixation must be suspended, that is, disengagement must occur prior to the saccade. It is assumed that disengagement can also begin with the removal of the fixation stimulus. This being the case, the time normally required for disengagement is not required in the gap condition, which leads to shorter saccadic latencies in the gap condition as compared to the overlap condition. This may occur regardless of the direction of attention, or other task requirements not involving the ocular fixation mechanisms. Since gap effects were found in all of the current experiments regardless of the task requirements, these results support the idea that the gap effect depends on the events at fixation, as specified by the ocular disengagement hypothesis (Fischer & Ramsperger, 1986).

Thus, the ocular disengagement hypothesis offers an explanation of the gap effect that is congruent with the majority of the current research (Kingstone & Klein, 1993a; Kingstone & Klein, 1993b; Reuter-Lorenz et al., 1991; Reuter-Lorenz et al., 1995; Tam & Stelmach, 1993; Tam & Ono, 1994). That is, an ocular mechanism exists which disengages the eye from the fixation point before the eye moves to the target (Fischer & Ramsperger, 1986; Tam, 1989; Tam & Stelmach, 1993).

GENERAL CONCLUSIONS

Several explanations for the gap effect have been proposed, such as

reflexive saccades (Reuter-Lorenz et al., 1991; Reuter-Lorenz et al., 1995), attentional disengagement (Braun & Breitmeyer, 1988; Fischer, 1987), warning effects (Reuter-Lorenz et al., 1995), and ocular disengagement (Fischer & Ramsperger, 1986; Saslow, 1967; Tam, 1989; Tam & Stelmach, 1993). Of these explanations, only one seems to be able to account for the results of the current experiments. It is stated in the ocular disengagement hypothesis that removal of the fixation stimulus in the gap condition by-passes the need for ocular disengagement before an eye movement to a peripheral target. The explanation rests solely on the offset of the fixation stimulus and fixation disengagement regardless of other task demands. In the current research, gap effects were present whether the participant performed a simple pro-saccade task, an anti-saccade task, or a search task before executing a saccade. Thus, the gap effect appears to be generated by the *offset of fixation* rather than reflexive saccades, target facilitation, attentional disengagement or warning effects. Accordingly, ocular disengagement theory provides the best explanation of how the gap effect is generated under a variety of task and stimulus conditions. Finally, the appearance of the gap effect in voluntary and reflexive saccade tasks suggests that these two types of saccades share a common fixation disengagement process.

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Appendix A

Footnotes

¹ Reflexive saccades and express saccades are typically defined as saccades with latencies of 80-150 ms (Reuter-Lorenz et al., 1991; Weber et al., 1992). The difference between reflexive and express saccades is that express saccades form a separate peak within a multi-modal distribution of saccadic latencies. The express saccade peak is centered at 100 ms, while regular and slow saccade peaks are centered at 150 and 200 ms, respectively. Reflexive saccades refer to any short latency saccades that are not anticipatory (Kalesnykas & Hallett, 1987; Weban-Smith & Findlay, 1991). Kalesnykas and Hallett (1987) proposed that the minimum latency for a reflexive saccade would be between 100-120 ms.

² The ISCAN eye-tracking system samples the eye position every 16 ms (60 Hz) which is below the rate required to discriminate between express saccades, fast-regular saccades and slow saccades.

³ Weber and Fischer (1994) did not test saccadic responses in overlap conditions. Although saccadic latencies increased on gap trials when distractors were presented, it could not be determined whether this increase in latency was indicative of the elimination of the gap effect (c.f., Reuter-Lorenz et al., 1991).

⁴ A 2x6x8 (search type X error type X ISI) Anova revealed a significant effect of error type, $F(5,35) = 72.8$, $MSe = 1.361$, $p < 0.0001$. Post-hoc analysis (Tukey's) revealed higher percentages of catch trial errors than any other type of error ($p < .05$).

⁵ It is assumed from subjects' latencies that the -100 ms overlap ISI effectively "becomes" a gap condition, since the fixation marker typically was removed before subjects could find the target and prepare a saccade. This appeared to be the case in Experiment 3 and Experiment 4. A trend in this direction was also apparent in pilot data that used the target identification task (Craig et al., 1994).

⁶ In terms of the search by ISI interaction: a) for the serial search task, SRT's were longer for the -500 ms overlap ISI than for all gap ISI's, while the -100 ms overlap ISI SRT *only* differed from the 200 ms gap ISI (Tukey's; $p < 0.05$), and b) for the parallel search task, SRT's were longer for the -500 ms overlap ISI than for all gap ISI's, while the -100 ms overlap ISI differed from all gap ISI's *except* the 200 ms gap ISI (Tukey's: $p < 0.05$).

Appendix B

Reaction Times to Search Stimuli: Pilot Research

Pilot work has indicated that the horizontal and vertical lines and the 2 and 5's meet Treisman's (1982, 1988) criteria for parallel, pre-attentive searches and serial, attentive searches, respectively. Manual reaction times were collected for each set of stimuli as the number of distractors was varied. The purpose of varying the number of distractors was to determine if reaction times would increase with increased number of distractors, which would indicate a serial search. It was expected that manual reaction times for target (2) detection would increase with the number of distractors (5's) with the digit stimuli (since these stimuli cannot be distinguished by a single unique feature). Since the line stimuli can be distinguished by a single feature, participants should be able to find the target (--) with a parallel search of the stimulus array. If this is the case, reaction times should not increase as the number of distractors (|) increases.

The stimuli used are described in the method section of Experiment 1 and presented in Figure 3a and 3b, with the exception being the size of the stimulus array. Stimulus arrays consisted of 1, 2, 3, or 4 items. In the 1 item array, the target stimulus was presented on one side of fixation, while the distractor was presented on the opposite side of fixation. In the 2 item array, a target and a distractor were presented on one side of fixation, while two distractors were presented on the other side of fixation. In the 3 item array, a target and two

distractors were presented on one side of fixation, while three distractors were presented on the other side of fixation. In the 4 item array, a target and two distractors were presented on one side of fixation, while four distractors were presented on the other side of fixation. Twelve trials were presented per array size, for a total of 48 trials per session. Target items were presented on half of the trials while on the remaining trials, no target was presented; instead, another distractor was presented in place of the target. On trials where the target appeared, it appeared on the left or right for an equal number of trials. Participants were asked to participate in six sessions of the serial search task (digit stimuli) and six sessions of the parallel search task (line stimuli).

Participants were asked to maintain fixation on a central fixation marker (which was always present) and determine whether or not a target stimulus had been presented, and indicate their response (yes/no) as quickly as possible on a button box. The stimulus array remained on-screen until the participant responded or until two seconds had elapsed.

The manual reaction time data from two participants was collected. The mean reaction times as a function of stimulus array size (1, 2, 3, or 4), response (target present/target absent) and search task (parallel/serial) for both participants are presented in Table 1. For the parallel search task (line stimuli), reaction times

Table 1

Mean Manual Response Times (ms) for Two Participants for Positive and Negative Target Detection Responses for Targets Embedded in Variable Size Arrays in Parallel and Serial Search Tasks

		Positive				Negative			
		Array Size							
Participant#	Search	1	2	3	4	1	2	3	4
1	Parallel	447	473	455	463	569	564	519	540
	Serial	465	504	533	562	607	656	749	792
2	Parallel	416	390	382	391	565	579	562	553
	Serial	463	558	697	654	737	922	1169	1256

did not increase as the number of distractors increased. However, for the serial search task, reaction times increased as the number of distractors increased.

It was concluded from these data that the stimuli to be used in Experiment 3 and 4 did meet the requirements for parallel and serial search tasks (Treisman, 1982, 1988). That is, detection of horizontal line was not impaired by the presence of distractors (vertical lines). Conversely, detection of the number 2 was impaired by increasing the number of distractors (5's).

Appendix C

**Summary of the Overall Analysis of Variance of Mean Saccadic Latencies and Error Rates for Experiment 1
(Unilateral Detection)**

I. Saccadic Reaction Time

Source	DF	Anova SS	Mean Sqr. MSE	F Value	Pr > F
SRCH	1, 7	26.74	26.74	901.7	0.03
ISI	7, 49	48326.78	6903.83	392.1	17.61
SRCH*ISI	7, 49	177.65	25.38	37.9	0.67

II. Error Rate

Source	DF	Anova SS	Mean Sqr. MSE	F Value	Pr > F
SRCH	1, 7	0.158	0.158	0.029	5.49
ISI	7, 49	0.159	0.023	0.020	1.14
SRCH*ISI	7, 49	0.070	0.010	0.018	0.56

III. Mean Saccadic Latencies (ms) and Error Rates (%)

SEARCH	ISI	SRT		ERR	
		Mean	SD	Mean	SD
Serial	-500	230.06	35.06	0.016	0.086
Serial	-100	227.44	25.99	0.026	0.124
Serial	0	186.81	25.77	0.010	0.077
Serial	100	180.94	34.12	0.031	0.173
Serial	150	183.19	37.90	0.031	0.118
Serial	200	180.06	36.39	0.010	0.077
Serial	300	186.81	34.94	0.026	0.086
Serial	500	194.50	36.39	0.031	0.124
Parallel	-500	226.38	33.33	0.052	0.172
Parallel	-100	230.81	27.30	0.042	0.154
Parallel	0	187.00	34.50	0.010	0.077
Parallel	100	179.13	38.34	0.036	0.188
Parallel	150	179.56	38.56	0.052	0.214
Parallel	200	181.88	41.69	0.042	0.236
Parallel	300	184.94	39.86	0.036	0.165
Parallel	500	192.81	45.85	0.047	0.208

Appendix D

Summary of the Overall Analysis of Variance of Mean Saccadic Latencies and Error Rates for Experiment 2 (Anti-saccades)

I. Saccadic Reaction Time

Source	DF	Anova SS	Mean Sqr. MSe	F Value	Pr > F	
SRCH	1,7	267.39	267.38	889.79	0.30	0.6006
ISI	7,49	16034.72	2290.67	184.63	12.41	0.0001
SRCH*ISI	7,49	407.09	58.16	57.23	1.02	0.4318

II. Error Rate

Source	DF	Anova SS	Mean Sqr. MSe	F Value	Pr > F	
SRCH	1,7	0.001	0.001	0.185	0.00	0.9476
ISI	7,49	1.033	0.148	0.056	2.62	0.0222
SRCH*ISI	7,49	0.492	0.070	0.063	1.11	0.3713

III. Mean Saccadic Latencies (ms) and Error Rates (%)

SEARCH	ISI	SRT		ERR	
		Mean	SD	Mean	SD
Serial	-500	258.06	38.80	0.083	0.454
Serial	-100	254.81	29.09	0.073	0.198
Serial	0	243.63	29.38	0.042	0.236
Serial	100	237.38	23.88	0.125	0.356
Serial	150	231.69	29.59	0.063	0.236
Serial	200	235.19	28.21	0.089	0.338
Serial	300	230.69	32.66	0.047	0.188
Serial	500	241.50	36.83	0.109	0.308
Parallel	-500	266.06	29.86	0.115	0.478
Parallel	-100	262.75	31.01	0.104	0.356
Parallel	0	247.38	31.47	0.026	0.124
Parallel	100	238.93	26.11	0.068	0.177
Parallel	150	231.56	24.67	0.094	0.533
Parallel	200	232.56	23.80	0.068	0.388
Parallel	300	231.06	26.23	0.052	0.264
Parallel	500	245.75	39.43	0.089	0.339

Appendix E

**Summary of the Overall Analysis of Variance of Mean Saccadic
Latencies and Error Rates for Experiment 3
(Unilateral Search)**

I. Saccadic Reaction Time

Source	DF	Anova SS	Mean Sqr. MSE	F Value	Pr > F
SRCH	1,7	84743.30	84743.30	1199.38	70.66 0.0001
ISI	7,49	28150.26	4021.47	417.27	9.64 0.0001
SRCH*ISI	7,49	896.37	128.05	312.18	0.41 0.8914

II. Error Rate

Source	DF	Anova SS	Mean Sqr. MSE	F Value	Pr > F
SRCH	1,7	2.77095	2.77095	0.19199	14.43 0.0067
ISI	7,49	0.89748	0.12821	0.09821	1.31 0.2678
SRCH*ISI	7,49	0.80348	0.11478	0.10169	1.13 0.3608

III. Mean Saccadic Latencies (ms) and Error Rates (%)

SEARCH	ISI	SRT		ERR	
		Mean	SD	Mean	SD
Serial	-500	402.75	37.03	0.130	0.350
Serial	-100	373.44	29.61	0.167	0.412
Serial	0	369.44	25.53	0.146	0.367
Serial	100	362.88	40.96	0.219	0.398
Serial	150	354.00	44.12	0.193	0.461
Serial	200	360.75	35.76	0.146	0.295
Serial	300	366.56	35.33	0.151	0.495
Serial	500	364.75	41.81	0.182	0.406
Parallel	-500	359.06	29.73	0.047	0.188
Parallel	-100	321.50	17.62	0.089	0.188
Parallel	0	316.69	22.74	0.141	0.295
Parallel	100	307.56	22.13	0.078	0.259
Parallel	150	309.88	27.12	0.099	0.263
Parallel	200	310.75	28.80	0.104	0.267
Parallel	300	305.69	21.67	0.099	0.330
Parallel	500	311.75	31.17	0.120	0.266

Appendix F

**Summary of the Overall Analysis of Variance of Mean Saccadic
Latencies and Error Rates for Experiment 4
(Bilateral Search)**

I. Saccadic Reaction Time

Source	DF	Anova SS	Mean Sqr. MSe	F Value	Pr > F
SRCH	1,7	180780.85	180780.85	3296.81	54.84 0.0001
ISI	7,49	39252.64	5607.52	449.50	12.48 0.0001
SRCH*ISI	7,49	2001.21	285.89	97.44	2.93 0.0120

II. Error Rate

Source	DF	Anova SS	Mean Sqr. MSe	F Value	Pr > F
SRCH	1,7	17.01267	17.01267	0.31811	53.48 0.0002
ISI	7,49	0.56888	0.08127	0.19432	0.42 0.8863
SRCH*ISI	7,49	0.15638	0.02234	0.19149	0.12 0.9969

III. Mean Saccadic Latencies (ms) and Error Rates (%)

SEARCH	ISI	SRT		ERR	
		Mean	SD	Mean	SD
Serial	-500	409.25	34.09	0.213	0.412
Serial	-100	383.06	29.39	0.255	0.740
Serial	0	364.19	29.51	0.276	0.198
Serial	100	361.63	39.82	0.250	0.519
Serial	150	365.88	33.34	0.271	0.707
Serial	200	354.81	34.98	0.271	0.591
Serial	300	360.63	30.65	0.271	0.667
Serial	500	372.88	32.21	0.276	0.792
Parallel	-500	341.44	43.39	0.042	0.236
Parallel	-100	312.25	30.22	0.036	0.139
Parallel	0	287.13	36.13	0.078	0.165
Parallel	100	280.38	35.18	0.078	0.165
Parallel	150	287.51	38.48	0.094	0.264
Parallel	200	294.31	37.13	0.089	0.165
Parallel	300	282.69	33.52	0.089	0.226
Parallel	500	285.31	34.38	0.089	0.301

Appendix G

**Summary of the One-Way Analyses of Variance of Mean Saccadic
Latencies for Serial and Parallel Search Tasks for
Experiment 4 (Bilateral Search)**

I. Serial Search

Source	DF	Anova SS	Mean Sqr. MSE	F Value	Pr > F
ISI	7,49	17120.00	2445.71	303.87	8.05 0.0001

II. Parallel Search

Source	DF	Anova SS	Mean Sqr. MSE	F Value	Pr > F
ISI	7,49	24133.85	3447.69	243.07	14.18 0.0001

IMAGE EVALUATION TEST TARGET (QA-3)

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