THE INFLUENCE OF RESPONSE PRIMING, COMPETITION, AND INHIBITION ON MOVEMENT TRAJECTORIES

By

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A Thesis
Submitted to the School of Graduate Studies
in Partial Fulfillment of the Requirements
for the Degree
Philosophae Doctorate

McMaster University

RESPONSE PRIMING, COMPETITION, AND INHIBITION

PHILOSOPHAE DOCTORATE (2002)	McMaster University
(Kinesiology)	Hamilton, Ontario

TITLE:	The influence of response priming, competition, and inhibition on movement trajectories.
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NUMBER OF PAGES:	xii, 240

ABSTRACT

Fundamental to the theories of action-based attention is the notion that response-producing processes are automatically initiated when an object receives attention. In support of action-based theories, movement trajectories have been found to deviate in the presence of non-target stimuli even when the stimuli do not present a physical barrier to the movement (Howard & Tipper, 1997; Welsh, Elliott, & Weeks, 1999). A model of response activation has been proposed to explain these deviations. Predictions based on the model are that, if a response is active at the moment of response activation, then the response will contain characteristics of both the target and non-target response. If the non-target response is inhibited at the time of response initiation, then the response will contain characteristics that are opposite to the non-target response. The five experiments reported in this dissertation were designed to test this model.

In the first experiment, it was found that the trajectories of the rapid-aiming movement to a target location deviated towards the location of a simultaneously presented non-target stimulus. This finding replicated earlier work (Welsh et al., 1999). The results of the second experiment supported the hypothesis that movement deviation away from the location of the non-target stimulus was the result of inhibition of the response to that stimulus. In the third experiment, the target location was precued to examine the effects of response priming on selective action. Consistent with predictions, when the target response was validly cued, no significant distractor interference was observed. On the other hand, if the distractor was presented at the cued location while the target was presented elsewhere, then the movement veered towards the location of the distractor. A similar precuing methodology was employed in the fourth experiment to explore the effects that response priming and inhibition associated with valid and invalid cues have on the trajectory of the target movement when the target is presented in isolation (without a simultaneously presented non-target stimulus). The results of this experiment were generally congruent with the model of response activation.

The final study was designed to examine how inhibitory processes, hypothesized to be associated with negative priming and inhibition of return, would affect movement preparation and execution. Consistent with previous work, the presence of the distractor in the prime trials caused deviations in the movement trajectories towards the location of the non-target stimulus. Inhibition of return and negative priming effects, however, were not found. Facilitation effects associated with colour repetition and the lack of competition in the probe trials were the likely causes underlying these latter null effects. Overall, the results of the present series of studies suggest that the model of response activation is able to predict deviations in the path of aiming movements under competitive conditions. Development of the model in terms of the interaction between perception and action systems is required to enable it to account for all effects associated with selective attention.

ACKNOWLEDGEMENTS

I would like to take a minute or two to thank those who, through their love and support, helped to make this possible. I know I am going to miss a few people who are really deserving of a "thank you", and for that I am sorry. Believe me, I did my best to remember everyone. As I did in my M.Sc. thesis Acknowledgement section, I will thank everyone in the style of a Hollywood "B" movie (in order of appearance). I am doing it this way because it will probably be the easiest way to remember everyone. Also, I would not feel right putting people "in order of the amount of support", because how do you compare the thanks needed for teaching me that the most important thing in life is to know how to do everything yourself to teaching me how to post hoc and interpret a huge stinkin' four-way interaction?

To my parents, my bother and sister, and my grandparents, thanks for all the support and patience you have shown me over the years. What each of you, in your own way, have taught me about life and living with peace is invaluable.

In terms of my academics, I cannot give enough thanks to the seemingly unending knowledge, support, and advice of my supervisor Digby. Although you and Elaine all but shoved me off that bridge in New Zealand, you did let me tear down your dinning room ceiling (only to force me to put them back up again). You cannot imagine how lucky I feel that you went against all conventional wisdom and took a young Argo fan into your lab and then around the world.

A LARGE and very appreciative thanks must go to my committee, Drs. Timothy Lee, Bruce Milliken, and Janet Starkes, for their thoughtful and very timely comments. Thank you so much for your efforts in helping me get finished on time. Thanks also to Drs. Sue Becker, Lee Brooks, and Eric Buckolz for your work on my committee.

And where would I be without my wife-to-be, Netty. I am not sure, but I know I would not be as happy and excited about the future as I am now. Thank you so much for putting up with my late nights, my lack of playtime lately, and my music. We've done so many great things in the few years we've together, I can't wait to find out where we go to in the next 45 years (+).

To end off this acknowledgement section, I would be remiss if I did not mention: the help I have received around the lab from Luc Tremblay (without whom I would not have any data to talk about, nor would I know so many "key" French phrases), Dom Simon (with whom I've shared so many ideas about how to solve both academic and worldly problems), Jamie Coull (the smartest of the "traitors"), John Cullen, John Moroz, the Passion Pals – Nat, Sara, and Rachel, my 'Fest Friends - Roddy and Teddy (not to mention Aurora and Finch), lil' Jennie D and our friendly Fire Fox Tara, the Hockey fellas, and all the others who have made me laugh or were being willing participants in these studies.

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PREAMBLE

The research presented in this dissertation was designed to examine the viability of a model of selective action. The model was developed to explain the effects that processes, traditionally associated with visual selective attention, have on movement organization and execution. The results of five experiments are reported in three for-submission style manuscripts. In the first manuscript, the basic tenets of the model are developed and the results of three experiments are reported. In the first experiment, an attempt was made to replicate the finding that a simultaneously presented non-target stimulus caused a deviation in the path of the target aiming movements towards the non-target location (Welsh, Elliott, & Weeks, 1999). As the results of Experiment 1 were consistent with those of Welsh et al. (1999), the purpose of Experiment 2 was to test the hypothesis that deviation away from the non-target location was the result of inhibition of the response to that location. In Experiment 3, a precuing methodology was integrated with the visual search paradigm to test the hypothesis that the trajectory effects observed in the previous experiments would be eliminated if the participant had already selected (primed) the response to the target location.

The second manuscript is a report of a single experiment in which the precuing technique was employed to test predictions of the effects of response priming and inhibition on movement. The final manuscript consists of the description of an experiment designed to examine what effects the establishment of inhibitory codes would have on future action. Overall, the results of the experiments indicate that the model of response activation is able to accurately predict the effects of a non-target stimulus on the current action. However, it is noted that consideration and integration of perceptual and retrieval processes is necessary to make the model more complete.

Prior to and following the three manuscripts are General Introduction and Conclusion sections, respectively. These sections have been included to provide a larger theoretical and historical context for the work presented in the dissertation. As such, subsections on movement organization and selective attention are presented in the General Introduction. The subsection on movement organization provides a brief description of past and current thinking about the characteristics of rapid goal-directed movements and the processes they are thought to represent. Following the subsection on movement organization, a review of the theorectial development of action-based theories of selective attention is detailed. The final subsection of the introductory section is dedicated to setting up the specific context for the work presented in the dissertation by providing a brief review of the literature demonstrating the effects that the processes of selection have on movement planning and execution.

The General Conclusion begins with an overview of each of the five experiments. Following the overview, the results are interpreted and placed into the context of the concepts of action-based attention presented in the General Introduction. The General Conclusion ends with discussion of directions for future research and development of models of action-based attention.

GENERAL INTRODUCTION

The ability to acquire objects in complex environments is fundamental for the survival of humans or any sentient being. For example, in order to feed itself, a chimpanzee must be able to differentiate the fruit from the leaves of a tree and then grasp the fruit. Initial investigations of selective behaviour considered it to consist of two separate, but interacting processes. First, the target object must be selected from the non-target, or distracting, objects and a movement must be planned to seize the selected object. As this serial independence between attention and action was the thinking of the time (and indeed is still pervasive today), exploration of selective attention processes began with investigations of the ability of people to selectively attend to or filter out specific stimuli in the environment (e.g., Broadbent, 1954; Eriksen & Eriksen, 1974). Paradigms typically employed to examine the selection phenomena involved either rapid vocal or arbitrary key press responses to the detection of a target stimulus placed among a series of distracting, non-target stimuli and, as such, neglected to incorporate physical interaction with the stimuli (see Allport, 1993). Likewise, motor control researchers have looked at the abilities of people to move to and manipulate objects when presented in isolation (the absence of non-target objects) (e.g., Coull, Weir, Tremblay, Weeks, & Elliott, 2000; Marteniuk, MacKenzie, Jeannerod, Athens, & Dugas, 1987). That is, the environments in which motor acts are studied typically have only a single target object with which the participant interacts. Only recently has the connection between the processes of selective attention and movement been examined in the same experiment (e.g., Tipper, Lortie, & Baylis, 1992). These new paradigms have lead to the development of action-based theories of attention. What follows is a brief historical review of each area of research and how they have come to be linked.

Movement Organization

The study of rapid, goal-directed aiming movements effectively began with the work of Woodworth (1899). In this seminal monograph he described a series of studies designed to understand some of the basic principles of rapid aiming movements. Participants were asked to complete a series of aiming movements with a pencil on a piece of paper that was moving perpendicular to the direction of the aimed pencil. Based on an analysis of these pencil tracings and the conditions under which they were created, Woodworth proposed that there were two phases of a rapid aiming movement: the initial-impulse and current-control phases. The initial-impulse (a.k.a., ballistic or primary) phase of aiming movements is characterized by a rapid and relatively invariant acceleration that is thought to represent the preprogrammed portion of the movement. The current-control (a.k.a., corrective, homing-in, or secondary) phase of the movement is characterized by discontinuities in the acceleration profile late in the movement and is thought to represent the performer's attempt to use sources of online visual and kinesthetic feedback to ensure that the movement is completed accurately.

Since the publication of Woodworth's monograph, many motor control researchers have sought to discover the processes involved in the ballistic and corrective stages of movement (see Elliott, Helsen, & Chua, 2001, for a recent review). There has been advancement in what is known about how efficient motor programming is learned, and how different sources of afferent information are used to ensure the accurate completion of a movement (see Schmidt & Lee, 1999). Although the ability of performers to learn to program and execute efficient movement has been the topic of a large body of research, the present work is focused on attention and how it affects the programming and execution of movement.

Selective Attention

The cocktail party problem is the classic example used to demonstrate the fundamental question that researchers of selective attention attempt to answer (Cherry, 1953). In a crowded room in which dozens of conversations occur simultaneously, how is it possible that we are able to screen out the irrelevant conversations and process only the words of our conversation partner? Because humans have a limited capacity to process information, the ability to selectively process information is necessary to prevent overload or chaotic behaviour. Since James (1890) first formalized the abstract concepts that define attention, research has been focused on the limitations and mechanisms that underlie our ability to process information in a selective manner. To achieve this goal, often times the opposite question is posed: how do the properties of the irrelevant stimuli interfere with our ability to complete our primary task?

Early work in the area of selective attention stemmed from this interest in assessing the limits of the ability to process information by examining how well people can selectively attend to information coming from different sources (Broadbent, 1954; Cherry, 1953). The preferred procedure at the time was the dichotic listening task. In the dichotic listening task, the participant was presented with two different series of auditory stimuli (e.g., a voice saying numbers) to each ear via a set of headphones. The task of the participant was to focus attention on one ear and only report on the information presented to that ear. The measure of interest was the amount of interference that the presentation of the second (unattended) series of stimuli had on the ability to report the primary (attended) stimuli. Interference in these tasks was indexed as the inadvertent reporting of words from the unattended ear, or as simply an inability to report the words from the attended ear. Based on the findings of a series of studies indicating that participants were able to selectively process and report on the stimuli in the attended ear with little or no interference, Broadbent (1958) proposed a single-channel filter model of attention. The basic premise of this model is that, as the title suggests, attention acts as a filter that allows only the stimuli that meet certain criteria to pass through early reception stages of perception to receive further identification processing.

Broadbent's filter theory did not withstand rigorous empirical tests, however. Most notably, it was found that information presented to the unattended ear could be recognized when that information was relevant to the participant. For example, participants would often hear their name if it was presented to the "unattended" ear (Moray, 1959). A similar effect of non-task information was reported much earlier with the discovery of the Stroop effect (Stroop, 1935). The Stroop effect refers to the increased time to report the colour of a font (e.g., red) when the text is a word of a different colour (e.g., "blue") relative to when the text is a non-colour word (e.g., "dog"). Thus, it was discovered fairly early that non-task information can affect primary task performance if that information is relevant to the performer or to the task at hand.

In the 1970's, a paradigm equivalent to the dichotic listening task for the visual modality was developed. In visual search paradigms, the participant is presented with a display consisting of a target stimulus placed in an array of non-target stimuli (e.g., Eriksen & Eriksen, 1974). As with the dichotic listening task, the job of the participant is to detect and respond to the presence of the target stimulus while selectively ignoring the non-target stimuli coexisting in the display. The main concern of these studies was how the location and action properties of the non-target stimulus affects (interferes with) the participants' ability to quickly and accurately respond to the target stimulus. The principal hypothesis behind these studies is that, by assessing the amount of interference the distracting stimulus has on the target response, it could be determined when and by what coordinate system (or frame of reference) non-target stimuli are filtered out by the visual attention system to ensure successful task performance.

Results from the diverse range of studies employing the visual search paradigm have fostered the development of numerous models of selective attention. For example, Eriksen and Eriksen (1974) found that the interference effect was related to the distance between the target and the distractor. They found that a distractor only caused a significant interference effect if the distractor was within 1° of visual angle. They also found that the interference effect increased with decreasing distance between the target and the distractor within that 1° of visual angle. Based on these results, Eriksen and Eriksen (1974) proposed that visual attention moves through the environment like a spotlight or zoom lens. If a non-target stimulus is presented within the spotlight, then that stimulus is selected for further processing along with the target stimulus and interferes with the processing of the target stimulus. If the non-target stimulus is outside this spotlight, then it is not selected for further processing and does not interfere with identification of the target stimulus.

Despite the diversity of models that have been proposed, a consensus seems to be developing regarding the mechanisms of selection. That is, while earlier attempts at describing the selection process only emphasized the excitation of the stimulus matching the target properties (e.g., Broadbent, 1958), more recent research has illuminated the important role that active inhibition of non-target stimuli has in the selection process (see Houghton & Tipper, 1994 for a review). Some of the strongest evidence supporting the idea of active inhibition of the non-target stimuli has come from the discovery of the negative priming phenomena (Neill, 1977; Tipper, 1985).

As described earlier, the typical visual search task consists of the participant being presented with a visual display containing both target and non-target stimuli from which the performer is asked to select the target stimulus and complete the appropriate response. It is hypothesized that, during the selection process, not only does the stimulus matching the properties of the target receive excitatory feedback, but the stimuli that do not match the target receive inhibitory feedback (Houghton & Tipper, 1994). Interestingly, if the distracting stimulus is presented as the target on the immediately following trial, the response to the once-distractor-now-target stimulus is slower than if the target stimulus on that trial was different from either the target or distractor on the previous trial (e.g., Milliken, Tipper, Houghton, & Lupiáñez, 2000). A dominant explanation[1] forwarded for the slower response times for the once-distractor-now-target stimulus relative to any other stimulus is that an inhibitory code has been placed on the properties associated with the distractor on trial n that interrupts the coupling between that stimulus and the response to that stimulus on trial n+1.

About the same time that visual search researchers were discovering the lasting effects of inhibition on response times, researchers interested in how attention can be selectively focused on a particular location in space uncovered a similar inhibitory aftereffect. This effect was discovered through the use of the precuing technique. In these types of tasks, participants are presented with a series of possible target locations. One of these locations is then predictively cued, telling the performer that, more often than not, the target will be presented at that location. Following the cue, the target stimulus is presented at one of the possible target locations and participants are asked to make a speeded response when they detect the appearance of the target. As predicted, if the target location was predictively precued, responses to the detection of the target were faster than if the target appeared at an uncued location (e.g., Jonides, 1981; Posner, Nissen, & Ogden, 1978).

Posner and Cohen (1984) altered the typical precuing technique by: 1) changing the nature of the cue such that it was not predictive of the future location of the target; and, 2) requiring the participants to reorient their attention back to the central fixation point from the cued location via a brief cue presented at the fixation point. Under these conditions, it was observed that response times to a target at the cued location were shorter than for a target at the uncued location when there was a very brief cue-target onset asynchrony. However, as the cue-target onset asynchrony increased beyond 300 ms, response times to a target appearing at the cued location were actually longer than those at the uncued location. Similar to the negative priming effect, this inhibition of return effect is thought to be caused by a lasting inhibitory code that has been formed to impede the reorienting of attention to a particular stimulus after attention has recently been removed from that stimulus.

Although it is apparent from the work reviewed here that great gains have been made in understanding the behavioural characteristics of attention, a major criticism of this work is that the investigators typically utilize tasks that involve arbitrary modes of indicating the detection of the target stimulus (Allport, 1993; Tipper et al., 1992). Tasks that are typically used, such as keyboard button pressing (Tipper, Brehaut, & Driver, 1990), toggle or joystick manipulation (Milliken et al., 2000), and simple force generation (Coles, Gratton, Bashore, Eriksen, & Donchin, 1985), have been suggested to dissociate the direct perception, attention, and action links that have evolved and developed together (e.g., Gibson, 1979; Tipper et al., 1992). Given the general belief that the processes that cause both inhibition of return and negative priming effects have also been framed in an evolutionary context (e.g., to aid in the visual search for food; see Posner & Cohen, 1984; Tipper et al., 1990), it may be that the employment of such arbitrary tasks to study the processes of selective action has been convenient, but limiting. As such, an underlying theme of the work presented in this dissertation and elsewhere (i.e., Tipper et al., 1992) is that to truly understand the processes of selective attention, they should be studied in the context of goal-directed action. This line of thinking has lead to the development of action-based theories of selective attention.

Action-based Selective Attention

The premotor theory of attention proposed by Rizzolatti and colleagues was one of the first models of interactive selective attention and movement systems (see Rizzolatti, Riggio, & Sheliga, 1994 for a review). Noting that the processes of spatial attention and movement share the same pragmatic mapping systems and have overlapping neural networks, they suggested that these two systems are in fact a unitary system. As such, they forwarded that attention is distributed in terms of the to-be-performed action. A similar proposal was made by Tipper and colleagues. Tipper et al. (1992) reported a series of experiments in which participants completed rapid aiming movements to a target location with and without the presence of a competing, non-target location. It was found that a competing stimulus caused the greatest increase in response time (an interference effect) when it was located along the path of the movement or when it was located in the space ipsilateral to the moving hand. Based on these results, they proposed that when two stimuli are presented simultaneously, responses are automatically planned to both the target and non-target stimuli and subsequently compete for activation. The result of the competition between target and non-target responses is reflected in the observed temporal effects in movement planning and completion (see also Meegan & Tipper, 1998).

In support of action-based theories of attention, the presence of a non-target stimulus has also been shown to interfere with execution of goal-directed aiming movements. However, there has been a discrepancy in the direction of these effects. Although both Tipper, Howard, and Jackson (1997) and Howard and Tipper (1997) reported experiments in which movements deviated away from a non-target stimulus, in a study by Welsh et al. (1999) movements were found to veer towards the competing location. To explain the differences in the results of these studies, Welsh et al. suggested that the deviation towards the distracting stimulus was the result of response competition, whereas deviation away from the non-target stimulus was the result of its importance as a movement cue or as an object that was to be avoided.

The purpose of the present work was to test a more comprehensive explanation of these trajectory effects. The basic premise of the to-be-tested model is that deviation of the observed response towards or away from the non-target location is based on where, in the process of response activation, the inhibition of the competing response occurs. It was hypothesized that if a movement was initiated before the competing response was inhibited, then the initial movement trajectories would have components of both the target and non-target response, resulting in a deviation towards the competing location. However, if the competing response was inhibited prior to movement initiation, then a deviation away from the distractor location was expected. Thus, the key to the response activation model is the activity level achieved by each competing response at the time of response initiation.

The set of experiments presented herein were designed to test this model of response activation by investigating how the processes hypothesized to underlie some recently discovered attentional phenomena affect movement organization and execution. Specifically, these studies were intended to explore the effects of inhibitory (i.e., inhibition of return and negative priming) and priming processes (i.e., valid precue information) on the performer's ability to quickly and accurately move to a target location. Although changes in the temporal measures of response programming and execution were analyzed, the dependent measures of focus were kinematic. Kinematic effects dominated the discussion because very specific predictions about the effects of inhibition and response priming on movement trajectories could be made based on the model of response activation. As discussed earlier, it was proposed that inhibition of a competing response prior to movement initiation would result in movement trajectories deviating away from the distractor, whereas the simultaneous activation of a competing response would result in a trajectory veering towards the distractor. Thus, by using the response activation model as a guide, a test was made of the hypothesized processes thought to underlie selective action.

Overview of Experiments

The first paper of the series is a report of three experiments whose results helped to define the parameters of the model of response activation. In the first experiment, an attempt was made to replicate the deviation effects found in Welsh et al. (1999). Following the replication of the Welsh et al. (1999) effects in the first experiment, the second experiment was designed to test the hypothesis that the deviations away from the non-target location found in the studies by Howard and Tipper (1997) and Sheliga, Riggio, and Rizzolatti, (1994, 1995) were the result of the inhibition of the response to the non-target location. This test was conducted by varying the onset of the distractor stimulus relative to the onset of the target. The purpose of the final experiment reported in the first paper was to examine the effects of response priming on the distractor interference effects observed in the first two experiments. Specifically, it was hypothesized that if the target location was predictively precued, then the subsequent movement to that location would not be affected by the distractor. Alternatively, if the distractor was presented in the cued location, then the deviation effects observed in the previous experiments should be observed. In sum, the results of the three experiments were consistent with the predictions based on the model of response activation, and the remainder of the paper was dedicated to reviewing and reinterpreting the results of previous research on selective action in reference to the model.

Based on the success of the model to predict the trajectory characteristics during the selection process, the purpose of the experiments described in the second and third papers was to explore the ability of the response activation model to explain other phenomena associated with selective action. Specifically, it was examined how the processes hypothesized to cause inhibition of return and negative priming effects affect movement planning and execution. Because the inhibition of return and negative priming effects are thought to arise from inhibition of the current target response established because of the action taken on the previous trial, it was predicted that when inhibition of return and negative priming were observed, deviation away from the locations associated with these effects would occur. Although predictions based on the model of response activation were realized for inhibition of return in a cue-target paradigm, all other predicted effects of inhibition were not. The results of these experiments expose the need for further development of the model of response activation. Most apparent is the need to incorporate retrieval and/or perceptual processes into the model if it is going to be able to account for all phenomena associated with selective action (see also Tipper, 2001).

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Footnote

1. There are explanations for the negative priming effect that are not in agreement with the inhibition hypothesis (e.g., Neill, Valdes, Terry, & Gorfein, 1992). However, it is beyond the scope of this review to discuss these alternative hypotheses in detail (see Tipper, 2001 for a recent review and critical appraisal of these competing theories).

STUDY 1

An abbreviated version of this manuscript has been submitted for publication. I was the major contributor to every aspect of this research project including experimental design, data collection and analysis, and write-up of the study.

Movement Trajectories in the Presence of a Distracting Stimulus: Evidence For a Response Activation Model of Selective Reaching

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Abstract

Consistent with action-based theories of attention, the presence of a non-target stimulus in the environment has been shown to alter the characteristics of goal-directed movements. Specifically, it has been reported that movement trajectories both veer away from (Howard & Tipper, 1997) and veer towards (Welsh et al., 1999) the location of a non-target stimulus. The purpose of the present paper was to test a response activation model of selective reaching conceived to account for these variable results. In agreement with predictions based on the model, the direction of the trajectory changes in the movements were determined by the activation levels of each competing response at the moment of response initiation. The results of the present work, as well as those of previous studies, are discussed within the framework of the model of response activation.

Hand Deviations Towards Distracting Stimuli: Evidence For a Response Activation Model of Selective Reaching

In order to effectively reach to and grasp objects in a complex visual environment, two processes must be completed - the target object must be selected from the competing, non-target objects and a movement must be planned to the selected object. Although the processes of selective attention and movement organization have been investigated independently, action-based models of visual selective attention have recently surfaced. For example, Rizzolatti and colleagues have proposed a pre-motor theory of attention (see Rizzolatti, Riggio, & Sheliga, 1994 for a review). Citing evidence such as shared spatial and motor mapping systems and increased activity in early visual perceptual centers (superior colliculus) when the task involved a oculomotor response (see Hikosaka & Wurtz, 1989 for a review), they suggest that the attentional and motor systems may be a series of intact systems that code external events for action. Likewise, affordance theories of attention and perception-action coupling, rooted in ecological psychology, have suggested that actions are automatically organized to work with the object concomitant with the process of perceiving the object (e.g., Michaels, 1988). More recently, Lyons (2001) demonstrated that attention is distributed to the graspable location of the target object regardless of the possibility of grasping the object in real life interactions (e.g., when viewing a picture of a giraffe, attention is drawn to the neck and head of a giraffe relative to the body similar to being drawn to the handle of a cup (see also Tucker & Ellis, 1998)).

Tipper, Lortie, and Baylis (1992) have also proposed a model of action-based selective attention. This model is based on a series of studies that moved away from the arbitrary key-pressing or toggle-moving tasks that are commonly employed in the study of attention (e.g., Eriksen & Eriksen, 1974) and, instead, required participants to complete rapid 3D manual aiming movements to target locations with or without the presence of a competing, non-target stimulus. These studies revealed that attention is distributed through the movement environment relative to the to-be-performed action. Specifically, they found that a competing stimulus interferes with the planning of the target movement when the distracting stimulus is closer to the starting location of the effector, the "proximity-to-hand" effect, or is located in the same side of space as the anatomical origin of the effector, the "ipsilateral" effect (see also Meegan & Tipper, 1998). Consistent with both the premotor and affordance theories of attention, Tipper and colleagues suggested that the presentation, and subsequent perception, of both target and non-target stimuli elicit an automatic initiation of independent processes intended to program responses to each of the stimuli. Due to this early parallel processing, the response to the non-target stimulus must be inhibited in order for the target response to emerge. It is this combined response programming and subsequent inhibition that results in the participant having longer reaction and movement times in situations when distractor stimuli are present in the environment relative to when the target is presented alone (Tipper et al., 1992).

To explore the ramifications of the presence of non-target objects on reach-to-grasp movements, a number of researchers have examined not only the temporal aspects of movement, but also the spatial characteristics of the movement trajectory. The results of these studies have demonstrated seemingly inconsistent effects in that reaching movements have been found to veer away from (e.g., Tipper, Howard, & Jackson, 1997;

Tresilian, 1998) and towards (e.g., Tipper, Howard, & Houghton, 1999; Welsh, Elliott, & Weeks, 1999) the location of non-target objects and/or locations. A number of hypotheses have been forwarded in an attempt to account for these differences. The following is a brief review of each explanation and the results that lead to its development.

The Response Vector Model

Tipper and colleagues (Howard & Tipper, 1997; Tipper et al., 1997) were the first to investigate the effects of the presence of a non-target stimulus on response programming and inhibition on reach-to-grasp movements from an attentional point of view. With some minor variation, the general finding of these two studies was that the path of the movement veered away from the non-target stimulus; a pattern of results consistent with the notion of response competition and subsequent inhibition. Tipper et al. (1997) suggested that the presentation of multiple stimuli resulted in the initiation of independent response (movement) producing processes for each of the stimuli. Georgeopolous (1990) has shown that cells in motor cortex code for a specific direction of the response, firing most when a movement is planned in that direction and less frequently as the movement direction deviates from the preferred direction. As such, Tipper et al. (1997) proposed that populations of cells are responsible for coding each of the competing movements with the direction of each movement being represented as a vector sum of the firing rates of each population of neurons (see Figure 1a and b for an adapted diagram of Tipper et al., (1997) response vector diagram). Importantly, although the independent and competing responses code for movements to locations in different directions, the response processes may share some neuron populations in the motor cortex. When the neurons coding for the competing response are inhibited as selection occurs (through a process to be referred to as selective inhibition for the remainder of the text; see Houghton & Tipper, 1994 for a more in-depth discussion of the selection process), the neuronal pools shared by both response processes are affected. Thus, the result of the non-target response inhibition is an overall biased movement trajectory vector that codes for a movement that veers away from the non-target location (Figure 1d). Earlier studies by Sheliga, Riggio, and Rizzolatti (1994; 1995) that examined action-based accounts of selection in saccadic eye movements have found results that are consistent with the response vector model.

More recently, Houghton and Tipper (1999; see also Tipper et al., 1999) developed their response vector model to account for movement trajectories that veer towards the non-target locations. Based, again, on the work of Georgeopolous (1995) who reported that the movement directions are refined by a network of mutually excitatory and inhibitory links between the neurons in the motor cortex, Houghton and Tipper (1999) proposed a secondary selection mechanism that works via the neuronal architecture of the motor cortex. When a response is coded in the movement system, the cell that maximally responds to that movement direction selectively enhances the firing rates of the neighboring cells that code for a similar direction. As the distance between the cells increases (and thus the differences in the direction that the cells code for), the collateral enhancement effects decrease and eventually become inhibitory on cells coding for directions that do not match with the direction of the active response. Houghton and Tipper (1999) suggest that this on-center, off-surround (oCoS) mechanism works to enhance the target response selection by further suppressing the activity not associated with the target response (i.e., the non-target response).

Interestingly, Houghton and Tipper (1999) proposed that the oCoS mechanism is not a very efficient mechanism for selection of the target response, and is secondary to the selective inhibition mechanism. It was forwarded that the type of response that each mechanism works to select differs in terms of salience (salience being defined as the strength of activation of the response initiated by the presentation of a stimulus). Because selective inhibition is more powerful, it is responsible for eliminating competing responses that arise from stimuli with greater salience. As a result, competing objects/stimuli that initiate a strong response producing process, are selected out via selective inhibition and, thus, cause the final movement trajectory to veer away from the location of the non-target. On the other hand, the oCoS mechanism, being the weaker of the two mechanisms, works to inhibit responses to object/stimuli of little salience. Selection based on the oCoS mechanism, however, is often incomplete leaving a portion of the non-target response active in the motor system. The result of the partially active non-target response is a movement trajectory that deviates towards the location of the non-target stimulus.

The results of the study by Tipper et al. (1999), in which they adapted the methodology used by Sheliga et al. (1995) to include recording of hand movement trajectories, were consistent with these predictions. In Experiment 1 of the study by Tipper et al. (1999), they instructed participants to complete both a saccade and a rapid aiming movement with the hand to a target location based on a go/no-go signal presented at a precued location away from the target. They found that, while they replicated

Sheliga et al.'s (1995) finding that the trajectory of the eye veered away from the location of the signal, the hand slightly deviated towards the location of the signal en route to the target. To explain these results, they suggested that, because the signal to move (or not to move) was visual, the participant must resist making an eye movement to the location of the visual signal while preprogramming the saccade to the target location. As such, the location of the signal has great salience to the visual system and response processes initiated to that location must be inhibited in order for the target response to emerge. This selective inhibition results in the trajectory of the saccade deviating away from the location of the signal. However, as Tipper et al. (1999) suggest, because the location of the signal has very little salience for the hand system, selective inhibition against a response to the cued location is not required. As a result, when the signal is presented at the cued location, the response automatically initiated by the presentation of the go/no-go stimulus is only partially selected out by the weaker oCoS mechanism. Hence, the active, yet diminished, non-target response caused slight deviation towards the location of the signal.

Obstacle Avoidance Hypothesis

Although the response vector model accounted for the observed kinematic interference effects associated with the presence of a non-target stimulus in the movement environment, an alternative interpretation has been suggested. Tresilian (1998) suggested that in the reach-to-grasp tasks employed by Tipper and colleagues, as well as those of Castiello (1996) and Jackson, Jackson, and Rosicky (1995), the competing, non-target objects can not be ignored and thus do not fit with the traditional definition of “distractors”. As a result, Tresilian proposed that the observed trajectory changes were likely the result of object avoidance, not simply the result of response inhibition. In a series of studies, Tresilian and colleagues (e.g., Mon-Williams, Tresilian, Coppard, & Carson, 2001; Tresilian, 1998) have revealed that similar deviations in the path of the movement occur as the result of the need to position the hand to pick up a target blocks without colliding with other blocks placed around it. These changes in the movement trajectory occurred even though the object was not directly in the path of the movement. In this way, Tresilian has suggested that, although the movements in the Tipper et al. studies did not, in most cases, pass directly over the non-target objects, the participants may have perceived them as potential obstacles, or important sources of information and, as such, proposed that "any veering is always due to the perceived obstructing effect of the nontarget" (p. 354, Tresilian, 1998).

More recently Tresilian has softened this position (Tresilian, 1999). In this paper, it was acknowledged that selective processes may play a role and a dual mechanism of movement trajectory changes was suggested - one that encompasses both object avoidance strategies and selective processes. Although our research originates in the alternative selective attention camp, we agree with Tresilian that object avoidance strategies can play a role in altering movement trajectories. Indeed, it is intuitively obvious that the actor will choose a route to the target that would prevent collision or occlusion of a non-target object if the non-target object is: 1) directly in the path of the moving limb; 2) near the path of the limb but could cause damage to the moving limb (e.g., a sharp edge) or break if inadvertently contacted (e.g., a fragile glass figurine); or, 3) important for the actor to maintain in vision. As will be reported below, selective processes also play a significant role in movement trajectory changes.

The Response Activation Model

Although the object avoidance hypothesis can account for the deviations away from the non-target locations, what remained to be confirmed is whether it is simply the perception of a non-target object that will cause a deviation in the path of the movement or whether the object has to physically take up space. The study conducted by Welsh et al. (1999) was designed to test that question. In the Welsh et al. (1999) study, participants were required to move a mouse on a graphics tablet in order to move a cursor on a computer screen to a target location. On some trials the target location was accompanied by a simultaneously presented non-target stimulus. Because the movements were completed in a virtual environment, the possibility of a collision between the non-target stimulus and the effector en route to the target location was eliminated. Thus, if a deviation away from a non-target, especially when it is directly along the path of the movement, is observed then simply perceiving the stimuli may be sufficient for the actor to adopt an avoidance strategy. If, however, these non-target stimuli bias the movement trajectory towards the non-target location or if deviation away from the non-target is roughly equivalent regardless of its location, then it is likely that processes involved in target selection are a dominant mechanism behind the observed trajectory changes.

In contrast to many of the results reviewed above, Welsh et al. (1999) found that: 1) the distractor did not produce a significant increase in reaction time, movement time, or total response time; and, 2) movement trajectories were actually drawn towards the distractors, rather than being repelled from them. This attraction was strongest when the non-target stimulus was located in central space or on the same side of space as the anatomical origin of the effector - similar to the ipsilateral effect (Tipper et al., 1992). Interestingly, these kinematic effects were not associated with any temporal interference. To account for these results, Welsh et al. (1999) forwarded a "horse race" hypothesis of response competition. Similar to the response vector model of Tipper et al. (1997), the notion of response competition began with the premise of early parallel programming of responses to both the target and the competing, non-target stimuli. However, by incorporating recent findings associated with the stop-go paradigm (McGarry & Franks, 1997) and electrophysiological studies of selective attention (Coles, Gratton, Bashore, Eriksen, & Donchin, 1985), Welsh et al. (1999) suggested that the two independent and parallel response processes raced for activation. As with the response vector model, it was suggested that the neuronal coding of the two competing responses shared some neuron populations (see Figure 1c) resulting in the observed response initially containing both target and non-target characteristics. The initially combined response was subsequently corrected on-line as inhibitory processes eventually eliminated the competing response and allowed the target response to emerge.

The response competition hypothesis fits well with the observed ipsilateral effect of the non-target stimulus on movement trajectories. Specifically, due to the necessity of interhemispheric transfer of stimulus information (Berlucchi, Heron, Hyman, Rizzolatti, & Ultima, 1971; Poffenberger, 1912), responses to locations in ipsilateral space are typically organized and completed in less time than those to locations in contralateral space (e.g., Elliott, Roy, Goodman, Carson, Chua, & Maraj, 1993; Fisk & Goodale, 1985). As such, response processes initiated to an ipsilateral non-target stimulus would have a brief "head start" relative to a competing contralateral stimulus. Welsh et al. suggested that the result of this head start was that it took longer for selective inhibition to eliminate the competing response and, thus, more of the non-target response was incorporated into the initial movement trajectory. The result of the non-target response incorporation was that the target movement initially deviated toward the distractor and then was corrected on-line. Overall, these results are in opposition to the notion that a distractor needs only to be perceived to produce aiming movements away from it. Moreover, as it would be difficult to argue that a simultaneously presented non-target stimulus that differed from the target stimulus only in color would not be very salient to the actor, these results are opposite to predictions based on the response vector model (Houghton & Tipper, 1999). That said, the results of the Welsh et al. (1999) study are consistent with the concept of the response vector (Tipper et al., 1997).

To account for these various effects, we propose a <u>response activation</u> model of selective reaching. Because the response activation model has evolved out of the work reviewed above, it also shares many of the basic premises of the response vector model of Tipper, Houghton, and colleagues - most importantly, the automatic initiation of independent response producing processes to action-relevant stimuli that are coded in the motor system by populations of neurons that may overlap. The critical difference between the response vector and the response activation models is that the latter is based on the premise that the direction of the movement trajectory depends on the activation level of each competing response at the moment of response initiation, not solely on the salience of the competing stimulus. Indeed, we predict the opposite effects of salience -

objects of greater action-relevance (salience) will initiate responses that are tougher to inhibit because of a tighter perception-action link. As such, responses to stimuli of greater action-relevance will remain in an active state for a longer period of time, resulting in more of the competing action being incorporated into the initial response, and, in this case, causing deviation towards the non-target location. What we propose to be the important determining factor of initial movement trajectories, under conditions in which obstacle avoidance is not at issue, is the temporal location of inhibitory process intervention on the competing non-target response. If a competing response has been inhibited (activation levels returned to below baseline) prior to movement initiation, then the trajectory should veer away from non-target locations, regardless of whether or not it is a physical obstruction to the target movement. On the other hand, if the non-target response is in an active state (above baseline levels), initial movement trajectories will deviate towards the non-target location. The purpose of the present studies was to test these predictions.

The first experiment was designed to begin testing the response activation model of selective reaching by attempting a replication of Welsh et al. (1999). In the second experiment, a more direct test of the hypothesis was made by varying the onset of the distractor stimulus relative to the target. In short, it was predicted that if distractor onset was much earlier than target onset, movement deviation away from the non-target location would result because selective inhibition would have had sufficient time to inhibit the competing response. Alternatively, it was predicted that distractor onset just prior or simultaneous to target onset would cause deviation towards that location because that competing response would still be active in the motor system at the moment of response initiation. In the final experiment, the notion of the importance of action relevance was tested by combining a predictive precue paradigm with the visual search paradigm.

Experiment 1

The purpose of Experiment 1 was to attempt a replication of the temporal and trajectory effects of Welsh et al. (1999) in a 3D environment. It is important to reproduce the findings of Welsh et al. (1999) because, although the virtual movement space was mapped onto the real moving space of the effector by virtue of a mirror, this mapping may not have been perfect. Therefore, it is possible that the differing temporal and kinematic findings of that study could be the result of translational issues in working from real to virtual space. Indeed Lyons, Elliott, Ricker, Weeks, and Chua (1999) found diminshed and inconsistent temporal interference effects when employing an apparatus and task similar to that of Welsh et al. (1999). Hence, a duplication of the Welsh et al. (1999) findings with 3D movements in a real environment is necessary.

As such, participants were required to make rapid aiming movements with their dominant hand away from the body to one of five possible target locations arranged in a column along the midline. On 80% of the trials, a distractor was also presented in one of the other four locations. As the target locations were light emitting diodes (LEDs), similar to the Welsh et al. (1999) study, no collision was possible with the competing locations.[1] Recorded movement trajectories were then dissected into their component axes and analyzed. If the distracting location need only be <u>perceived</u> for the actor to adopt an object avoidance strategy (Tresilian, 1998), movements made when a distractor was along the path of the movement should be higher and/or veer to the right of the distractor, whereas distractors appearing farther away from the home position than the target should have no effect on the movement. If the response vector model (Houghton & Tipper, 1999; Tipper et al., 1997) is correct, then movements programmed and completed when a distractor is between the home position and the target should be higher and perhaps longer than those to the same target when no distractor was present. Similarly, a distractor beyond the target should cause a lower and shorter overall movement trajectory relative to a condition without a distractor. In contrast, predictions based on the response activation model are that, until target response selection/correction occurs, movement trajectories should contain both target and non-target response components. Therefore, a distractor between the target and the home position should cause a lower, shorter trajectory whereas a distractor beyond the target would result in a higher, longer trajectory. Finally, in contrast to predictions based on the object avoidance hypothesis, no significant left-right deviations would be expected if either the response vector or response activation models are correct.

A secondary purpose of Experiment 1 was to attempt to extend the study of action-based selective attention by examining the "proximity-to-hand" effect. Tipper et al. (1992; see also Meegan & Tipper, 1998) reported that a distractor located closer to the starting location of the hand than the target resulted in longer response times (interference) than a distractor located further from the starting location of the hand than the target (hand-centered frame of reference). An explanation of this finding could be that movements of a shorter amplitude are programmed and completed in less time than movements of a greater amplitude (Fitts & Petersen, 1964). Thus, because of the relatively greater "strength" and speed of the response programming to locations close to the effector, the interference caused by a competing stimulus should be proportional to the signed difference between the distance from the start position to the target and the distance between the start position and the distractor plus a constant (Interference $\propto$ $(D_{distractor} - D_{target}) + A$). For example, if the target is in Location 3 (Figure. 2), then a distractor at Location 1 should cause the greatest amount of interference, followed by a distractor at Location 2, with little or no interference resulting from a distractor at Location 4 or 5. Similarly, a distractor in any location should have little effect on movements to Location 1, whereas movements to Location 5 should be affected by a distracting stimulus in any location with the greatest interference from a distractor in Location 1 and the least from Location 4.

Method

Participants

The participants of this study were 12 men and 12 women (n = 24) naïve volunteers from the McMaster University community. The age of the participants ranged from 19-31 yrs. All reported being right-handed and having normal or corrected-to-normal vision at the time of data collection. Informed consent was obtained prior to data collection and participants were financially compensated for their time.

Apparatus and Task

Participants sat at a table in front of a wooden board (18 cm wide by 67 cm long by 4 cm high) painted black. Embedded in the wood were 5 LEDs (2 cm diameter)

(Dialight, series 557) arranged in a straight line (see Figure 2). The surfaces of the LEDs were not perfectly flush with the surface of the wood (5 mm in height). On any given trial, each LED could be illuminated green or red and served as the potential target/distractor locations. Participants were instructed to begin with the index finger of their dominant hand on the home position (an unpainted 2 cm square section of the board 10 cm in front of the LEDs) and move as quickly as possible to the red location while ignoring the green location, should a green LED be illuminated. Participants were also told that fixation of Location 3 (the center location) would help them to rapidly locate the target location. These instructions were given to attempt to have the participants maintain consistent initial retinal stimulation in order to test the influence of the hand-centered frame of reference (see Tipper et al., 1992). Because there is no reason to believe that the participants were not taking advantage of this strategic suggestion, eye movements were not monitored.

In order to record the trajectory of the hand movement, participants wore a metal ringed guitar pick that had an infrared light emitting diode (IRED) secured to its upper surface. The pick was worn on the index finger of the dominant hand such that the IRED was located over the fingernail. An Optotrak™ recording system recorded the location of the IRED at a rate of 200 Hz or 333 Hz. In addition to wearing the IRED, half the participants wore a pair liquid crystal occlusion goggles (Translucent Technologies, Toronto, ON; Milgram, 1987). The lenses of these goggles can change from an opaque to a transparent state in less than 4 ms and were used to prevent the participant from seeing the movement environment while the target/distractor combination for the next trial was set. The timing of the lens opening and the simultaneous initiation of the recording of the position of the IRED were controlled by a Stoelting (Wood Dale, IL) laboratory controller (Model No. 56100). For those who did not wear goggles, illumination of the target/distractor LEDs was triggered by the experimenter via a Lafayette Millisecond Timer (model 50013). Triggering of the timer not only illuminated the LEDs, but also simultaneously initiated the recording of the IRED.

Procedure

Each participant was tested individually in a single session that lasted approximately 45-60 mins. The experimental session consisted of 5 practice trials and 250 test trials (255 total trials). The 250 test trials were made up of 10 blocks of 25 randomly ordered trials. Each target/distractor combination appeared once within each block. An optional rest period was offered after every 2 blocks (50 trials).

During the experimental session, one half of the participants wore the liquid crystal goggles while the other half wore nothing over their eyes.[2] Two slightly different trial procedures were used for the “Goggles” and “Natural” groups. For the “Goggles” group, a given trial would begin with the lenses in an opaque state and the participant's index finger on the home position. While the lenses were closed, the particular target/distractor combination was set and illuminated. Then a verbal "Ready" cue was given from the experimenter followed by a 1-3 s variable foreperiod. At the end of the foreperiod, the lenses became transparent and remained in this state for 2 s. Participants were instructed to, upon regaining vision of the environment, move their finger to the red target as quickly as possible and remain there until the lenses became opaque again. The participant was then told to return the finger to the home position and await the next

"Ready" cue.

The procedure for the "Natural" group was as follows: The participant initiated the trial by placing the index finger on the home position. The experimenter then set the target/distractor array and gave the same "Ready" cue. At the end of the 1-3 s variable foreperiod, the target/distractor location(s) illuminated. Participants were instructed to move as quickly as possible to the red target location and remain there until the LED(s) were extinguished (2 s from illumination). When the LED(s) were turned off, the participant was to return to the home position and await the next trial.

Data Reduction and Dependent Variables

The raw displacement files were filtered using a second-order dual-pass Butterworth filter with a low-pass cutoff frequency of 10 Hz. The displacement profiles were then differentiated twice using a 2-point central finite difference algorithm to obtain instantaneous velocity and acceleration. All temporal dependent variables were obtained from these profiles using custom software (Chua & Elliott, 1993). Movement initiation was defined as the first sample in which the velocity of the movement in the primary axis of movement (y axis) reached a threshold of 30 mm/s and remained above the threshold for more than 72 ms (15 or 24 consecutive samples). Thus, reaction times were calculated by multiplying the number of samples recorded from the beginning of data recording to movement initiation by the sampling rate. Similarly, movement termination was defined as the first sample in which the movement velocity fell below 30 mm/s and remained there for 72 ms. Hence, total response time was calculated by multiplying the number of frames from the beginning of movement recording (stimulus presentation) to movement termination by the sampling rate. Movement time was calculated by subtracting reaction time from total response time.

To examine the effects of distractor location in the trajectory of the movement, the displacements along each axis of the resultant 3D displacement profiles were analyzed separately using custom-made software. The trajectory variables analyzed were the average displacements in x, y, and z axes. Using the home position as the origin (0, 0, 0), average displacement was calculated by dividing the sum of all the displacement values recorded at each sample from movement initiation to movement termination by the number of samples in that same period. This value provides an indication of the average movement in that axis. Specifically, average displacement in z (average height or AveH) provides an indication of how much, over the course of the whole movement, the finger was attracted or repelled by the competing stimulus in terms of the height of the movement. Similarly, average displacement in the primary axis of movement (AveY) and average left(-)/right(+) displacement (AveX) was also calculated to provide an indication of how the length and sideways deviation of the movement was affected by the presence of a distractor, respectively.

Data Analysis

Prior to analyzing the data, trials on which a recording error (IRED was lost from sight of the cameras) or movement error (participant moved to the wrong location) was committed were removed from the data set. Per participant, recording errors ranged from 0 – 10% of the trials while movement errors ranged from 0 – 2% of the trials. After removing the errorful trials from the set, mean values of each temporal and trajectory dependent variable were calculated and submitted to separate repeated measures ANOVA for each target location (with No Distractor and the four other distractor locations as the different levels). Post hoc analysis of any significant effect involving three or more means was performed using Tukey's HSD ($p < .05$).

Results

Temporal

This analysis was conducted to examine the effects the presence of the distractor had on the temporal measures of the aiming movements. There were no significant effects of distractor location on any of the movements to any of the 5 targets in TT, RT, or MT (see Footnote 2 and Table 1).

Movement Trajectories

A two-step analysis was conducted to examine the affect of the distractor on the trajectories of the aiming movements. First, the trajectories of the movements to the different targets in the No Distractor condition were analyzed to investigate how the movements to each target differed fundamentally. Following this initial analysis, a second comparison was performed to examine how the movement trajectories to each target varied according to the location of the distractor.

In the initial analysis of the AveH of the movements to each target location in the No Distractor condition, it was found that the trajectories were significantly higher with each consecutive target location, F (4, 92) = 72.20, $p < .001$ (see Table 2). Of theoretical interest, significant effects were found in AveH for movements to Target 1, F (4, 92) =

3.56, p < .01, and for movements to Target 3, F (4, 92) = 5.29, p <.001. Congruent with the findings of Welsh et al. (1999), post hoc analysis revealed that the movements made to Target 1 were significantly higher when a distractor was in Location 4 and 5 then when there was no distractor present in the environment (see Figure 3) indicating that the participants were drawn towards the distractor at those locations. Similarly, post hoc analysis of the movements made to Target 3 revealed that movements were lower when the distractor was located in Location 1 or 2 than in Location 4. Further, movements to Target 3 when the distractor was in Location 1 were lower than those made with the distractor in Location 5 (see Figure 4). All other distractor locations were intermediate.

As a result of the similar trends noted in the movements to the other target locations (i.e., 2, 4, and 5), an additional analysis was performed. The data for this analysis were derived by subtracting each participant's mean AveH for the No Distractor condition from each AveH in which a distractor was present in the environment. The values were then placed in one of two pools based on whether the distractor was before or beyond the target location. These mean pooled values were then compared using a t-test. This analysis revealed that movements in which the distractor was Before the target were significantly lower (-.22 mm) than movements in which the distractor was Beyond the target (1.69 mm), t (23) = 3.28, p < .005.

The results of the analysis for AveY were consistent with the results obtained for AveH. Specifically, although a significant effect was only found in the initial analysis for movements to Target 4, F (4, 92) = 2.85, p < .05, a significant overall effect was found when the data were pooled, t (23) = 2.86, p < .01. As was found in AveH, it appears that the participants were drawn towards the distractor because a distractor Before the target caused shorter movements relative to when no distractor was present (-1.11 mm) than when the distractor was Beyond the target (1.83 mm).

Although the results of AveH and AveY indicate that participants were drawn towards the distractor, they may still have been avoiding a perceived object by deviating further to the right when the distractor was between the target and the home position. Such was not the case, however, as none of the individual target analyses or the pooled analysis, t (23) = 1.31, $p > .20$, approached conventional levels of significance for AveX.

Discussion

Overall, the finding that the presence of the distractor caused the hand to deviate towards it replicate those of Welsh et al. (1999) and support the response activation model of selective reaching. As described above, we suggest that the deviation of the movement trajectory towards the distractor is the result of independent response processes (Coles et al, 1985; McGarry & Franks, 1997) being represented and programmed in overlapping areas of the motor cortex. The result of the shared neuron pools is that the initial response (in this case indexed by the movement trajectory) contained both target and non-target response components.

Although this pattern of trajectory change is indicative of both target and non-target response characteristics being incorporated into the initially executed response (i.e., there was co-activation of both responses), it may be that the emphasis placed on the speed of the movement in the instructions caused the participants to adopt a strategy in which they trade-off speed for accuracy. This suggestion is consistent with the lack of distractor interference in the temporal measures (cf., Meegan & Tipper, 1998; Tipper et al., 1992). For example, it is possible that the participants chose to move based on the first detected difference in the environment, initially to a location central to the two stimuli, and then correct the movement on-line. Although there is no direct evidence from Experiment 1 that would discount this argument, we suggest that this is unlikely. Evidence from other studies suggests early coactivation of independent responses. For example, the finding in the Welsh et al. (1999) study that distractors ipsilateral to the target had the larger interference effect is difficult to explain via a simple speed/accuracy trade-off (i.e., if people were trading speed for accuracy, then the size of the deviations should not have been dependent on the spatial location of the distractor). Moreover, to preview, the pattern of results from Experiment 2 indicate that the deviations towards the non-target location in the present study are the result of independently initiated response processes to both the target and non-target stimuli.

Regarding the secondary purpose of Experiment 1, it is interesting to note that there was no evidence of the hand-centered frame of reference (Meegan & Tipper, 1998; Tipper et al., 1992). That is, the interference effects on the movement trajectory were observed regardless of whether the distractor was before or beyond the target location. It must be pointed out, however, that in the present study the hand-centered and retinal-centered maps overlapped and, thus, are confounded.[3] To elucidate, in the hand-centered frame of reference of Tipper and colleagues, a stimulus closer to the starting position of the hand than another will be more salient to the actor and thus initiate response producing processes of greater relative "strength" than the other stimulus. Hence, a distractor located along the path of the movement (which is by definition closer to the starting location than the target) will cause greater interference than a distractor beyond the path of the movement. In contrast, according to the 2D retinal-centered frame of reference (i.e., Eriksen & Eriksen, 1974), the projection of a non-target stimulus on the retina that is closer to the projection of the target will cause a larger interference effect than one farther from the target. Because of the angle at which the participants were viewing the board, distractors beyond the target location would be closer to the target than their counterpart on the other side of the target (e.g., if the target appeared at Location 3, then a distractor in Location 4 would project to a location on the retina that would be closer to the projection of the target than the projection of a distractor in Location 2). Thus, in the present study, a distractor closer to the starting location of the hand may have been more salient in the hand-centered frame of reference, but a distractor beyond the target would be more salient in the retinal-centered frame of reference (but see Tipper, et al., 1992, Experiment 1). Because there is evidence that movements might be organized using several different frames of reference simultaneously (Bekkering & Pratt, 2001), the confounding of hand- and retinal-centered frames of reference did not allow as fine-grain an analysis of the hand-centered frame as hoped. However, it appears that participants were utilizing both hand- and retinal-centered frames of reference to plan their movements. This finding is congruent with recent work by suggesting that movement planning can be based on both spatial and object-centered (i.e., multiple) coordinate systems.

On a final note, the finding that participants were drawn towards the distractor is inconsistent with the suggestion that a non-target stimulus need only be perceived for the actor to adopt an avoidance strategy (Tresilian, 1998). Indeed it is hard to argue that people did not perceive the non-target stimulus, otherwise the presence of the non-target stimulus would not have caused a deviation in the movement. Again, this is not to suggest that people do not avoid objects, but that an avoidance strategy will be adopted only when the actor judges the non-target object as a potential hazard. It must be acknowledged here that the second type of object avoidance (veering away from a location in order to keep it in view) was not likely at issue in the present study as the non-target stimulus did not contain important movement information (i.e., it was not a cue (Howard & Tipper, 1997)). Thus, the results of the present study generated no evidence in support of or against this aspect of the object avoidance hypothesis.

Experiment 2

In sum, the results of Experiment 1 replicate those of Welsh et al. (1999) and are in opposition to those of Tipper and colleagues who have reported deviations away from the non-target stimulus (e.g., Howard & Tipper, 1997). To reconcile these conflicting results, we have proposed that the observed trajectory changes in selective reaching movements are the result of the interaction between competing responses programmed in parallel and the temporal location of the inhibition of the competing response relative to movement initiation. Specifically, it is suggested that if a response is inhibited prior to movement initiation, the resulting movement trajectory will deviate away from the competing location. In contrast, if inhibitory processes are not complete before the competing response reaches the threshold of activation, the resulting movement trajectory will initially deviate towards the non-target location. The purpose of Experiment 2 was to test these predictions by varying the temporal onset of the competing, non-target stimulus relative to onset of the target stimulus (stimulus onset asynchrony or SOA).

As in Experiment 1, participants were required to move as quickly as possible to the target (red) LED while ignoring the distractor (green) LED should one appear. Unlike Experiment 1, however, the illumination of the target could occur at five different SOAs. SOA was calculated by subtracting the time of target stimulus onset from the time of non-target stimulus onset. Hence, a negative SOA refers to a situation in which the non-target stimulus appeared before the target stimulus, whereas a positive SOA refers to a situation in which the target appeared first. The five SOAs were: -750 ms, -250 ms, 0 ms, +250 ms, and +550 ms.

The -750 ms SOA was chosen because researchers investigating the inhibition of return phenomenon have demonstrated that minimum cue-target SOAs of 200-300 ms are required to establish this type of inhibitory field (see Klein, 2000 for a review). However, Howard, Lupianez, and Tipper (1999) investigated trajectory effects using an inhibition of return paradigm and found that, although RT was significantly longer after a cue-target SOA of 600 ms, there were no significant deviations in the movement trajectory at this SOA. Thus, it was hypothesized that a 750 ms SOA may provide sufficient time for inhibitory processes to affect the competing response and a movement trajectory away from the competing location would occur. The -250 ms SOA was chosen based on similar logic. That is, because of the time required to establish inhibition against a response, it was predicted that this SOA would allow for partial inhibition of the competing response or even perhaps return the activation levels to baseline. However, Howard et al. (1999) found that movements following invalid cues at a cue-target SOA of 200 ms caused movements to deviate towards the location of the cue. As such, marginal or no trajectory effects were expected in this condition. The 0 ms, or simultaneous, SOA condition was included to attempt a further replication of Welsh et al. (1999). As such, it was predicted that movement trajectories following the simultaneous presentation of the target and distractor stimuli would result in deviation towards the non-target stimulus.

Similar to the contrasts made in Experiment 1, predictions based on the response vector model (Howard & Tipper, 1997) would be that deviation away from the distractor should result in the 0 ms SOA condition. Predictions of trajectory deviations in the –750 and –250 ms SOA conditions based on the response vector model are more difficult to formulate because it does not take into account the temporal aspects of response inhibition. It may be proposed that, because the non-target stimulus appears before the target, its salience will decrease and thus deviation towards the distractor should occur; an effect that should be exaggerated in the –750 ms SOA condition.

The two positive SOAs were chosen to investigate whether a distracting stimulus presented on-line could affect the movement trajectory. Specifically, the +250 ms SOA was chosen because this would place the distractor onset right at or near the end of the RT period (based on the average RTs of Experiment 1). Thus, if the response processes were indeed in a race for activation and the response, once initiated, is completed without regard to changes in the environment, then the "head start" of the target response process should allow this movement to be completed without contamination from the non-target response. However, if response planning/execution is a continuous process, then the appearance of the non-target stimulus near the end of the RT period may result in the non-target response catching-up near the end of movement completion and, thus, interfere with the termination of the movement. Finally, the 550 ms SOA was chosen because the average RT in Experiment 1 ranged from 296-320 ms and average TTs from

585-829 ms. Thus, a 550 ms SOA was chosen because distractor onset would follow movement initiation, but occur, on average, before movement termination. Thus, if the appearance of a competing stimulus can affect on-line corrective processes we might still see effects at this SOA. In this way, it could be determined whether the appearance of a distracting stimulus affects on-line control of the movement. As for the –750 and –250 ms SOA conditions, there is uncertainty as to what predictions based on the response vector model would be for movements in the positive SOA conditions. Given that a main tenet of both models is the automatic initiation of response-producing processes to action-relevant stimuli, it is likely that predictions based on the response vector model would be an absence of trajectory effects in the 250 and 550 ms SOA conditions.

In order to investigate whether the above predictions would also be apparent in markers of movement planning, kinematic measures were also analyzed. For background, aiming movements, such as those involved in the present study, are usually composed of two distinct phases - a primary movement and one or more corrective submovements (Woodworth, 1899; see also Elliott, Helsen, & Chua, 2001 for a recent review). The primary, or "get there", movement is characterized by a ballistic acceleration and an inverted-U shaped velocity profile and is believed to represent the programmed portion of the movement. The kinematic markers of peak acceleration (PA) and peak velocity (PV) are thought to reflect the programming of the initial muscular impulses designed to get the limb into the vicinity of the target. The secondary corrective, or "homing-in", submovements begin later in the movement. They are characterized by discontinuities in velocity and acceleration that are believed to reflect the online use of afferent feedback to enable the accurate termination of the movement.

The corrective phase of the movement usually occurs between peak deceleration and the end of the movement. Given the assumptions of what PA and PV signify, these kinematic measures were analyzed to investigate whether the characteristics of the competing response are also resonated in these markers of response programming.

Method

Participants

Thirteen volunteers (6 men and 7 women aged 21-28 yrs) from the McMaster University community took part in this study. None of these participants were involved in Experiment 1. All participants were: 1) naïve to the purpose of the study; 2) right-hand dominant; 3) had normal or corrected-to-normal vision at the time of data collection; and, 4) financially compensated for their time. Data from one participant was removed due to excessive recording errors.

Apparatus

In general, the apparatus employed in Experiment 2 was identical to that of Experiment 1. There are three important exceptions. The first was that, in order to decrease the number of trials and the overall time taken to collect the data, two of the LEDs (Location 2 and 4) were covered with black tape. Thus, there were only three, not five, possible target/distractor locations in Experiment 2. Secondly, the onset of the target/distractor LEDs were now controlled by a four-bank timer (Lafayette Instrument Co.: Model # 52010) such that each LED could be illuminated independently. The timer was also linked to the Optotrak™ movement recording system via an external computer

(PEX System with AMD K6 2 processor). The timer, LEDs, external computer, and Optotrak™ were interfaced such that the illumination of the target (red) LED was simultaneous to the initiation of movement recording for that trial. Finally, because the results of Experiment 1 showed that there were no differences between the Goggles and Natural protocols, only the Natural protocol was used. Thus, the liquid crystal goggles were not used in Experiment 2 (or in Experiment 3).

Procedure

Data collection took place over 2 sessions that lasted 45 – 60 min each. Whereas three participants chose to complete both sessions in the same day, the other 10 completed the study over two days, separated by no more than four days. Prior to the first collection session, participants were screened (via self-report) for visual ability and handedness, using an adaptation of Bryden's (1977) handedness questionnaire. Upon arrival at each experimental session, an explanation of the task was given. Participants were instructed to begin each trial by placing the index finger of their dominant hand on the home position. Once on the home position, a verbal "Ready" cue would be given from the experimenter. Following the "Ready" cue was a random foreperiod of 1-3 s that ended with the illumination of the target and/or distractor LED(s). Participants were instructed to move as quickly as possible to the target (red) location while ignoring the competing (green) location. Instructions were specific about moving only when the target location illuminated.

Subsequent to the explanation of task requirements, participants completed 10 (first session) or 5 (second session) familiarization trials consisting of randomly chosen experimental trials followed by 165 experimental trials. Participants completed the experimental trials over 5 blocks of 33 trials during each session (345 total trials: 15 familiarization and 330 experimental). At the end of each block, participants were given the opportunity to have a break. Each block of 33 trials consisted of 1 trial of each of the 33 experimental conditions (3 Target Locations (1,2,3) X 2 Distractor Conditions (where the distractor was in one of the other positions) X 5 SOA (-750 ms, -250 ms, 0 ms, 250 ms, 500 ms) plus 3 no distractor trials (one for each target location)).

Ten random orders of the 33 trials were constructed. Trials were randomized with the constraint that no target or distractor location or SOA could be performed more than three times in a row. Participants completed one block of each of the ten random orders. These blocks were ordered differently for each participant.

Data Reduction and Analysis

Movement trajectories were recorded by the Optotrak™ system at a frequency of 500 Hz. The recorded displacement profiles were filtered with a dual-pass Butterworth filter with a low-pass cut-off at 12 Hz and then differentiated twice, using a two-point central difference algorithm, to obtain instantaneous velocity and acceleration. Custom-made software (Chua & Elliott, 1993) was used to obtain the performance measures of RT, MT, and TT, and the kinematic measures of peak velocity (PV) and peak acceleration (PA) in the primary axis of movement (y axis). The trajectory measures of AveH, AveY, and AveX were calculated from the displacement profiles using a separate program.

As in Experiment 1, all trials on which recording errors (<1 – 10% per participant) occurred were eliminated from the data set. Trials on which the movement was initiated to the distractor LED in the –750 and –250 ms conditions, had a lower RT than 100 ms, or was completed to the distractor location were classified as movement errors and were also removed from the analysis (0 – 2% of total trials per participant). Mean values for each dependant variable were calculated and then submitted to three separate analyses. The initial analysis was a one-way repeated measures ANOVA that compared the mean values of the dependent variable for movements to each of the three targets in the No Distractor condition. This analysis was performed to assess whether or not there were discernable differences between the movement planning and execution phases to each target. In the second analysis, difference scores for movements to each target for each dependent variable (each mean No Distractor value subtracted from the mean Distractor value) were calculated and submitted to a 5 SOA (-750, -250, 0, 250, 550) X 2 Distractor Location repeated-measures ANOVA. This second analysis examined the effects of the distractor on movement planning and execution for movements to each individual target. Finally, the difference scores for each dependent variable were pooled according to the spatial location of the distractor relative to the target (Before, Beyond). These difference scores were then submitted to a 5 SOA by 2 Distractor Location repeated measures ANOVA. Post hoc testing of all effects involving more than 2 means was conducted using Tukey's HSD ($p < .05$).

Results

Temporal

This series of analyses were conducted to examine the effects the presence of the distractor had on the temporal measures of the aiming movements.

Total Time. The initial analysis on the movements completed to each target in the No Distractor condition revealed a significant effect for TT, $\underline{F}$ (2, 22) = 90.64, $\underline{p} < .001$. It was found that TTs to Target 1 were shorter than to Target 2, which were in turn shorter than TTs to Target 3 (Table 3). This effect of amplitude on TT was not surprising (Fitts & Peterson, 1964).

Unlike in Experiment 1, the presence of a distractor significantly affected movements to each target. However, the analysis of the difference scores revealed that the presence of a distractor actually shortened TTs in certain SOA conditions. There were main effects for SOA in movements to Target 1, $\underline{F}$ (4, 44) = 9.35, $\underline{p} < .001$, Target 2, $\underline{F}$ (4, 44) = 5.22, $\underline{p} < .005$, Target 3, $\underline{F}$ (4, 44) = 12.03, $\underline{p} < .001$, and in the pooled analysis, $\underline{F}$ (4, 44) = 15.40, $\underline{p} < .001$. Post hoc analysis of these effects revealed that in all cases, -750 ms and -250 ms SOAs were associated with shorter TTs than the 0 ms, 250 ms, and 550 ms SOAs. The only exception was for movements to Target 2 at the 0 ms SOA in which TTs were not different from any other TT.

In addition to the effects for SOA, there was a significant main effect for Distractor Location for movements to Target 2, $\underline{F}$ (1, 11) = 7.43, $\underline{p} < .05$, and significant interactions between SOA and Distractor Location for movements to Target 1, $\underline{F}$ (4, 44) = 2.77, $\underline{p} < .05$, and Target 3, $\underline{F}$ (4, 44) = 3.70, $\underline{p} < .05$. Post hoc analysis of these effects and interactions revealed no consistent pattern. Specifically, for movements to Target 2, a distractor in Location 1 caused a greater facilitation effect than when the distractor was in Location 3. For movements to Target 3, a distractor in Location 1 also had a greater facilitation effect than a distractor in Location 2, but only in the –750 ms SOA condition. In contrast, for movements to Target 1, a distractor in Location 3 had a greater facilitation effect than a distractor in Location 2, but again, only in the –750 ms condition. Thus, although it seems that a hand-centered reference frame is being used for movements to Targets 2 and 3, a retinal frame seems to be employed for movements to Target 1 (assuming participants were fixating centrally (Location 2) prior to stimuli presentation). No such effects or interactions involving Location were present in the pooled analysis; likely the result of the above Target-based effects counteracting each other.

Reaction Time. The initial analysis of RTs of the movements completed to each target in the No Distractor condition revealed a significant effect, F (2, 22) = 11.46, p < .001. RTs were found to be longer when the participant was required to move to Target 3 than to Targets 1 and 2, which were equivalent.

It was also found that the presence of a distractor significantly affected movement planning to each target. Consistent with the effects for TT, the analysis of the difference scores revealed that the presence of a distractor actually shortened RTs in certain SOA conditions. Specifically, there were significant main effects for SOA at each target location: Target 1, F (4, 44) = 10.14, p < .001; Target 2, F (4, 44) = 8.25, p < .001; and, Target 3, F (4, 44) = 15.71, p < .001. Post hoc analysis of these effects revealed that in all cases, -750 ms and -250 ms SOAs were associated with shorter RTs than the 250 ms and 550 ms SOAs. In addition, movements to Target 1 and 3 in the -750 ms and -250 ms SOA conditions also had shorter RTs than movements in the 0 ms SOA. For movements to Target 3, there was also a main effect for Distractor Location, F (4, 44) = 4.92, p < .05, and an interaction between SOA and Distractor Location, F (4, 44) = 4.07, p < .01. Post hoc analysis of the interaction indicated that a distractor in Location 1 had a greater facilitation effect than a distractor in Location 2, but only in the –750 ms SOA.

Results of the final analysis, in which the data were collapsed across target, are consistent with the findings for each target. Post hoc analysis of the significant main effect for SOA, F (4, 44) = 18.41, p < .001, revealed that conditions in which the distractor was presented prior to the target had shorter movement planning times than any of the other SOAs. No other effect approached conventional levels of significance.

Movement Time. Not surprisingly, the analysis of the movements to the targets revealed that MT increased with each increase in the distance the participant had to move, F (2, 22) = 156.48, p < .001. Again, this is consistent with previous work on the effects of movement amplitude on MT.

The presence of a distractor did not have a reliable effect on MT. Indeed, the only significant effect in MT was a main effect for Distractor Location in the analysis for the movements to Target 2, F (1, 11) = 8.09, p < .05. When participants were moving to Target 2, participants had longer MTs when the distractor was in Location 3 than when it was located in Location 1. Pooling the data did not strengthen the effects of the distractor.

Summary. The results of the analysis for the temporal measures of movement indicate that the presence of the distractor facilitated the initiation of the movement, but did not affect the execution time of the movement itself. Interestingly, the movement planning facilitation effect only occurred when the distractor was presented prior to the target. The facilitation effect could have resulted for two reasons. First, participants may have been using the onset of the distractor stimulus as a cue to anticipate target onset. Second, the appearance of the distractor stimulus could have automatically initiated response-producing processes, bringing the participant closer to the threshold of response initiation (i.e., priming the movement circuitry). Thus, when the target appeared soon after, the already active motor system incorporated the extra stimulation to surpass the threshold and the response emerged. Although both accounts are viable, the fact that there was variability in the onset of the distractor before the target (i.e., -750 ms or –250 ms SOAs were presented randomly) could be used to argue against the "anticipatory cue" explanation of the facilitation effect. In addition, the analysis of the Kinematic and Trajectory data will help to distinguish between the two explanations. For example, if participants were using the distractor as an anticipatory cue to preplan their movements to one of the other two locations, then there should be no differences between the characteristics of the movements completed in the -750 and -250 ms SOA conditions. However, if this decrease in RT is the result of the initiation of response producing processes that bring the participant closer to the threshold of action, then the movement kinematics and trajectories should have some portion of the competing response incorporated into it.

Kinematic

This series of analyses were conducted to examine the effects the presence of the distractor had on the kinematic measures of the aiming movements. Changes in these measures as a function of the location of the distractor could provide indications of the integration of characteristics of the non-target response into the plans prepared for the target response.

Peak Acceleration. It was anticipated that both PA and PV would be higher in movements of greater amplitude. These expectations were confirmed as post hoc analysis of the effect of Movement Distance, F (2, 22) = 38.87, p < .001, indicated that PA was higher with each increase in movement amplitude (Table 4).

It was also found that the PAs of the movements were affected by the presence of a distracting stimulus. Consistent with the response activation model, the effect of a distractor was dependent on SOA and Distractor Location. For movements to Target 1, there was a main effect for SOA, F (4, 44) = 6.61, p < .001. Post hoc analysis of this effect revealed that PAs were lowest in the –750 ms, +250 ms, and +550 ms SOAs and highest in the –250 ms SOA. The PA for movements in the 0 ms SOA was found to be intermediate. It was higher than the PA for –750 ms SOA, but not different from the rest. The analysis for the movements to Target 2 revealed an interaction between SOA and Distractor Location, F (4, 44) = 11.30, p < .001. This interaction resulted from the participants achieving lowest PAs when the distractor was in Location 3 in the –750 ms SOA condition only. All others were equivalent. No significant effects were found for PAs for movements to Target 3.

Importantly, when the data were collapsed across target locations, there was a main effect for SOA, F (4, 44) = 3.11, $p < .05$, and an interaction between SOA and Distractor Location, F (4, 44) = 7.91, $p < .001$. Post hoc analysis of the interaction for PA revealed a reversal in the effects of a distractor on PA in the –750 ms SOA, and –250 ms and 0 ms SOA conditions. Specifically, PAs were higher when the distractor was Before the target than when the distractor was Beyond the target in the –750 ms SOA, whereas PAs were higher when the distractor was Beyond the target than when it was Before the target in the –250 ms SOA. Similar to the effect for movements in the –250 ms SOA condition, there was a non-significant trend for movements in the 0 ms SOA to have higher PAs when the distractor was Beyond the target.

Peak Velocity. Parallel to the findings for PA, there was a higher PV with each increase in movement amplitude, F (4, 44) = 308.17, $p < .001$. The PV of the movements was also affected by the presence of the distracting stimulus. The direction of these effects, again, depended on the location of the target and distractor, as well as the SOA. For movements to Target 1, post hoc analysis of the main effect for SOA, F (1, 11) = 11.49, $p < .001$, revealed that PVs to Target 1 were lowest in the –750 ms condition and highest in the –250 ms condition. PVs in the 0 ms SOA were also higher than in the –750 ms condition, but all other conditions were intermediate. For movements to Target 2, PVs depended not only on the SOA, but the Location of the distractor. Post hoc analysis of the interaction between SOA and Distractor Location, F (4, 44) = 2.85, $p < .05$, revealed that movements to Target 2 had higher PVs when the distractor was in Location 1 than when the distractor was in Location 3, but only in the –750 ms SOA condition.

Although there were no other significant differences, a trend in the direction opposite to that for the –750 ms SOA condition was found in the 0 ms SOA condition. An effect of Distractor Location that was found in movements to Target 3, F (1, 11) = 16.53, p < .005, indicating that movements had a lower PV when the distractor was in Location 1 than when the distractor was in Location 2. The interaction was not significant.

When the data were collapsed across Target, the analysis revealed only a significant interaction between SOA and Distractor Location, F (4, 44) = 6.52, p < .001. PVs were found to be higher when the distractor was Beyond the target location than when the distractor was Before the target in both the –250 ms and 0 ms SOA conditions (see Figure 5). While not reaching conventional levels of significance, there was a trend in the opposite direction (PVs lower the distractor was Beyond the target than when the distractor was before the target) in the –750ms SOA condition.

Summary. The results of the analysis of the movement kinematics suggest that participants were not simply using the onset of the distractor as an anticipatory cue. Rather, it seems that the shorter movement initiation times are indicative of the priming of the motor system by the illumination of the distractor stimulus. This conclusion is reached because of the reversal of the effects for two negative SOAs and the 0 ms SOA. To begin with, the initial analysis of the movements to each target in the no distractor condition revealed that movements had higher values of PA and PV (both of which are markers of programmed response parameters) as the movement extent increased. Consistent with the notion of a "combined response" when the competing response is still active, PAs and PVs were higher when the distractor was farther from the home position than when the distractor was closer to the home position than the target in the –250 ms and 0 ms SOA conditions. Further support for the model of response activation comes from the findings that the pattern of PA and PV was reversed in the –750 ms SOA condition. That is, in general, PAs and PVs for movements when the distractor was located Beyond the target location were lower than when the distractor was Before the target. This reversal of effects in the -750 ms condition is likely the result of participants being able to inhibit the competing response. Thus, they were repelled from that location. Further evidence for this interpretation is provided by our analysis of the spatial trajectories

Movement Trajectory

This series of analyses were conducted to examine the effects the presence of the distractor had on the trajectories of aiming movements. As with the kinematic analyses, changes in the movement trajectories in the presence of the distractor could provide indications of the integration of characteristics of the non-target response into the plans prepared for the target response.

AveH. Consistent with the results of Experiment 1, the AveH of the movements increased with each increase in distance moved, $F\ (2, 22) = 82.75$, $p < .001$ (see Table 5). For the movements to the individual targets in the presence of the distractor, the analysis for movements to Target 1 did not reveal any significant effects. For movements to Target 2, there was a significant main effect for Distractor Location, $F\ (1, 11) = 11.53$, p

< .01, and an interaction between SOA and Distractor Location, F (4, 44) = 3.00, p < .05. Post hoc analysis of the interaction revealed that movements made to Target 2 when the distractor was in Location 1 were higher than those when the distractor was in Location 3, but only in the –750 ms SOA condition. All other conditions were equivalent. There was also a significant main effect for SOA for movements to Target 3, F (4, 44) = 12.90, p < .001. Consistent with idea of shared movement characteristics, post hoc analysis revealed that movements were lower in the –250 ms than in all other conditions. Interestingly, although movements in the –750 ms were higher than those in the –250 ms condition, they were lower than movements in the 0 ms and 550 ms SOA conditions.

The pooled analysis revealed a main effect for SOA, F (4, 44) = 9.07, p < .001, and an interaction between SOA and Distractor Location, F (4, 44) = 4.20, p < .01. Consistent with the suggestion that there is a combined response in the –250 ms SOA condition, responses were lower when the distractor was Before the target than Beyond the target. Surprisingly, there was no distractor-location dependent difference in the average height of the movements in both the –750 ms and 0 ms SOA conditions. There was, however, a reliable difference in the AveH for movements in the 250 ms condition. This effect was in the same direction as the effect for –250 ms SOA in that a distractor Before the target caused lower movements than a distractor Beyond the target.

AveY. Because movements were completed to targets at different distances from the home position, it was not surprising that the initial analysis of the AveY for each target location in the no distractor condition was greater for Target 3 than for Target 2, which was in turn greater than for Target 1, F (4, 44) = 951.92, p < .001.

As found in the analyses of the temporal and kinematic measures, the effects of the distractor on movement trajectories depended upon target and distractor location and SOA. For movements to Target 1, there was a significant main effect for SOA, F (4, 44) = 2.76, $p < .05$. Consistent with the notion that people deviated away/are repelled from an inhibited location, post hoc analysis revealed that movements were shorter in the –750 ms SOA condition than those in the 0 ms SOA. No other conditions were different from each other. Similarly, post hoc analysis of the significant SOA by Distractor Location interaction for movements to Target 2, F (4, 44) = 3.84, $p < .01$, indicated that when participants were moving to Target 2, movements veered away from the distractor when it was presented –750 ms prior to target presentation, but veered towards the distractor in –250 ms, 0 ms, 250 ms SOA conditions.

The timing of the appearance of the distractor also affected movements to Target 3 as revealed in a main effect for SOA, F (4, 44) = 4.81, $p < .005$. This effect did not follow the trend of the movements to Target 1 and 2. Specifically, movements to Target 3 were shorter during the -250 ms SOA than during both the 0 ms SOA and the +550 ms SOA, with all other conditions being intermediate. Although the finding of the movements in the -250 ms condition being shorter than those in the +550 ms SOA (with a trend in the same direction for movements in the –750 ms SOA) is consistent with the results of the temporal and kinematic data, the finding that -250 ms SOA movements are also shorter than the 0 ms is difficult to explain.

The analysis for the pooled data was consistent with the model of response activation and the findings of the movements to the individual targets. Specifically, there was a significant main effect for SOA, F (4, 44) = 4.96, $p < .005$, and an interaction between SOA and Distractor Location, F (4, 44) = 6.64, p < .001 (see Figure 6). Inline with the notion that by -750 ms, participants had inhibited their responses to the non-target location whereas in the -250 ms SOA condition the competing response is still active, there was a reversal in the direction of the movement effects. At -750 ms SOA, the movements veered away from the distractors, whereas in the -250 ms SOA, movements deviated towards the distractor. Interestingly, movements also deviated away from the distractor in the 550 ms SOA.

Average Left-Right Displacement. The initial analysis revealed no AveX differences between movements to each target when no distractor was present, F (2, 22) = 1.30, p < .3. There were also no significant differences between movements to Target 1, 2 or 3 when the distractor was present. In the pooled analysis, there was only a main effect for SOA, F (4, 44) = 3.05, p < .05. Post hoc analysis of this effect indicated that movements made in the –250 ms SOA veered to the left, whereas movements in the –750 ms and 550 ms SOA conditions deviated to the right. All other SOA conditions were intermediate.

Summary. The results of the trajectory analysis indicate that participants were repelled from the distractor when it was presented 750 ms prior to the target, whereas they were drawn towards the distractor when the distractor was presented 250 ms prior to or simultaneously with the target. That is, movement trajectories in the –750 ms SOA condition were longer and higher when the response to the distractor elicited a shorter, lower trajectory and were shorter and lower when the competing response elicited a longer and higher trajectory than the target response. In contrast, movement trajectories in the –250 ms SOA condition, and less consistently in the 0 ms SOA condition, were shorter and lower when the competing response was shorter and lower and, longer and higher when the competing response was longer and higher than the target response.

Discussion

The results indicate that when participants had enough time to inhibit the competing response (-750 ms SOA condition), this inhibition resulted in a movement trajectory that deviated away from the distractor location. Moreover, when the time between distractor and target onset was insufficient to allow the participant to inhibit the non-target response (during the 0 ms condition), the programmed response contained characteristics of both responses resulting in a movement that deviated towards the non-target location. An unexpected result was that people also deviated towards the non-target location in the -250 ms SOA (see also Howard et al., 1999). In fact, the deviations in the -250 ms SOA condition were more consistent than in the 0 ms SOA condition. Finally, it was found that a distractor presented after target presentation did not reliably affect the goal-directed movement.

Although only tentative predictions were made based on the response vector model, these results are not consistent with these predictions. This is especially true for the pattern of results found in the –750 and 0 ms SOA conditions where it was forwarded that deviations toward and away from the distractor would be found, respectively. In fact, the opposite was found.

On the contrary, the overall pattern of results found in Experiment 2 is congruent with the response activation model. Specifically, the set of findings from Experiment 2 seem to indicate that the sudden presentation of the action-relevant distractor stimulus automatically initiates response-producing processes for a movement to that stimulus. These processes bring the actor closer to a threshold of activation. If the response to the distracting stimulus is inhibited prior to movement initiation, then activity of the neurons in the movement system coding for that movement is reduced to below baseline levels resulting in a movement that deviates away from the location of the distractor (Figure 1d). However, if the competing response is not inhibited, then the response-producing processes activated by the subsequent presentation of the target stimulus quickly push the overall activation level beyond threshold and the response is initiated. The finding of a shorter RT in the -250 ms SOA condition supports this notion. In addition, because the competing response is active at the moment of movement initiation in this condition, the initial movement contains characteristics of both responses and the movement deviates towards the distractor location. Lastly, the finding that distractor presentation after target presentation did not affect movement planning and execution is consistent with the notion of independent response processes racing for activation. Similar to the lack of an interference effect of distractors in contralateral space found in Welsh et al. (1999), this latter finding leads to the conclusion that the non-target response was unable to interfere with the programming of the target response. This is likely due to the target response having a large head start on the competing response. Thus, it seems that under these movement conditions, once the target movement was selected or has emerged, it was not affected by a competing response.

An issue remaining from Experiment 1 was whether the deviations towards the non-target location was the result of participants adopting a speed-accuracy trade-off strategy in which they would react as quickly as possible to the presentation of the stimuli and initially plan the movement to a central point. As in Experiment 1, the presence of a distractor did not increase TT, RT, or MT, but did affect movement trajectories when the target and distractor was presented simultaneously. These effects were replicated despite the fact that participants were specifically instructed to begin their movements only upon the illumination of the target LED. Further, it was found that distractor presentation actually decreased response-programming times when it was presented prior to the target relative to the no distractor condition and the conditions in which the distractor appeared simultaneous to or after target presentation. Because movement trajectories were affected in a manner similar to Experiment 1 while the instructions and conditions of the Experiment 2 necessitated identification of the target location for movement initiation, it seems that the findings of Experiment 1 were not the result of the participants adopting a specific speed-accuracy trade-off strategy.

Experiment 3

Although the effects of simultaneously presented stimuli on movement planning and execution have been investigated (e.g., Tipper et al., 1992; Welsh et al., 1999), when reaching to objects in typical daily interactions within a cluttered environment, the actor often has the target object/movement selected prior to searching the environment and moving to that location. For example, when reaching for a pint of beer placed on the table just moments before, the performer organizes the movement based on the remembered location of the glass. As a result, competing non-target objects on the table (e.g., salt shaker, a different glass) do not interfere the movement (other than perhaps obstacle avoidance). However, if someone moves the glass from where it was placed and replaces it with a different glass, a rapid readjustment to the movement plan is required (i.e., the glass must be relocated and then a new movement must be planned to obtain it). Experiment 3 was designed to extend the exploration of the effects of response competition on movement by artificially creating situations such as the one described above. From a theoretical point of view, Experiment 3 was designed to examine how predictive precue information affects movements to targets in the presence of competing stimuli.

Throughout Experiment 3, the participant was precued to a particular location and then had to complete a movement as fast as possible to the subsequent presentation of the target at that cued location or at one of the two uncued locations. As in Experiments 1 and 2, the target was often accompanied by a competing non-target stimulus that was to be ignored. In total, there were four types of movement condition: 1) Valid-Target Alone - the target appeared in the cued location without the presence of a competing stimulus in the environment; 2) Valid-Competitive - the target appeared in the cued location with a simultaneously presented competing stimulus at one of the other two locations; 3) Invalid-Target Alone – the target appeared in one of the other two non-cued locations without the presence of a competing stimulus in the environment; and, 4) Invalid-Competitive – the target appeared in one of the uncued locations with a competing stimulus in the cued location. Based on the tenets of the response activation model, specific predictions were made about how movement planning and execution would be affected by each of the conditions. These predictions were also based on the assumption that the participants would be using the predictive advanced information to preprogram their movements (e.g., Rosenbaum, 1980) and that the preprogramming of the movements would be represented in the motor system as an increase in the activity of the neurons coding for that response. The increase in activity of these neurons would be above baseline, but below the level necessary for response initiation (threshold).

The first prediction was that there would be a temporal cost associated with an invalid precue. This temporal cost would be the result of the reprogramming of the target response. Further, because the participant was partially preprogramming the wrong response, hence the activity of the neurons coding for that response would be above baseline, it was predicted that an invalid cue would be associated with a movement trajectory that veered toward the cued location. The second prediction was that when the target location was validly cued, the movement to the target location would be unaffected by the presence of a distractor. This result was predicted because, if the participant was using the advance information, the response to the valid location would be preprogrammed. As such, similar to the + 250 and +550 ms SOA conditions in Experiment 2, the target response would have a head start on the competing response and thus emerge uncorrupted.

The final prediction was that distractor interference would be observed in the condition in which the distractor is presented in the cued location and the target is presented elsewhere (Invalid-Competitive condition). This prediction is again based on the assumption that the participants preprogram their responses to the cued location. Thus, the sudden appearance of the distractor in the precued location was expected to further increase the activity of the neuron populations coding for that response. As such, more time would be required to inhibit that now non-target response. Thus, it was predicted that the non-target movement characteristics would be incorporated into the initial movement towards the target location resulting in deviation towards the non-target location. It should be noted here that, although there would likely be little difference between the predictions based on the two models for the effects of the precue in the non-competitive conditions, this final prediction is in opposition to what would be predicted based on the response vector model (Tipper et al., 1999). Given that predictive precue information should increase the salience of a response to a particular location, then the salience of that precued location should be greater than any other location. If, according to the response vector model, salience determines the mechanism of selection, then the selective inhibition mechanism should be responsible for eliminating that response and veering away from that location should result.

Method

Participants

Twelve different participants were recruited from the same subject pool as in the previous experiments. This group was composed of 6 right-handed men, 5 right-handed women, and 1 left-handed man ranging in age from 19-29 yrs. All participants had normal or corrected-to-normal vision, were naïve to the purpose of the study, and were financially compensated for their time. The data from one participant were removed due to excessive recording errors.

Apparatus and Procedure

The movement environment was almost identical to that of Experiment 2 in that it consisted of three dual-color LEDs (1.5 cm diameter) arranged in a column, 18 cm apart, along the midline of the body. The only differences were that the LEDs were now embedded in an aluminum box (3 cm H X 58 cm W X 70 cm L) painted grey and that the start position was a circular white sticker (3 cm in diameter with an open 1 cm circular section in the middle) fixed to the surface of the box, 10 cm from the first LED. Onset and offset of the cue and target LEDs were controlled by the same four-bank timer as in Experiment 2. This timer was also interfaced with the Optotrak™ such that the recording of the location of the IRED was simultaneous to the illumination of the target/distractor combination.

Participants were required to begin with the index finger of the dominant hand on the start position and then complete a rapid aiming movement to the target location (green LED) with or without the presence of a simultaneously presented competing stimulus (red LED) in the environment. One to 1.5 s prior to the presentation of the target/distractor stimuli, participants received predictive precue information about the location of the target via a brief (300 ms), green flash of the LED at one of the possible target locations. Participants were told that they could use the advanced information to their "advantage". Participants were also asked to, upon completion of their movement to the target, remain on the target until the target LED was extinguished (1.7 s). When the target LED was extinguished, the participant was free to return the finger to the start position and await a "Ready" cue from the experimenter indicating the beginning of the next trial.

On 75% of the trials, the target appeared in the cued location (valid trial), while on the other 25% the target was located in one of the other two locations (invalid trial). On a percentage of both the valid and invalid trials, a distractor stimulus was presented simultaneous to the presentation of the target stimulus. Thus, there were four types of trials: 1) Valid-Target Alone (VTA) - 25% of total trials; 2) Valid-Competitive (VC) - 50% of total trials; 3) Invalid-Target Alone (ITA) - 12.5% of total trials; and, 4) Invalid-Competitive (IC) - 12.5% of the total trials.

Participants were tested individually in two sessions of approximately 45 min each. Seven of the participants chose to complete both sessions in the same day, whereas the other 5 completed the sessions over two days that were not separated by more than 4 days. Each session began with the experimenter instructing the participant on task requirements. Following these instructions, the participant completed 8-10 practice trials and then 4 blocks of 48 experimental trials (8 blocks and 384 trials in total). At the end of each block of trials, the participants were given the opportunity to take a break. Trials were presented in a random order with the constraint that each condition was to be presented in the proper experimental percentage within each block.

Data Reduction and Analysis

All movements were recorded via the Optotrak™ at a frequency of 500 Hz. and were analyzed employing the same procedures as in Experiment 2. The data for trials on which the participant initiated a movement upon cue presentation (<1 % of trials) or had a RT of <100 ms (<2% of trials) were eliminated from the set. Recording errors resulted in the elimination of a further 1-9% of trials. Based on the predictions arising from the response activation model, five specific questions were asked and separate analyses on the mean values of each dependent variable were performed to answer these questions. The specific questions asked and the description of the statistical analyses used to answer the questions are detailed below.

Results

1) Were the movements to the targets different from each other?

The purpose of this analysis was to test if the movements to each target, in the simplest condition, differed from each other. As such, the mean values for each dependent variable for movements to each target in the VTA condition were submitted separately to a one-way repeated measures ANOVA with Target (1,2,3) as the factor. Post hoc analysis of significant effects was completed using Tukey's *HSD*, *p* < .05.

As in Experiment 2, the results of this analysis revealed significant effects for TT, *F* (2, 20) = 357.01, *p* < .001, RT, *F* (2, 20) = 14.09, *p* < .001, and MT, *F* (2, 20) = 356.70, *p* < .001 (see Table 6). Post hoc analysis revealed that TTs and MTs were shorter for movements to Target 1 than Target 2, which were in turn shorter than movements to Target 3. Similarly, RTs to Targets 1 and 2 were shorter than RTs to Target 3. Although the RTs to Target 1 were shorter than those to Target 2, these differences were not statistically different.

Consistent with the results for MT, significant effects were found in the kinematic dependent measures of PA, *F* (2, 20) = 31.32, *p* < .001, and PV, *F* (2, 20) = 852.85, *p* < .001 (see Table 7). Whereas it was found that PV was higher for movements to Target 3 than Target 2, which were both higher than movements to Target 1, the analysis for PA revealed that PAs were greater for movements to Target 2 and 3 than Target 1, but were not different than each other.

The analysis of the movement trajectories revealed effects for AveY, $\underline{F}$ (2, 20) = 3982.74, $\underline{p} < .001$, and AveH, $\underline{F}$ (2, 20) = 138.02, $\underline{p} < .001$, and AveX, $\underline{F}$ (2, 20) = 6.02, $\underline{p} < .01$ (see Table 8). Not surprisingly, it was found that movements were longer and higher for movements to Target 3 than to Target 2, which were in turn higher and longer than movements to Target 1. Interestingly, movements to Target 3 had a leftward bias relative to the movements to Target 1. Movements to Target 2 were intermediate and not statistically different from movements to Target 1 or 3.

2) Did precuing the target location affect movement planning and execution?

This analysis was conducted in order to determine if the participants were taking advantage of the advance information and, if so, how the advance information affected movement execution. For this analysis, mean values of each dependent variable in the VTA and ITA conditions were submitted to a planned comparison. Post hoc testing to determine the direction of significant effects, as well as how the location of the invalid precue affected movement planning and execution, was done in steps. First, difference scores for each target were calculated by subtracting the mean VTA values from the mean ITA value. These difference scores were then pooled according to the location of the cue relative to the target (i.e., Before or Beyond). The mean values of the pooled difference scores were then submitted to a one-way ANOVA with Location (Before, Beyond) as the factor. The MS_{error} term from this analysis was then used to calculate a critical value (Tukey's HSD, $p < .05$) to test whether differences existed between the two locations and a theoretical value of "0" (no effect).

The planned comparison analysis of the temporal measures revealed significant effects for TT, F (1, 10) = 24.21, p < .001, and RT, F (1, 10) = 17.84, p < .01. Post hoc analysis revealed that, although TTs and RTs were significantly greater than zero, indicating that the participants were using the precue information to help preplan their movements, the location of the cue did not differentially affect movement planning. No significant effects were found for MT or for any of the kinematic or trajectory measures.

3) Did the presence of a distractor affect movement planning and execution when the cue was valid?

To answer this question, mean values of each dependent variable were submitted to a separate planned comparison in which the VTA movements were compared to the movements in the VC conditions. Significant effects were found in TT, F (1, 10) = 29.02, p < .001, RT, F (1, 10) = 20.71, p < .005, and PV, F (1, 10) = 5.10 p < .05. The direction of these effects is described below (see question 5). No other effects approached conventional levels of significance.

4) Did the presence of a distractor affect movement planning and execution when the cue was invalid?

For this analysis, mean values of each dependent variable were submitted to a separate planned comparison in which the VTA movements were compared to the movements in the IC condition. It was found that the presence of the distractor in the invalid condition affected TT, F (1, 10) = 43.65, p < .001, RT, F (1, 10) = 9.79, p < .05, MT, F (1, 10) = 11.72, p < .01, and AveH, F (1, 10) = 7.20, p < .05. Again, the direction of these effects is described below (see question 5). No other effects approached conventional levels of significance.

5) Did the validity of the cue and/or the location of the distractor differentially affect movement planning and execution?

This analysis was conducted with two purposes. First, this analysis was conducted to determine whether or not the trajectory effects observed in the previous two experiments can be eliminated with the valid precue information and enhanced by the invalid information. The second purpose was to determine whether or not the direction of the effects on the movement was dependent on the location of the distractor. As such, difference scores were calculated by subtracting the mean value of the VTA condition from the mean values of the VC and the IC conditions for each target. These difference scores were pooled according to their location relative to the target (Before or Beyond) and then submitted to a 2 Validity (Valid, Invalid) X 2 Distractor Location (Before, Beyond) two-way repeated measures ANOVA. In order to determine whether or not the validity of the cue and the location of the distractor affect movement planning and execution, the mean values of the difference scores involved in significant effects were compared to each other and a theoretical value of "0" (no interference) using the MS_{Error} to calculate a critical value (Tukey's HSD, $p < .05$).

The analysis of the temporal measures of movement revealed significant main effects of Validity in TT, $F(1, 10) = 30.26$, $p < .001$, RT, $F(1, 10) = 6.37$, $p < .05$, and MT, $F(1, 10) = 12.26$, $p < .01$. Post hoc analysis of these effects revealed that, in each measure, not only was the interference effect (an increase in movement planning and execution times) caused by the distractor greater in the Invalid condition, but only in the IC condition was interference significantly different from zero. There was also a significant main effect for Distractor Location in MT, F (1, 10) = 6.21, $p < .05$. Consistent with a hand-centered reference frame, post hoc analysis of this MT effect revealed significant interference only when the distractor was presented in a location that was closer to the hand than the target. None of the interactions reached conventional levels of significance.

The kinematic measures of movement were also affected by the presence of a distractor. Main effects were found for Validity in PA, F (1, 10) = 8.34, $p < .05$, and for Distractor Location in PA, F (1, 10) = 7.68, $p < .05$, and PV, F (1, 10) = 17.93, $p < .005$. These effects, however, were superceded by significant interactions between Validity and Distractor Location in PA, F (1, 10) = 11.26, $p < .01$, and PV, F (1, 10) = 41.99, $p < .001$. Post hoc analysis of these effects revealed that significant interference was only found in the Invalid condition. Specifically, PAs were lower in the Invalid-Before condition than in all others, which were not different. As well, PVs were lowest in the Invalid-Before condition and highest in the Invalid-Beyond condition, while the PVs for movements in both the Valid conditions were not different than zero nor each other (see Figure 7).

Finally, the analysis of the movement trajectories revealed several significant effects. There was a main effect for Validity in AveH, F (1, 10) = 7.47, $p < .05$, that indicated that the participants moved higher following Invalid precues than following Valid precues. The interaction between Validity and Distractor Location in AveH, however, fell short of conventional levels of significance, F (1, 10) = 2.26, $p < .17$. The analysis of AveY revealed a main effect for Distractor Location, F (1, 10) = 6.71, $p < .05$, and a Validity by Distractor Location interaction, F (1, 10) = 11.94, p < .01. Post hoc analysis of the interaction revealed that movements were shortest in the Invalid-Before condition and longest in the Invalid-Beyond condition (see Figure 8). Movements in both Valid movement conditions were of intermediate AveY and not reliably different from each other or zero. The presence of a distractor did not affect the left-right displacement (AveX) of the movement.

Discussion

With some exceptions, the predictions based on the response activation model were confirmed. That is, when the location of the target was validly cued, movements to the target locations were unaffected by the presence of a competing stimulus, whereas when the distractor was presented in the precued location, there was significant interference. Importantly, the analysis of the trajectory effects in the IC condition revealed that the participants were drawn towards the location of the distractor. This finding is in opposition to what would be predicted based on the response vector model of selective reaching (Tipper et al., 1999); recall that predictions based on the response vector model would be that trajectories would deviate away from the invalidly cued non-target location because of the increased salience of that location.

Although the trajectory effects predicted for the competitive conditions were confirmed, trajectory alternations following simple invalid movement cues were not. Specifically, it was predicted that if the participants were using the precue to preprogram their movements (as evidenced by the shorter RTs and TTs in the VTA than in the ITA conditions and exaggerated trajectory effects in the IC condition), then a veering of the movement trajectory toward the cued location should have been observed in the ITA condition. Such was not the case. Although there is no definitive answer as to why this result occurred, future work will be designed to examine the effects of precuing locations more thoroughly.

General Discussion

The primary purpose of the present series of studies was to examine three different hypotheses regarding the processes involved in moving to objects in cluttered environments. The first description of these processes came from a series of experimental and theoretical papers by Tipper, Houghton, and colleagues reporting that the trajectories of target-aiming movements veered away from or towards competing, non-target stimuli depending on the salience of the non-target object. In contrast, Tresilian (1998) proposed an object avoidance explanation of movements that veer away from all perceived non-target locations. Finally, Welsh et al. (1999) conducted a study in which a collision with the distracting stimulus was not at issue and found that participants were actually drawn towards the distractor. Taking the results of all these studies into account, we have now presented and tested a third possibility - the response activation model. According to response activation model, when the competing object does not obstruct the path of the target movement, the direction of the deviation in the movement is a product of the activation levels of each independent and competing response process at the moment of movement initiation. If a non-target response is in an active state, then observed movement will contain characteristics of both responses and a deviation towards the non-target stimulus will occur. In contrast, if the non-target response is inhibited prior to movement initiation, the observed movement will be characterized by a negative bias against that location and a deviation away from the non-target stimulus will occur. The results of the present series of experiments are supportive of the response activation model. Specifically, movements were drawn towards the competing, non-target stimulus when the non-target stimulus was presented simultaneously or immediately prior to the target stimulus, but were repelled from the non-target location when the non-target stimulus was presented early enough to be inhibited (Experiment 1 and 2). Further, movements were relatively uncontaminated when the distractor was presented after the target and when the target location was predictively precued (Experiment 2 and 3).

In relation to the alternative explanations of movement trajectory changes, the attractive nature of the distracting stimulus under certain movement conditions in the present study are difficult to reconcile with a strict interpretation of the object avoidance hypothesis (Tresilian, 1998). Although the model proposed by Tipper, Houghton and colleagues was designed to account for deviations towards and away from non-target locations, the results are also in opposition to predictions based on their notion of the effect of object salience. That is, they suggested that objects of action relevance (salience) initiate strong response processes that are completely inhibited by selective inhibition, whereas responses of lesser action relevance are only partially inhibited by the oCoS selection mechanism. As a result of these separate selection mechanisms, Tipper et al. (1999) proposed that the appearance of a non-target object of greater salience will result in movement trajectories that deviate away from that location while the appearance of an object of lesser salience will result in deviations towards that location. The results of Experiment 2 are incongruent with this proposal. Specifically, although it could be argued that the deviation towards the distractor in the -250 and 0 ms SOA conditions were the result of a relatively low salience of the distracting stimulus, the finding that movements deviated away from the exact same stimulus if presented -750 ms prior to target presentation does not fit with the response vector model. This pattern is incongruent because the salience of the distracting stimulus should be even lower in the -750 ms SOA condition than either the -250 or 0 ms SOA conditions. Further, in Experiment 3 when predictive precue information was given about the possible target location, increasing the salience of the cued location and decreasing the salience of the non-cued locations, movement trajectories deviations towards the cued (salient) location occurred when the distractor appeared in the cued location and the target simultaneously appeared at an uncued location.

While the results of the present study do not entirely fit with the response vector model, they are consistent with the basic premises of the model – early parallel response programming and the combined response vector (Tipper et al., 1992). Thus, we have incorporated these ideas into the response activation model. As described above, Tipper and colleagues have suggested that when two competing stimuli with action-based potential are present in the environment, responses to both stimuli are programmed in parallel. Moreover, these separate processes potentially share some common neuronal populations (see Figure 1a-c). We feel that the key to the differing results in the studies by Tipper and colleagues and our findings is in the temporal relation between movement initiation and inhibition of the competing response. Specifically, if the response is initiated prior to the effects of inhibition (Figure 1c), then the initial movement trajectory will be characterized by properties of the two competing responses (see also Welsh et al., 1999). However, if the competing response has been inhibited prior to movement initiation, either from some preexisting level of inhibition or if enough time has elapsed for inhibitory process completion, then a movement trajectory biased away from the competing stimulus would be expected. To elucidate these differences, a detailed examination of the tasks utilized in many of the key studies is provided. As Tipper and colleagues were the first to look at trajectory effects in reaching-to-grasp movements, the discussion will begin with a analysis of this work.

Although the tasks employed by Howard and Tipper (1997) and Sheliga et al. (1994, 1995) are very different, the processes leading to the observed movement alterations may be quite similar. In Howard and Tipper (1997), participants were required to reach to and grasp a colored block in one of four possible locations. Although on the majority of trials a competing non-target block was also placed in the environment, only the data for the trials on which a single block (thus no choice was required) was present in the environment were reported. Of importance to the present discussion was that a brief movement cue (36 ms flash of a LED) was presented at a central location that the participants had been fixating. If, as suggested in many models of attention described in the introduction, the onset of a stimulus at an attended location automatically elicits a response, then why did movements veer away from this location of the LED? The key is that the location of the LED was never a possible target location. Thus, participants may have established an inhibitory field, similar to an inhibition of return code (Posner & Cohen, 1984), on that location. This inhibition would repel a response from that location even before target response preparation processes were initiated. Similarly, in Sheliga et al. (1994, Experiment 1; see also Sheliga et al., 1995), participants were exogenously cued to one of four locations arranged in a row above fixation and then required to make a saccade to a fifth location that was directly below fixation based on the presentation of the imperative stimulus at any of the locations. They found that when the target appeared in the same location as the cue (valid trial), saccades deviated away from the location of the cue. An explanation similar to that used to reconcile the Howard and Tipper (1997) data can be employed here. Specifically, because participants were never required to complete a saccade to the cued location, an inhibitory code may have been placed on that location, thus biasing a movement in the direction opposite to the cue before response programming processes began.

The task utilized in the study by Tipper et al. (1997) was similar to that of Howard and Tipper (1997) in that participants were instructed to reach and grasp a target block located in one of four locations arranged in a square. On some trials, a competing, non-target block was placed in one of the other possible target locations. In this study, the participant was cued to the color of the target block via a flash of a similarly colored circle on a computer screen located 2.13 m in front of the participant. It was reported that movements that crossed over a non-target block in the near-right position always deviated away from this location. However, because the movements actually crossed directly over the block, an object avoidance explanation was given for this result. Of greater theoretical interest were the following two findings. First, when the target block was located in the left-far position of the array, a competing block placed in the left-near row position (not directly in the path of the movement) caused a rightward deviation away from it. Second, movements to a target in the left-near row position deviated towards the far row distractors. Interestingly, in Experiment 4 when movements were only completed to one of the two far row locations, the never-responded-to non-target block placed in the near row did not affect movement trajectories (apart from object avoidance of the near right position). To explain the finding that participants were repelled from near-row distractors but attracted to far-row distractors, Tipper et al. developed an explanation based on the idea of object salience. In this case, salience was determined by the distance the block was from the starting location of the hand - the closer the block was to the start position, the greater the salience of the block (see Tipper et al., 1997 for a more detailed description).

We propose an alternative non-attention based, and perhaps more parsimonious, interpretation of the trajectory effects. Specifically, it may be that participants were not drawn towards or repelled from the non-targets based on object salience, but instead, initial hand movements were drawn towards the center of the movement environment. We find this to be a viable alternative explanation because what Tipper et al. (1997) perhaps did not consider was oculomanual coupling and the effects that saccadic eye movements have on manual aiming movements. For example, Herman, Herman, and Maulucci (1981) demonstrated that eye and hand movements may share a common movement command (see also Bizzi, Kalil, & Tagliasco, 1971; Roucoux & Crommelinck, 1981). Thus, by extension, it can be suggested that early motor planning of both eye and hand movements share an endpoint and that the hand movement is corrected on-line via afferent information (Binsted & Elliott, 1999).

In the present context, the task employed in the study by Tipper et al. (1997) required participants to first fixate on a computer screen that was outside the movement environment and then make an eye movement to identify, locate, then move to the target. For movements in the target-alone condition, because there was no competition (hence no decision about the location of the target was required), participants were able to move their eyes directly to the target. Because, under these conditions, there was no discrepancy about the terminal endpoint of the saccade, the hand movement was unbiased. A similar explanation can be used for the data reported for Experiment 4 of Tipper et al. (1997) where targets were always located in the back row and the near distractors were never potential targets.[4] However, when movements were made with competing, non-target blocks located in the movement environment, initial saccades were likely directed towards the center of the environment such that the location of the target could be rapidly identified. Given eye-hand coupling of motor commands, such an initially central saccade would likely bias the manual aiming movement to the center of the display before on-line corrective processes worked to ensure accurate movement termination. Thus, the reported trajectory deviations are not necessarily related to competition between competing manual responses, but instead may be the result of the coupling between ocular and manual movements.

Finally, in Welsh et al. (1999) and Experiment 1 of the present study, participants were drawn towards the non-target stimulus. Two important differences exist between the tasks employed in these studies and those described above reporting movement trajectories that veered, for the most part, away from the non-target stimulus. First, in our work, both the target and the competing stimuli were presented simultaneously, whereas in the work of Sheliga, Tipper, and their respective collaborators, participants had some knowledge (a minimum of 150-300 ms visual inspection) of the environment and of the locations of the two competing locations prior to imperative stimulus onset. Second, in the latter work, participants were required to focus their attention at some location within the environment other than the possible end-points of the responses prior to the initiation of response programming processes. As such, it is suggested that participants in the present study were unlikely to have intentionally placed an inhibitory code on any responses prior to movement initiation[5] (cf., Howard & Tipper, 1997) and were able to complete the target hand movement with a more naturalistic coupling to the eye movements (cf., Tipper et al., 1997). With the sudden and simultaneous presentation of response stimuli in the present study, response processes to these stimuli were truly initiated in parallel, causing an early combined response that was corrected on-line.

In summary, it is suggested that the main differences between the studies in which attentional processes caused a disruption of the movement trajectories is the result of a preexisting (Howard & Tipper, 1997; Sheliga et al., 1994, 1995) or recently established (Experiment 2 of the present study) inhibitory code on the response to a particular location or an initially "combined" response due to response competition (Welsh et al., 1999; Experiment 1-3 of the present study). The response activation model of movement in complex environments detailed below is proposed to explain the interaction between competing stimuli and the observed response.

The Response Activation Model

The response activation model is based on the premise that attention and action are intimately linked such that attention is distributed based on the to-be-performed action. More specifically, it is proposed that attention is distributed throughout the environment, prior to the initiation of response programming processes, based on an response set that is created and then maintained in working memory. Contained within this response set are independently parameterized positive (priming) or negative (inhibitory) activation levels for response-related stimuli only. Non-related stimuli are neither primed nor inhibited and, hence, may be perceived at a low level but are not attended to. When response-related changes in the environment occur (e.g., the sudden onset of a target and/or a related non-target stimulus), these stimuli automatically initiate independent response-based processes that race toward a threshold activation level. The observed behavior, then, is determined by the level of activation achieved by each independent response process. These activation levels, of course, are determined by the resultant preexisting, parameterized levels of activation for each of the responses. Specifically, if preexisting or recently established levels of inhibition are strong enough to prevent the response to the non-target stimulus from reaching a positive level of activation, then the remaining inhibition will affect target response emergence in a competitive situation (-750 ms SOA condition of Experiment 2; see Figure 1d). Conversely, the priming of a response in the response set facilitates programming processes such that the response will reach activation threshold more quickly and be unaffected by competing responses (VC condition of Experiment 3; see Figure 1b). Finally, if more than one response is in an active state, then the initial response will be composed of characteristics of the competing responses (Experiment 1, - 250 ms and 0 ms conditions of Experiment 2, and IC condition of Experiment 3; see Figure 1c).

In the context of the current discussion, participants in Experiment 1 of the present study may have parameterized a response set based on the sudden appearance of a light (red) at one of the five possible target locations. However, because the appearance of the green light was also a sudden change in the environment in one of the five possible red light locations, a process for a response to the location of the green light was simultaneously initiated. Only when the target location was determined was the movement corrected to that location. In contrast, in Howard and Tipper (1997), the participant's response set was likely set to strongly inhibit the response to the cue LED. Thus, even though the cue would result in the automatic initiation of a response to the cue, the preexisting levels of inhibition parameterized in the response set were strong enough to not only inhibit the cued response, but also to bias the target movement trajectory away from the LED.

By extension, the response activation model can also account for action slips where "automatic" or overlearned responses are accidentally and erroneously completed (Norman & Shallace, 1986). Based on the model, an action slip can occur when either the inhibition parameter of the response set on the automatic action is not strong enough to prevent it from reaching the threshold of activation, or the response set is temporally lost from working memory allowing the non-target response to reach activation.

The response activation model is similar to one proposed by Houghton and Tipper (1994). In Houghton and Tipper model, the actor maintains a "template" in working memory that describes the properties of the to-be-selected inputs. When a stimulus matches the preset template, it generates excitatory feedback. In contrast, when a stimulus does not match the template, it receives inhibitory feedback. Our model proposed has three major differences from the model suggested by Houghton and Tipper (1994). The first difference is that response inhibition and priming are incorporated directly into the response set (template). Second, all response-related, and perhaps unexpected novel and startling, attention-grabbing stimuli, initially receive excitatory feedback (initiate response-producing processes). Non-target response-related stimuli are subsequently inhibited only when the target has been identified. Finally, because all response-related stimuli initiate response production processes, it is the preexisting level of inhibition/priming that determines the observed effect of this automatically elicited response activation. In this way stimuli that are completely unrelated to the task at hand do no interfere with the completion of the goal task. For example, when reaching for a ripe apple in a tree, the leaves not directly in the path of the movement do not interfere with the reaching action, whereas a premature or rotten apple near to the target apple will affect reaching.

An "Exceptional" Set of Data

It must be acknowledged here that certain results of a study reported by Tipper et al. (1999) do not fit with the response activation model. In this study, Tipper and colleagues adapted the task employed by Sheliga et al. (1995) to test their ideas of object salience. In the first experiment of the Tipper et al. (1999) study, participants were required to fixate a location at the center of a square demarcated by four LEDs (one at each corner) and then make a rapid saccade to a target located beyond the top of the square. The saccade was to be made as fast as possible following a 100 ms green flash of one of the LEDs. The participant was also asked to place a finger on a starting position located below the bottom of the square and then move this finger as fast as possible to the same target location following the same signal. Eye and finger movements were performed simultaneously. Importantly, the location of the LED that was to provide the go (green)/no-go (red) signal was known to the participant prior to presentation of the signal. Thus, the participants had to covertly orient their attention to the future location of the signal while maintaining fixation on the central starting location prior to receiving the cue to move. Following the tenets of the model of response activation, because the LED was never a possible target, this set of task requirements should result in movement trajectories that deviate away from the LED. Although eye movements demonstrated this pattern of results, hand movements veered towards the location of the cue. This latter finding obviously being inconsistent with the response activation model.

In a follow-up experiment, the task employed was identical to the original except that the choice to be made by the participant following the signal at the cued LED was not go/no-go, but now involved deciding which location to acquire. A green flash at the cued LED signaled the participant to move to the target (66% of the trials), whereas a red flash signaled the participant to move to the LED (33% of the trials). Similar to the results of Experiment 1, when moving to the target, eye movements deviated away from the location of the LED and hand movements veered towards the signaling LED. Interestingly, under these task conditions, saccadic deviations increased. Similar increases in the deviations of the hand movements were found as well, but only following illumination of the far LEDs.

Tipper et al. (1999) explained these results in terms of object salience. In Experiment 1, because the LED was the location of the movement signal, the location of the LED was very salient to the occulumotor system. As such, when the stimulus appeared there, selective inhibition (reactive inhibition in their terms) eliminated the competing response and caused a movement code that was biased away from the LED. Alternatively, because the LED had little salience to the manual-motor system, the small amount of response-related neural activity in the motor system resulting from the illumination of the LED was not large enough to warrant selective inhibition and, as such, was only partially inhibited by the oCoS mechanism. The partial inhibition resulted in a slight bias of the movement trajectory in the direction of the non-target LED. In Experiment 2, the LED became a possible target location and generally caused an increase in the size of the movement trajectory effects. The explanation given for the increase in the trajectory effects was that, due to the LED becoming a possible target location, the salience of the LED increased. To ensure that the saccade terminated on the typical (66% of the trials) target location, selective inhibition had to work harder and, thus, caused the exaggeration in the saccadic deviations. For the increased deviation in the hand movements, the explanation was more complex and speculative in nature. It was proposed that, because the LED was now a potential target location, the salience of the location of the LED increased for the hand as well. This increased salience caused stronger response processes that, for the far LEDs, were still not intense enough to warrant selective inhibition, while for the near LEDs (because of the hand-centered frame of reference) may have periodically required selective inhibition. For the movements to the target following far LED signals, because activity of the partially inhibited response was greater, the result was a larger deviation in the trajectory. Alternatively, for the movements to the target following near LED signals, because the responses to the movement to the LED were periodically subject to selective inhibition, stronger deviations towards the LED (resulting from partial oCoS inhibition) were averaged back by deviations away from the LED (resulting from selective inhibition) resulting in relatively unchanged deviations.

Overall, this particular pattern of findings is difficult to reconcile with the response activation model. Although saccadic deviation away from the LEDs in Experiment 1 (see our explanation of the Howard and Tipper (1997) results) and the deviation of the hand towards the LED in Experiment 2 (due to the presentation of an action-relevant stimulus at a potential target location) would be predicted based on the response activation model, the hand deviation towards the LED in Experiment 1 and the increased saccadic deviation away from the LED in Experiment 2 would not. Any attempt to explain these latter findings in the framework of the response activation model would be an exercise in speculation and thus will not be offered. However, it is also the case that the results of the Howard and Tipper (1997) study are inconsistent with the results and model reported in Tipper et al. (1999). Specifically, in Howard and Tipper (1997) and Experiment 1 of Tipper et al. (1999), the participants were required to orient their attention at a location that was never a possible target (therefore of low salience to the manual-motor system) and then complete a movement to a target whose location was known prior to the imperative movement signal. Despite this similarity in task requirements, deviation away from the non-target LED was reported by Howard and Tipper (1997), whereas deviation towards the non-target LED was reported by Tipper et al. (1999). Indeed, as suggested, more research is required to determine the mechanisms behind the pattern of results found in the Tipper et al. (1999) study.

Summary

Based on the work reviewed above, it can be concluded that the presence of non-target stimuli in the movement environment have a profound effect on the manner in which humans program and execute movements. Although it is evident that object avoidance strategies play a role in shaping a goal-directed movement, the processes involved in initiating and subsequently selecting the target response from competing responses are critical in determining the characteristics of the movement. In the present paper, a model of response activation was proposed to describe the processes involved in selection. With rare exception, the model of response activation can be employed to account for the reported deviations. Future work will be directed towards formalizing the model mathematically and exploring the effects different response sets on movement execution.

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Acknowledgements

This research was funded by a Canada Research Chair and an NSERC grant to Digby Elliott. This research was also supported by an NSERC scholarship to Timothy N. Welsh. As this paper is part of the Ph.D. dissertation of Timothy N. Welsh, the authors would like to thank Drs. Timothy D. Lee, Bruce Milliken, and Janet Starkes for their insightful comments and advice. The authors would also like to thank John Moroz for his technical support, Miriam Jonas for her assistance in data collection, and Dr. Luc Tremblay for his technical support and for his theoretical insights. Finally, the authors would also like to acknowledge Professor Tipper, Dr. Tresilian, and an anonymous reviewer for their comments on an earlier version of this paper.

Footnotes

1. As the LEDs were raised from the surface of the board, collision was possible with the LEDs if the participants chose to slide their finger along the surface of the board. Thus obstacle avoidance was necessary, although to a very limited extent.

2. The first twelve participants completed the study under the "Goggles" procedure. The analysis performed on this initial data set revealed trajectory, but no temporal effects of a distracting stimulus. This was an unexpected result given the statistically robust effects reported by Meegan and Tipper (1998) and Tipper et al. (1992) (but see Welsh et al., 1999). At first, it was thought that requiring the participants to wear the goggles with the lenses in the opaque state until they were cued to move prevented them from having any knowledge of the location of the possible target locations prior to imperative stimuli presentation. Thus, when they were given vision, they had to conduct a serial search (Treisman & Gelade, 1980) of the five target locations in order to locate the target for that trial. In this way, all of the four non-target locations may have acted as distractors eliminating the possibility of deciphering the effects of the one intended distractor. As such, data were collected from a second group of twelve participants that completed their movements under more natural conditions in which they did not wear the occlusion goggles and, thus, had full vision of the environment at all times. Analysis of the data collected under the "Natural" condition revealed exactly the same effects (or lack thereof) as under the "Goggles" condition. Subsequent two-way mixed ANOVAs conducted with Procedure as a between-subjects variable and Distractor Location as a within-subjects variable for each

dependent variable for each target location revealed only main effects for Procedure in RT (RTs under the "Natural" procedure were shorter than those under the "Goggles" procedure to all target locations with the exception of Target 5). As there were no interactions between Procedure and Distractor Location in any of the analyses, the results reported in the body of the text are those in which the data obtained from both procedures are combined.

3. We thank Steven Tipper for pointing this out to us.

4. We find Tipper et al.'s (1997) explanation of the null interference effects in their Experiment 4 (and those of Castiello (1996) and Jackson et al. (1995)) satisfactory as well. In all these task conditions, the participant know exactly where the end point of the movement would be prior to the imperative signal. Thus, as there was no decision to be made and no interference, the movement plan to that location was uncorrupted. This explanation fits well with our interpretation (i.e., when there is no conflict in eye and hand movement plans, the hand movement is unbiased).

5. Although not specifically examined, participants may have placed a negative priming code (Tipper, 1985) on the ignored non-target response from the previous trial or an inhibition of return code (Posner & Cohen, 1984) on the activated response from the previous trial (see also Milliken, Tipper, Houghton, & Lupiáñez, 2000). Future work will be aimed at exploring the effects of inhibitory processes associated with negative priming and inhibition of return on movement execution.

Table 1. Mean and standard deviation () Total Time (ms), Reaction Time (ms), Movement Time (ms) as a function of Target Location and Distractor Location for Experiment 1.

Dependent Variable	Target	No Dis	1	2	3	4	5	F ratio	p value <
TT									
	1	595 (88)	-	603 (88)	602 (82)	585 (77)	590 (84)	1.06	.39
	2	644 (82)	655 (93)	-	658 (86)	655 (78)	658 (81)	1.05	.39
	3	697 (90)	698 (87)	708 (90)	-	702 (90)	697 (82)	0.72	.58
	4	758 (90)	749 (89)	752 (91)	745 (88)	-	764 (83)	1.20	.32
	5	814 (105)	829 (99)	823 (91)	821 (96)	827 (93)	-	1.02	.40
RT									
	1	322 (77)	-	324 (80)	318 (68)	311 (61)	320 (65)	1.21	.32
	2	305 (63)	304 (67)	-	307 (60)	309 (62)	305 (63)	0.32	.87
	3	296 (62)	293 (56)	306 (68)	-	304 (62)	300 (57)	2.03	.10
	4	307 (58)	303 (68)	301 (59)	297 (60)	-	306 (51)	0.99	.42
	5	320 (69)	320 (76)	311 (80)	311 (64)	315 (67)	-	1.35	.26
MT									
	1	273 (52)	-	279 (47)	283 (53)	274 (61)	270 (52)	0.87	.49
	2	338 (54)	351 (58)	-	351 (58)	346 (53)	352 (52)	1.83	.13
	3	399 (61)	404 (66)	402 (60)	-	397 (60)	397 (63)	0.51	.73
	4	451 (63)	446 (58)	451 (63)	448 (70)	-	458 (63)	0.57	.69
	5	494 (78)	510 (66)	512 (63)	510 (67)	512 (61)	-	1.46	.23

Table 2. Mean and standard deviation () Average Height (mm), Average Displacement in Y axis (mm), and Average Displacement in X axis (mm) as a function of Target Location and Distractor Location for Experiment 1.

Dependent Variable Target	No Dis	1	2	3	4	5	F ratio	p value <
Average Height								
1	17.3 (5.1)	-	18.1 (6.3)	18.6 (6.8)	18.9 (6.2)	18.8 (6.0)	3.56	.01
2	22.5 (7.0)	22.4 (6.7)	-	22.5 (7.1)	23.0 (7.8)	22.2 (6.3)	0.68	.62
3	25.6 (7.9)	24.3 (6.9)	25.0 (7.4)	-	26.7 (8.6)	25.9 (8.3)	5.29	.001
4	30.4 (9.4)	30.0 (10.2)	30.2 (9.8)	30.0 (9.3)	-	29.7 (9.8)	0.33	.86
5	34.7 (11.7)	33.4 (11.7)	33.5 (11.8)	33.9 (11.2)	34.5 (11.8)	-	1.49	.21
Average Y Disp.								
1	147 (12.5)	-	146 (12.4)	149 (13.7)	148 (15.1)	145 (12.7)	1.35	.26
2	198 (14.5)	196 (13.6)	-	199 (14.2)	200 (15.2)	200 (15.4)	2.09	.09
3	253 (17.1)	252 (17.6)	251 (16.1)	-	254 (16.9)	255 (16.8)	1.56	.19
4	306 (19.5)	306 (18.1)	308 (18.0)	308 (15.6)	-	313 (15.7)	2.85	.03
5	360 (21.5)	359 (20.5)	358 (19.1)	363 (18.8)	363 (19.7)	-	1.21	.31
Average X Disp								
1	2.7 (7.6)	-	2.6 (7.3)	2.6 (8.0)	2.9 (7.4)	2.9 (7.5)	0.30	.88
2	1.6 (8.5)	2.5 (8.6)	-	2.1 (7.7)	2.0 (8.1)	2.0 (8.1)	1.05	.39
3	2.4 (9.4)	1.9 (9.1)	1.8 (8.7)	-	2.0 (8.7)	1.8 (9.8)	0.54	.71
4	1.1 (10.0)	1.3 (10.3)	1.6 (10.8)	1.5 (10.8)	-	1.0 (10.3)	0.62	.66
5	0.3 (11.3)	0.3 (10.8)	1.0 (11.5)	0.7 (11.5)	0.8 (12.4)	-	0.89	.48

Table 3. Mean and standard deviation () Total Time (TT), Reaction Time (RT), and Movement Time (MT) in ms as a function of Target Location, Stimulus Onset Asynchrony, and Distractor Location for Experiment 2.

DV/		Stimulus Onset Asynchrony														
Target		-750 ms			-250 ms			0 ms			+250 ms			+550 ms		
	ND	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
TT																
1	564	-	527	479	-	488	502	-	546	561	-	547	555	-	563	562
	(82)	-	(101)	(82)	-	(63)	(63)	-	(77)	(63)	-	(64)	(62)	-	(72)	(89)
2	655	631	-	623	609	-	619	647	-	668	665	-	674	659	-	671
	(69)	(72)	-	(90)	(103)	-	(76)	(96)	-	(72)	(68)	-	(82)	(72)	-	(80)
3	804	709	782	-	747	737	-	806	795	-	795	823	-	813	807	-
	(106)	(88)	(151)	-	(106)	(91)	-	(91)	(106)	-	(111)	(131)	-	(112)	(97)	-
RT																
1	310	-	274	231	-	241	245	-	298	305	-	290	298	-	302	304
	(58)	-	(87)	(78)	-	(44)	(44)	-	(52)	(48)	-	(46)	(45)	-	(50)	(53)
2	286	261	-	238	242	-	241	271	-	287	296	-	295	290	-	294
	(40)	(76)	-	(58)	(61)	-	(56)	(48)	-	(43)	(48)	-	(52)	(45)	-	(47)
3	343	231	304	-	262	264	-	332	326	-	325	344	-	339	351	-
	(60)	(45)	(136)	-	(49)	(49)	-	(50)	(60)	-	(51)	(68)	-	(57)	(61)	-

MT																
1	254	-	253	248	-	247	256	-	249	255	-	257	257	-	261	258
	(47)	-	(44)	(33)	-	(49)	(44)	-	(43)	(36)	-	(47)	(47)	-	(54)	(53)
2	369	370	-	385	367	-	377	376	-	380	370	-	380	369	-	377
	(49)	(42)	-	(61)	(50)	-	(43)	(60)	-	(40)	(46)	-	(48)	(45)	-	(61)
3	461	478	478	-	485	473	-	474	469	-	471	479	-	475	456	-
	(71)	(65)	(82)	-	(69)	(78)	-	(68)	(63)	-	(78)	(83)	-	(73)	(66)	-

Table 4. Mean and standard deviation () Peak Acceleration (PA) (cm/s^2) and Peak Velocity (PV) (mm/s) as a function of Target Location, Stimulus Onset Asynchrony, and Distractor Location for Experiment 2.

DV/		Stimulus Onset Asynchrony														
Target		-750 ms			-250 ms			0 ms			+250 ms			+550 ms		
	ND	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
PA																
1	1942	-	1795	1900	-	2127	2086	-	2085	1960	-	1945	1857	-	1863	1891
	(796)	-	(652)	(648)	-	(828)	(810)	-	(799)	(775)	-	(817)	(656)	-	(704)	(909)
2	2731	2943	-	2339	2823	-	2897	2733	-	2830	2837	-	2819	2747	-	2843
	(726)	(744)	-	(682)	(862)	-	(925)	(811)	-	(783)	(789)	-	(817)	(747)	-	(915)
3	3350	3289	3211	-	3243	3198	-	3330	3332	-	3350	3298	-	3373	3541	-
	(918)	(989)	(1006)	-	(898)	(1081)	-	(936)	(959)	-	(970)	(987)	-	(986)	(1029)	-
PV																
1	803	-	767	777	-	861	864	-	840	805	-	795	800	-	782	796
	(143)	-	(130)	(125)	-	(169)	(178)	-	(170)	(150)	-	(149)	(128)	-	(125)	(190)
2	1544	1578	-	1518	1541	-	1554	1545	-	1577	1561	-	1561	1561	-	1562
	(227)	(205)	-	(158)	(203)	-	(217)	(227)	-	(223)	(245)	-	(236)	(238)	-	(221)
3	2137	2121	2123	-	2080	2118	-	2122	2124	-	2066	2118	-	2099	2187	-
	(341)	(359)	(331)	-	(325)	(388)	-	(372)	(344)	-	(370)	(384)	-	(338)	(371)	-

Table 5. Mean and standard deviation () Average Height (AveH), Average Distance Traveled (AveY), and Average Left-Right Displacement (AveX) in mm as a function of Target Location, Stimulus Onset Asynchrony, and Distractor Location for Experiment 2.

DV/		Stimulus Onset Asynchrony															
Target		-750 ms			-250 ms			0 ms			+250 ms			+550 ms		
	ND	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
AveH																
1	11.5	-	11.7	11.7	-	11.0	11.5	-	11.9	12.2	-	11.9	12.2	-	11.6	11.2
	(3.2)	-	(4.1)	(3.4)	-	(3.2)	(3.8)	-	(3.7)	(4.1)	-	(3.4)	(4.1)	-	(3.4)	(3.5)
2	19.7	21.6	-	18.7	18.7	-	17.5	20.0	-	19.6	19.4	-	19.6	20.1	-	19.4
	(5.7)	(6.7)	-	(5.9)	(5.8)	-	(4.3)	(6.4)	-	(6.6)	(5.4)	-	(5.4)	(5.4)	-	(5.8)
3	27.2	25.6	25.2	-	22.6	24.5	-	27.9	26.9	-	26.3	26.3	-	26.7	27.8	-
	(7.7)	(7.9)	(8.3)	-	(7.5)	(6.5)	-	(8.2)	(8.2)	-	(8.0)	(8.8)	-	(7.1)	(8.4)	-
AveY																
1	63	-	59	60	-	62	62	-	63	63	-	62	62	-	62	62
	(9.3)	-	(8.2)	(8.5)	-	(6.2)	(7.4)	-	(8.6)	(9.5)	-	(8.9)	(9.5)	-	(8.1)	(10.1)
2	165	167	-	162	161	-	167	164	-	170	165	-	171	169	-	170
	(14.9)	(13.7)	-	(10.6)	(10.6)	-	(13.6)	(12.5)	-	(13.7)	(19.1)	-	(18.4)	(16.7)	-	(14.8)
3	272	278	276	-	263	270	-	278	279	-	276	277	-	279	280	-
	(21.3)	(16.7)	(20.7)	-	(29.4)	(19.0)	-	(15.6)	(16.2)	-	(14.4)	(18.1)	-	(16.8)	(17.9)	-
AveX																
1	-14.4	-	-14.0	-14.7	-	-14.4	-14.1	-	-14.48	-14.0	-	-14.4	-14.4	-	-14.4	-14.0
	(15.2)	-	(14.8)	(15.0)	-	(15.6)	(14.4)	-	(15.2)	(15.4)	-	(14.0)	(15.0)	-	(15.5)	(15.0)

2	-13.5 (15.5)	-13.2 (14.8)	- -	-14.1 (16.2)	-14.3 (15.5)	- -	-15.0 (15.7)	-13.8 (16.2)	- -	-13.0 (16.0)	-11.8 (18.9)	- -	-13.4 (16.2)	-13.2 (15.2)	- -	-13.2 (15.5)
3	-14.7 (15.5)	-13.1 (16.0)	-13.3 (16.4)	- -	-14.6 (16.8)	-14.7 (16.3)	- -	-14.8 (16.0)	-14.0 (16.8)	- -	-14.7 (16.6)	-14.0 (16.2)	- -	-13.2 (16.8)	-14.5 (16.8)	- -

Table 6. Mean and standard deviation () Total Time (TT), Reaction Time (RT), and Movement Time (MT) in ms as a function of Cue Validity and Location of the Cue and/or Distractor for Experiment 3.

		Valid				Invalid					
		Target Alone	Distractor Location			Cued Location			Cued/Distractor Location		
DV/ Target			1	2	3	1	2	3	1	2	3
TT											
	1	505	-	524	525	-	546	553	-	573	588
		(61)	-	(64)	(68)	-	(64)	(61)	-	(71)	(93)
	2	645	656	-	646	706	-	680	707	-	677
		(68)	(70)	-	(72)	(85)	-	(82)	(96)	-	(81)
	3	738	760	750	-	824	772	-	840	792	-
		(79)	(82)	(73)	-	(120)	(94)	-	(113)	(99)	-
RT											
	1	235	-	255	257	-	272	291	-	277	300
		(47)	-	(56)	(54)	-	(66)	(59)	-	(78)	(84)
	2	244	252	-	245	295	-	276	266	-	270
		(58)	(61)	-	(58)	(91)	-	(72)	(100)	-	(74)
	3	258	271	264	-	322	306	-	310	288	-
		(53)	(61)	(60)	-	(119)	(101)	-	(116)	(112)	-
MT											
	1	269	-	268	268	-	274	262	-	295	288

	(33)	-	(34)	(35)	-	(42)	(26)	-	(56)	(43)
2	400	404	-	401	411	-	404	441	-	406
	(49)	(52)	-	(50)	(67)	-	(48)	(63)	-	(48)
3	479	489	486	-	501	466	-	530	504	-
	(56)	(59)	(54)	-	(59)	(67)	-	(69)	(71)	-

Table 7. Mean and standard deviation () Peak Acceleration (PA) (cm/s^2) and Peak Velocity (PV) (mm/s) as a function of Cue Validity and Location of the Cue and/or Distractor for Experiment 3.

		Valid				Invalid					
	Target Alone	Distractor Location			Cued Location			Cued/Distractor Location			
DV/ Target		1	2	3	1	2	3	1	2	3	
PA											
1	1994	-	2014	2042	-	1973	2096	-	2140	2155	
	(483)	-	(446)	(514)	-	(520)	(484)	-	(591)	(511)	
2	2715	2707	-	2736	2660	-	2708	2243	-	2633	
	(705)	(717)	-	(706)	(772)	-	(769)	(596)	-	(797)	
3	3060	3087	2951	-	2870	3137	-	2690	2737	-	
	(888)	(845)	(802)	-	(713)	(795)	-	(762)	(759)	-	
PV											
1	780	-	804	797	-	793	813	-	847	877	
	(134)	-	(123)	(130)	-	(123)	(108)	-	(121)	(93)	
2	1557	1574	-	1564	1576	-	1570	1429	-	1578	
	(156)	(170)	-	(173)	(189)	-	(191)	(198)	-	(154)	
3	2162	2177	2145	-	2121	2217	-	2060	2105	-	
	(257)	(282)	(247)	-	(261)	(287)	-	(292)	(237)	-	

Table 8. Mean and standard deviation () Average Height (AveH), Average Distance Traveled (AveY), and Average Left-Right Displacement (AveX) in mm as a function of Cue Validity and Location of the Cue and/or Distractor for Experiment 3.

	Valid				Invalid					
	Target Alone	Distractor Location			Cued Location			Cued/Distractor Location		
DV/ Target		1	2	3	1	2	3	1	2	3
AveH										
1	15.1	-	15.2	15.4	-	15.9	15.6	-	16.3	17.0
	(2.8)	-	(2.6)	(2.7)	-	(2.3)	(2.7)	-	(3.2)	(3.2)
2	26.9	26.5	-	27.0	26.2	-	27.4	26.6	-	28.0
	(5.5)	(5.6)	-	(5.3)	(5.9)	-	(5.0)	(5.2)	-	(5.2)
3	38.6	38.6	39.2	-	38.5	38.9	-	39.8	38.4	-
	(8.6)	(9.1)	(8.2)	-	(10.2)	(10.0)	-	(9.6)	(9.8)	-
AveY										
1	59	-	57	59	-	59	59	-	65	67
	(5.0)	-	(4.3)	(45.0)	-	(6.3)	(4.8)	-	(8.2)	(11.3)
2	166	166	-	167	166	-	168	161	-	167
	(10.7)	(11.6)	-	(11.2)	(13.4)	-	(13.8)	(10.3)	-	(10.2)
3	271	273	271	-	278	269	-	267	271	-
	(12.7)	(17.5)	(14.4)	-	(16.2)	(20.1)	-	(16.4)	(19.6)	-
AveX										
1	-20.6	-	-20.7	-20.3	-	-20.7	-20.6	-	-20.7	-21.1

	(4.4)	-	(3.9)	(4.4)	-	(4.4)	(4.3)	-	(4.5)	(4.1)
2	-21.6	-22.1	-	-21.7	-22.1	-	-21.4	-21.6	-	-21.3
	(5.3)	(5.6)	-	(5.5)	(5.2)	-	(6.2)	(5.0)	-	(5.7)
3	-23.1	-23.7	-22.6	-	-23.0	-23.7	-	-23.9	-22.9	-
	(6.7)	(6.6)	(6.9)	-	(6.2)	(6.4)	-	(5.5)	(7.2)	-

Figure Captions

Figure 1. Diagram of response vector hypothesis. a) and b) are the independent response vectors programmed to each of the competing responses. c) is the diagram of the summation or competition between the responses which would result in an initial "averaged response" that consists of both target and non-target response characteristics. d) is the diagram of the effects of the inhibition of the competing response either as the result of preexisting inhibition (response activation model) or inhibition of the competing response during movement planning (response vector model). Adapted from Tipper et al., 1997.

Figure 2. Diagram of the movement environment for Experiment 1.

Figure 3. Mean AveH of the movements to Target 1 as a function of Distractor Location. SE bars are shown.

Figure 4. Mean AveH of the movements to Target 3 as a function of Distractor Location. SE bars are shown.

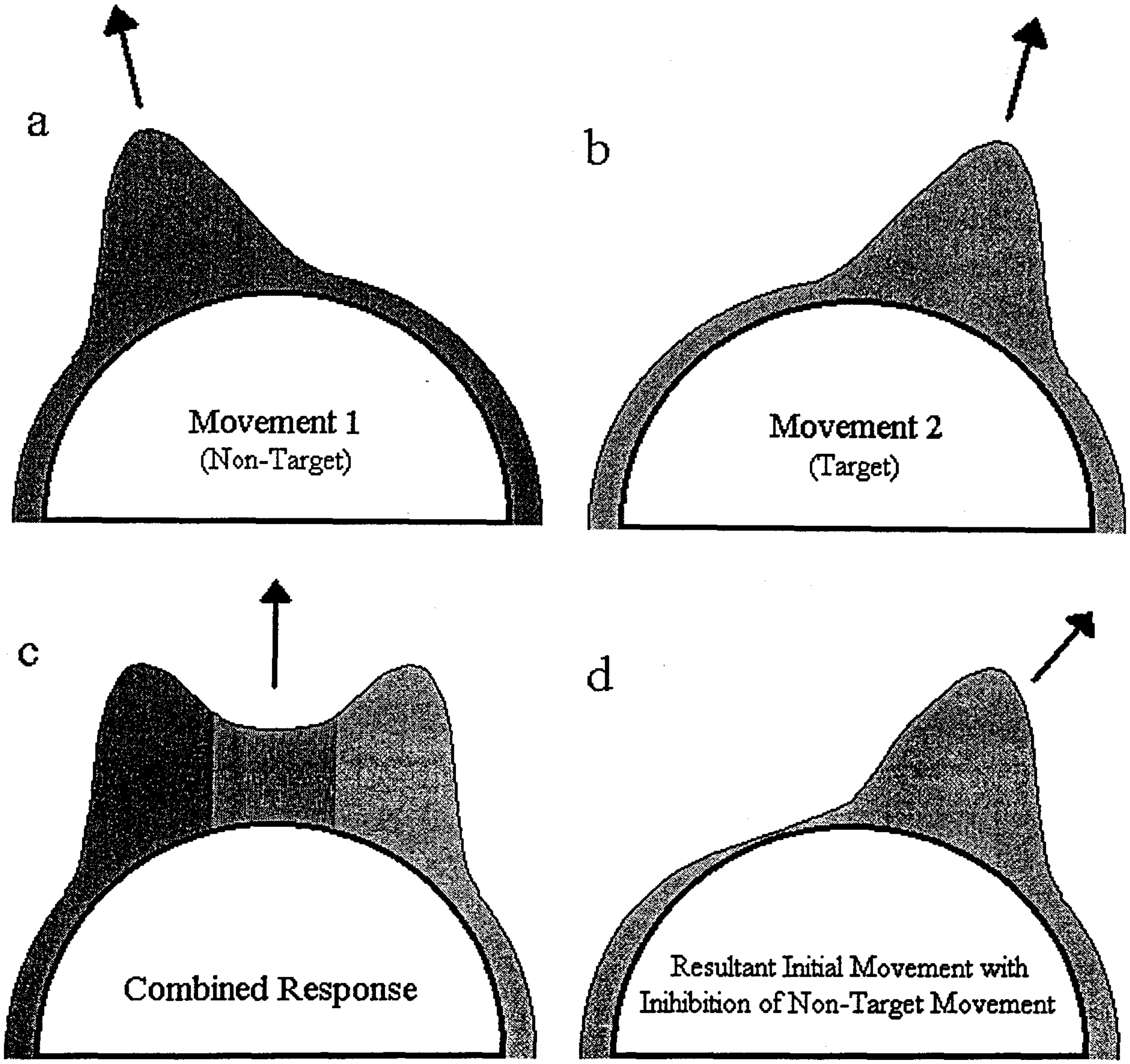
Figure 5. Mean Peak Velocity difference scores collapsed across target location as a function of Stimulus Onset Asynchrony. Values plotted represent the difference between the mean peak velocity for movements with a distractor present and the mean peak velocity for movements in the No Distractor condition. Thus, a negative value indicates that the distractor caused slower movements, whereas a positive value indicates that the distractor caused faster movements relative to the movements completed when there was no distractor in the environment. The solid line represents values for movements in which the distractor is closer to the start position than the target. The dashed line represents values for movements in which the distractor is farther from the start position than the target. SE bars are shown.

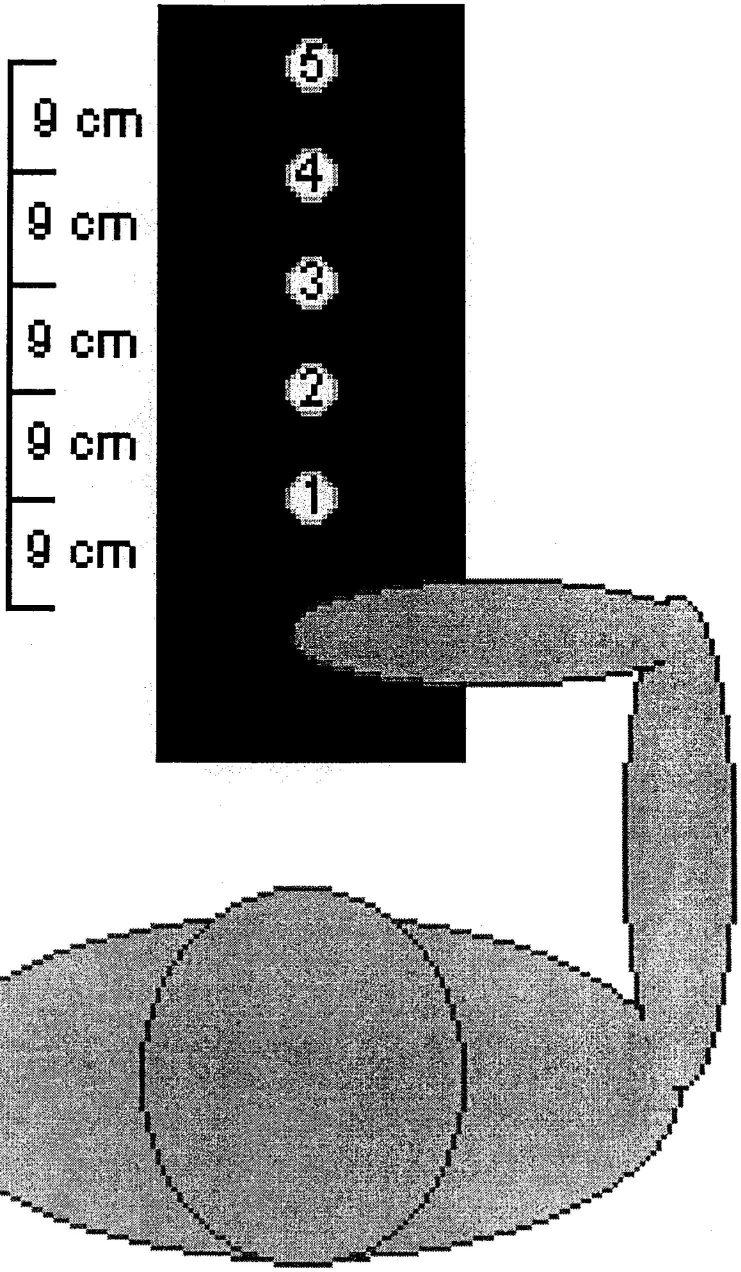
Figure 6. Mean AveY difference scores collapsed across target location as a function of Stimulus Onset Asynchrony. Values plotted represent the difference between the mean average displacement in the y axis for movements with a distractor present and the mean average displacement in the y axis for movements in the No Distractor condition. Thus, a negative value indicates that the distractor caused shorter movements, whereas a positive value indicates that the distractor caused longer movements relative to movements completed when there was no distractor in the environment. The solid line represents values for movements in which the distractor is closer to the start position than the target. The dashed line represents values for movements in which the distractor is farther from the start position than the target. SE bars are shown.

Figure 7. Mean Peak Velocity difference scores collapsed across target location as a function of Distractor Location. Values plotted represent the difference between the mean peak velocity for movements with a distractor present and the mean peak velocity for movements in the No Distractor condition. Thus, a negative value indicates that the distractor caused slower movements, whereas a positive value indicates that the distractor caused faster movements relative to the movements completed when there was no distractor in the environment. The solid line represents values for movements in which the target location was validly cued (VC condition). The dashed line represents values for movements in which the distractor was presented in the cued location (IC condition). SE bars are shown.

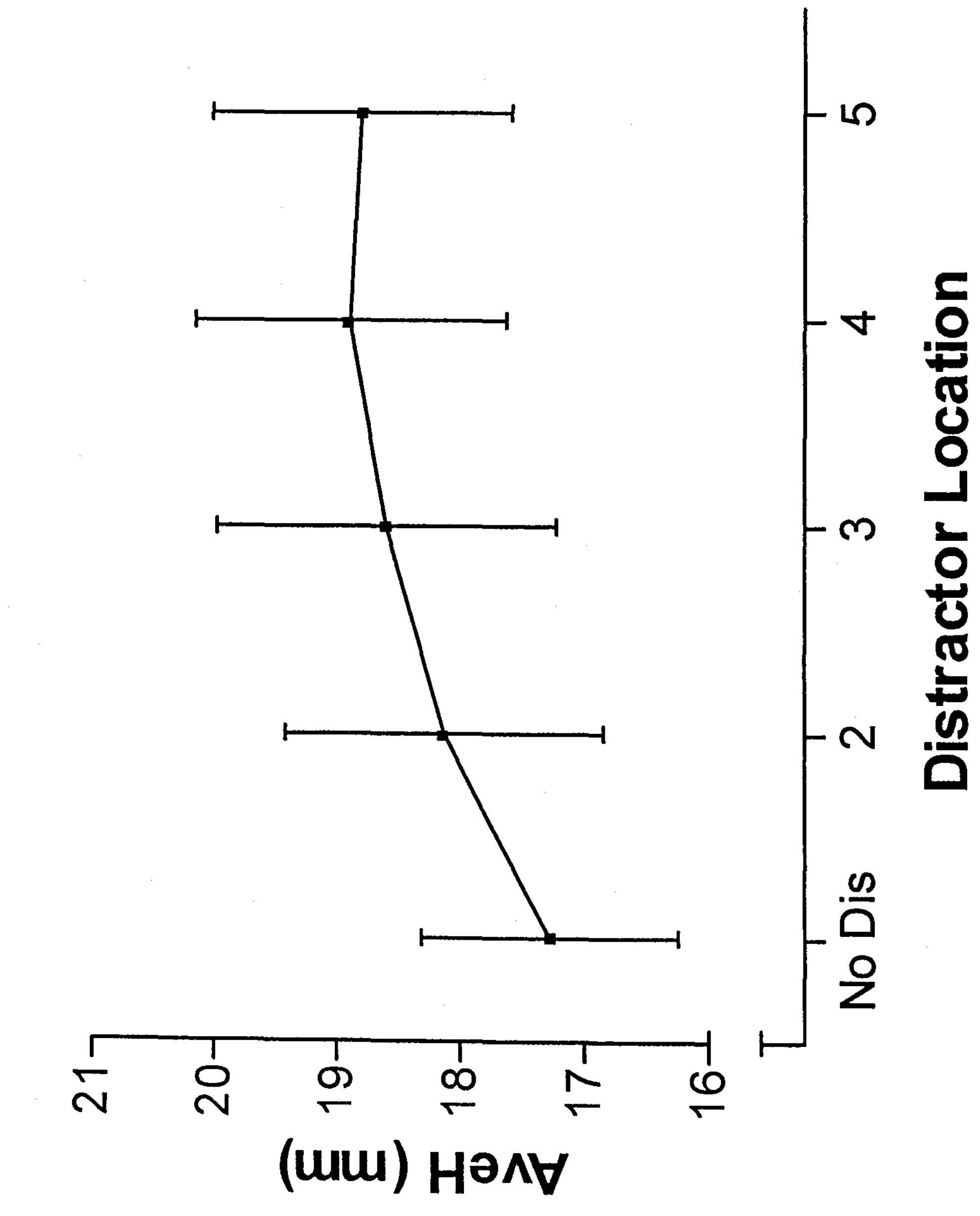
Figure 8. Mean AveY difference scores collapsed across target location as a function of Distractor Location. Values plotted represent the difference between the mean average displacement in the y axis for movements with a distractor present and the mean average

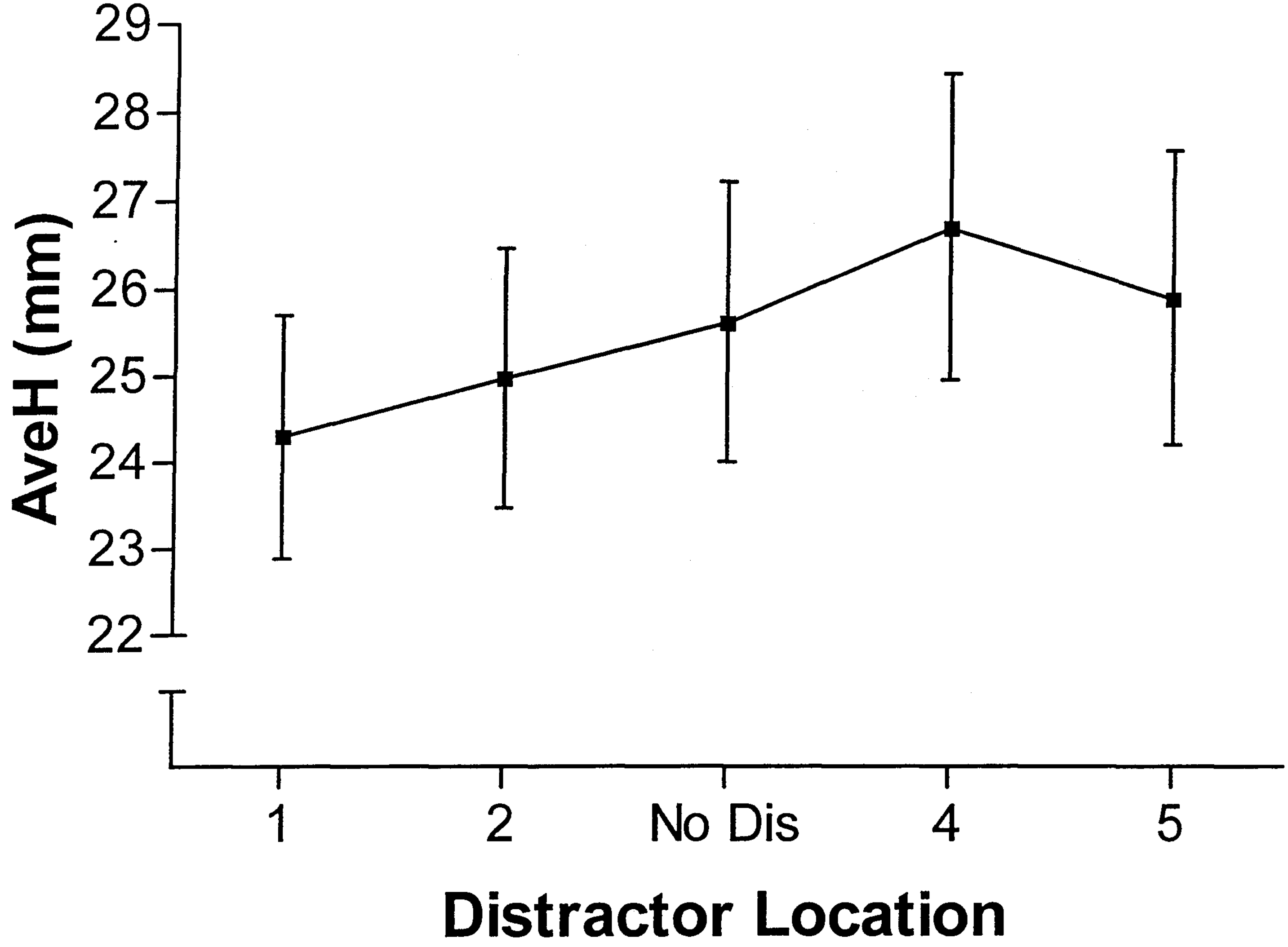
displacement in the y axis for movements in the No Distractor condition. Thus, a negative value indicates that the distractor caused shorter movements, whereas a positive value indicates that the distractor caused longer movements relative to the movements completed when there was no distractor in the environment. The solid line represents values for movements in which the target location was validly cued (VC condition). The dashed line represents values for movements in which the distractor was presented in the cued location (IC condition). SE bars are shown.

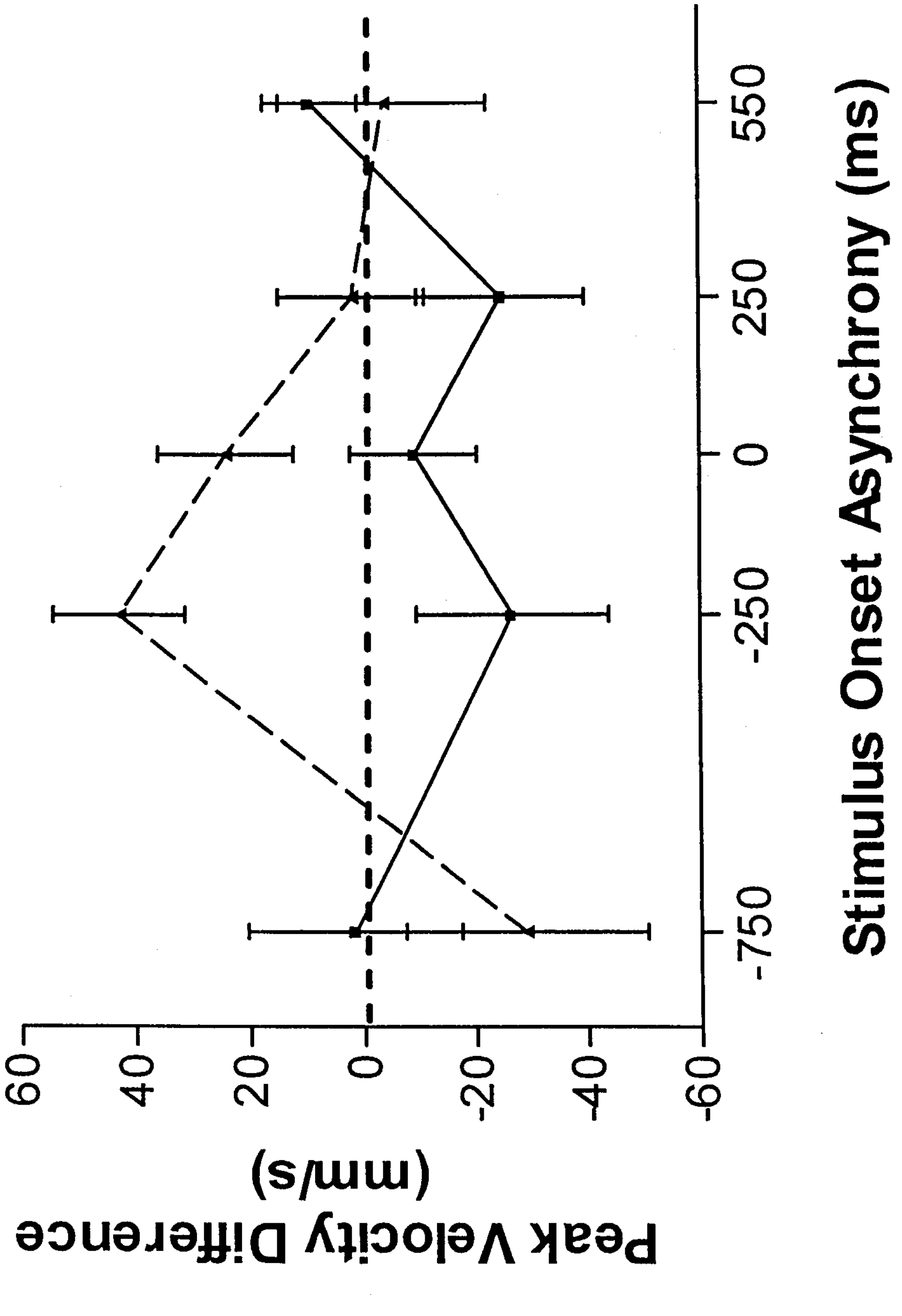

a
Movement 1
(Non-Target)
b
Movement 2
(Target)
c
Combined Response
d
Resultant Initial Movement with
Inihibition of Non-Target Movement

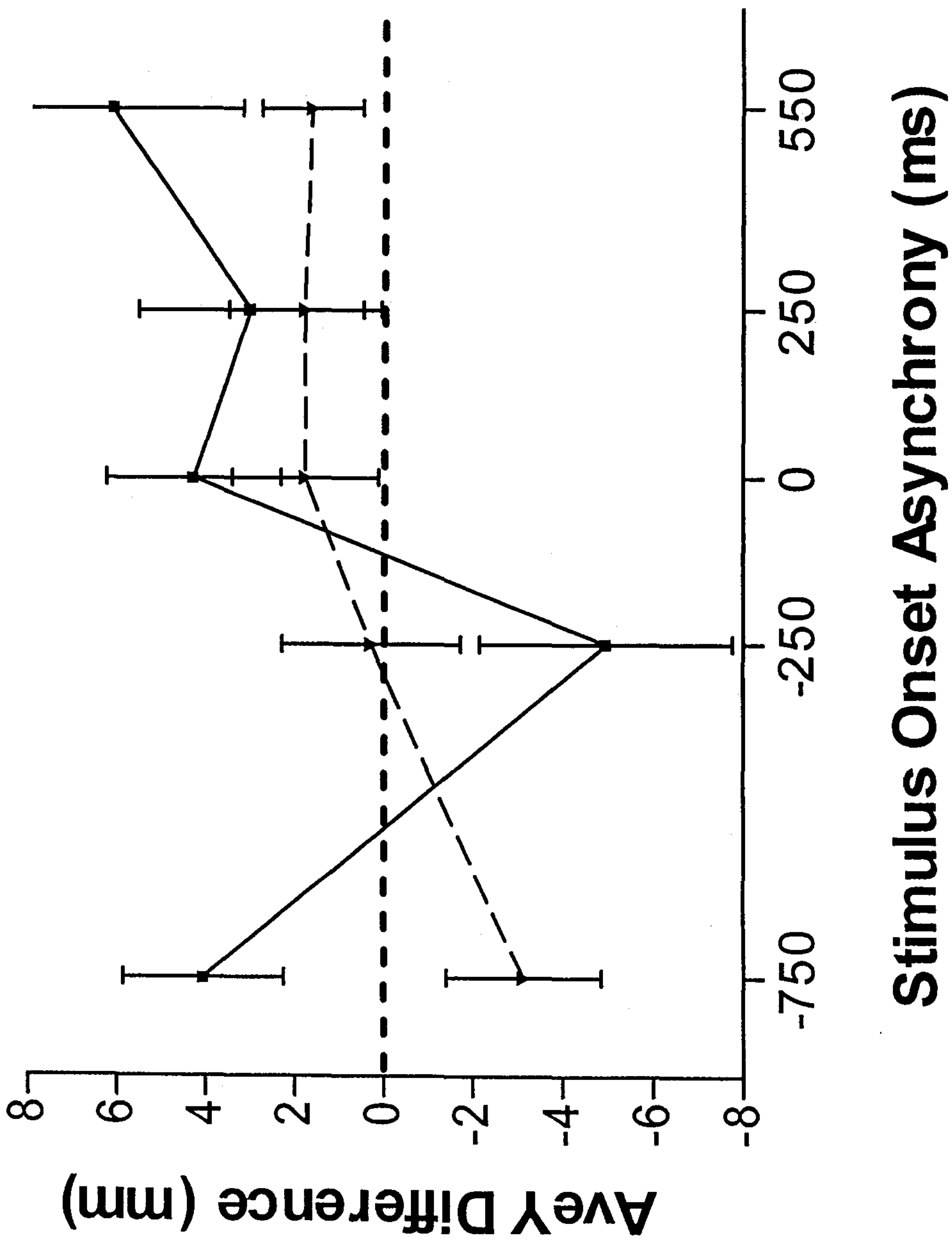


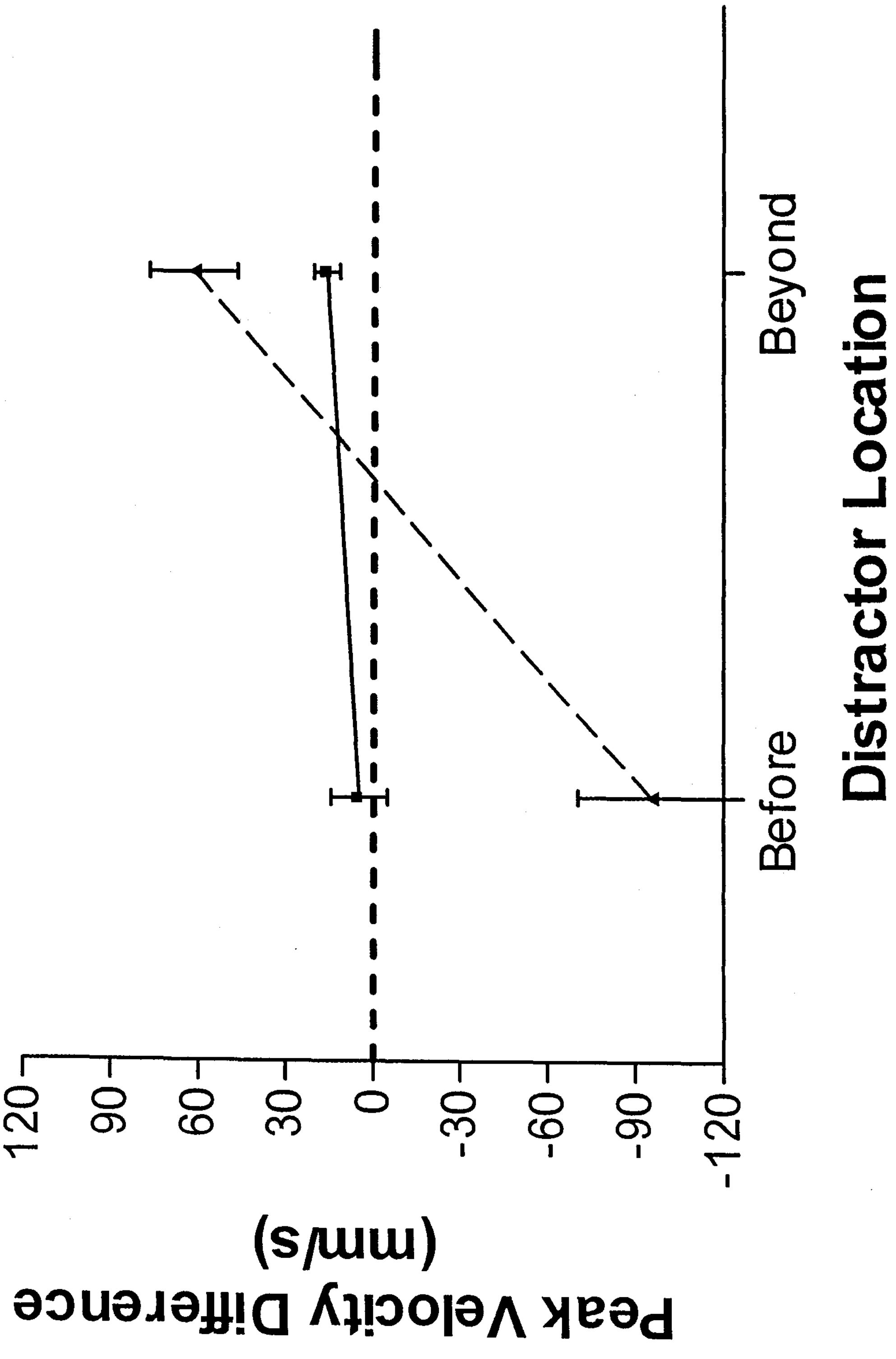
5
4
3
2
1
9 cm
9 cm
9 cm
9 cm
9 cm

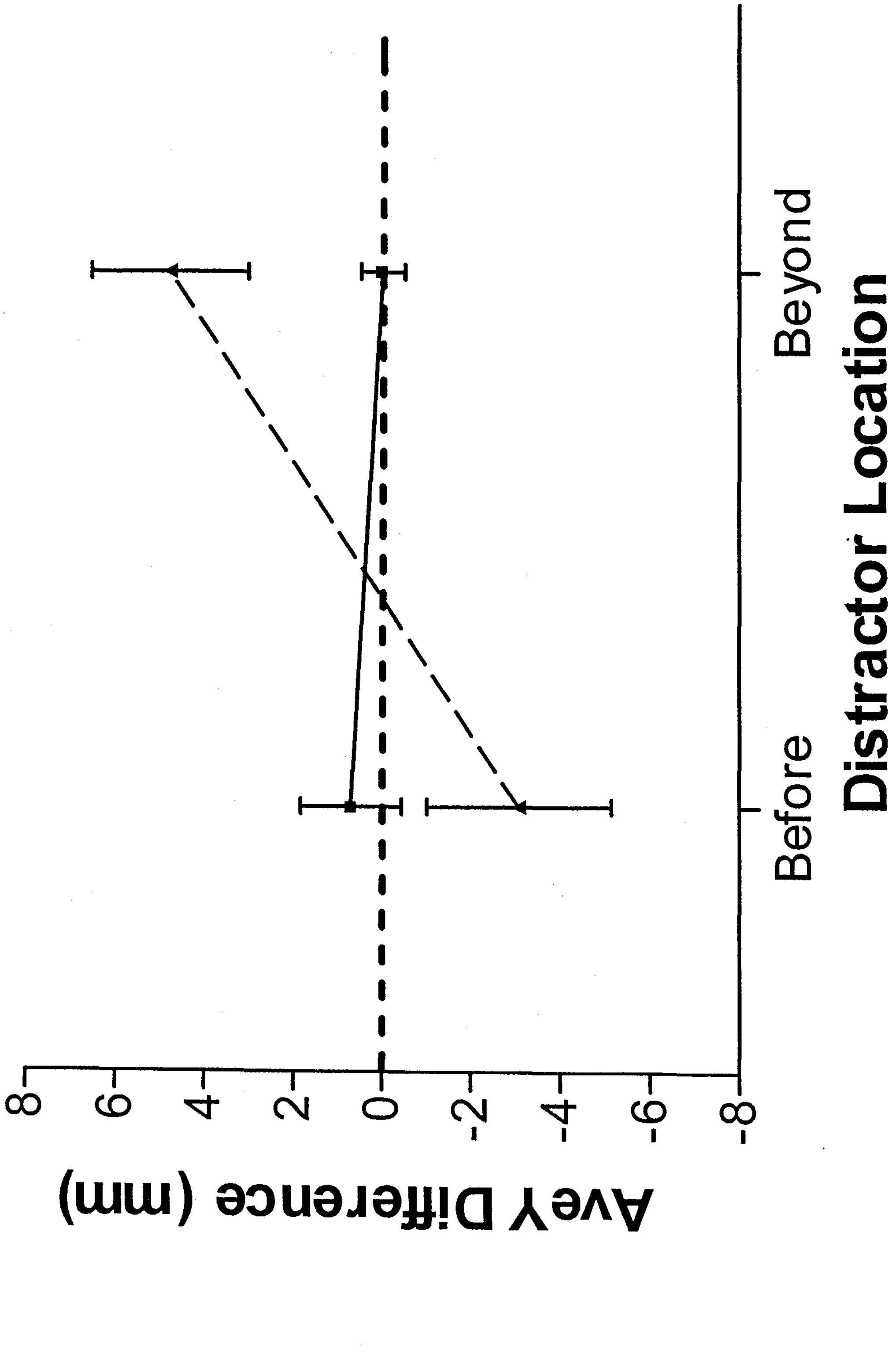

AveH (mm)
16
17
18
19
20
21
No Dis
2
3
4
5
Distractor Location


AveH (mm)
29
28
27
26
25
24
23
22
1
2
No Dis
4
5
Distractor Location


Peak Velocity Difference (mm/s)
60
40
20
0
-20
-40
-60
-750
-250
0
250
550
Stimulus Onset Asynchrony (ms)


AveY Difference (mm)
8
6
4
2
0
-2
-4
-6
-8
-750
-250
0
250
550
Stimulus Onset Asynchrony (ms)


Peak Velocity Difference (mm/s)
120
90
60
30
0
-30
-60
-90
-120
Before
Beyond
Distractor Location


AveY Difference (mm)
8
6
4
2
0
-2
-4
-6
-8
Before
Beyond
Distractor Location

STUDY 2

This manuscript has been submitted for publication. I was the major contributor to every aspect of this research project including experimental design, data collection and analysis, and write-up of the study. This paper has yet to be submitted for publication.

The Effects of Response Priming and Inhibition on Movement Planning and Execution

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Abstract

A precueing methodology was employed to test the ability of the model of response activation (Welsh & Elliott, submitted) to explain response priming and inhibitory effects in goal-directed action. Participants completed aiming movements to one of two locations following predictive (80% valid), non-predictive (50% valid), and anti-predictive (20% valid) precues at one of the two possible target locations. Consistent with the model, participants responded more quickly following valid precues than invalid precues in the 80% condition, and more quickly following invalid precues than valid precues in the 50% and 20% conditions. It was also found that movement trajectories deviated away from the cued location in the 50% condition. Inconsistent with the model, however, were the findings that movement trajectories in the 80% condition and the 20% condition deviated away from the cued location following an invalid cue and away from the uncued location following a valid cue, respectively. A strategy of overcompensation was offered to explain these latter trajectory results.

The Effects of Response Priming and Inhibition on Movement Planning and Execution

Based on work investigating the nature of action-centered theories of attention, Welsh and Elliott (submitted) proposed a response activation model of selective action. The basic tenets of the model are that an actor will approach a specific situation with a response set in working memory. Contained in this response set are parameterized values of responses to all the action-relevant stimuli in the environment. These parameterized values can be either excitatory or inhibitory and will depend upon both recent and past experience (e.g., learning) with this specific or similar set of environmental circumstances, and the actor's own goals and motivations. When presented with an action-relevant stimulus, that stimulus automatically initiates processes associated with a response to that stimulus (Rizzolatti, Riggio, & Sheliga, 1994; Tipper, Lortie, & Baylis, 1992). These processes then interact with the parameterized activity level for that response. If that particular response is already partially activated (a positive parameterization), then that response will emerge fairly rapidly. On the other hand, if the response specific to the stimulus is already inhibited (a negative parameterization), then the response will not emerge, or will emerge in a slow and contaminated manner. Because most behaviours do not occur in environments where only one action-relevant stimulus is present, it is often the case that multiple response-producing processes are initiated at any given time. The observed behaviour, then, is determined by the level of activation achieved by each of the competing responses.

Because the model of response activation evolved out of research investigating action in complex environments, it can account for the altered movement trajectories in the presence of action-relevant non-target stimuli found for rapid eye (Sheliga, Riggio, &

Rizzolatti, 1994) and hand movements (Howard & Tipper, 1997; Welsh, Elliott, & Weeks, 1999; see Welsh & Elliott, submitted for details). In short, deviations both towards and away from a non-target stimulus were accounted for by the temporal location of the effects of inhibitory processes on the non-target response. If the competing response was in an active state at the moment of response initiation, then characteristics of the non-target response were incorporated into the target response and deviation towards the non-target occurred (Welsh et al., 1999). In contrast, if the non-target response is inhibited prior to movement initiation, either because of preestablished inhibition or successful selection of the target response from the non-target response (see Houghton & Tipper, 1994 for a detailed explanation of the role of inhibition in selection), then deviation away from the non-target location will result (Howard & Tipper, 1997; Welsh & Elliott, submitted). Although the model can account for the effects of the non-target stimulus on the trajectory of the target movement, the present study was designed to test the model's ability to explain other attention-based phenomena. Specifically, the precuing technique was employed to explore the effects of response priming and inhibition on the temporal and kinematic measures of goal-directed aiming movements.

The Effects of Precues on Response Programming

The precuing technique has been a useful method for studying how the distribution of attention throughout the environment affects the time required to initiate a response to a target stimulus (e.g., Jonides, 1981; Posner, Nissen, & Ogden, 1978). In a typical precuing protocol, the participant is faced with a central fixation point surrounded by a number of possible target locations. Following the presentation of the fixation and possible target locations, the participant is given some advance information about the target location for that trial via a peripheral or a central, symbolic stimulus (cue). A brief time interval follows the cue in which only the fixation and possible target locations are present. This interval is ended by the presentation of the target. The participant's task is to respond (e.g., press a button) as quickly as possible to the presentation of the target. Similar precuing techniques have been utilized by researchers of motor behaviour to explore how response programming is affected by advance information (e.g., Rosenbaum, 1980).

Generally speaking, the results of the studies that have employed the precue methodology have found that valid, informative precues[1] decrease detection times and movement planning times while invalid, informative and valid, non-informative (see below) precues result in increased detection and movement planning times. The attentional explanation typically given for the facilitation effect is that attention has been drawn to or focused on the precued location, and that this focusing of attention facilitates stimulus detection at the cued location while hindering detection at the other locations. From the motor behaviour point of view, the explanation is that the precue information allows the actor to preprogram or prime a response, or a certain parameter of the response (e.g., direction), decreasing overall programming times. Following the tenets of action-based accounts of attention (e.g., Rizzolatti et al., 1994; Tipper et al., 1992), the latter, motor-oriented explanation may be more parsimonious. That is, even in simple detection tasks with arbitrary key press or vocal responses, it may be that in attending to a location, the actor is priming a response to a stimulus in that location. The result of this response priming is the quicker release of the response to the target presentation and thereby decreasing "detection" times.

Although valid, predictive precues have been found to decrease response initiation times, valid, non-predictive precues tend to slow response-producing processes. Posner and Cohen (1984) were the first to describe this effect. They found that, when attention was non-informatively drawn to a peripheral location (via a brief cue at a target location that was not related to the probability of the target), and then reoriented to the central fixation point, response initiation times were longer for a target appearing at the cued location than at the uncued location. Since Posner and Cohen's (1984) seminal work, the inhibition of return (IOR) effect has been replicated in arbitrary (button-pressing) hand (e.g., Maylor, 1985; Rafal, Calabresi, Brennan, & Sciolto, 1989) and foot responses (e.g., Spence, Lloyd, McGlone, Nichols, & Driver, 2000), as well as target-directed eye (e.g., Abrams & Dobkin, 1994) and hand (e.g., Howard, Lupiáñez, & Tipper, 1999) movements. Based on the fact that IOR occurs for a variety of response modes, it has been suggested that both detection- and response-based mechanisms underlie the IOR phenomenon (Abrams & Dobkin, 1994; Posner, Rafal, Choate, & Vaughan, 1985; see Klein, 2000 for a review). This latter view is congruent with action-centered theories of visual attention.

A Response Activation Explanation of Precuing Effects

The facilitation and inhibition effects associated with advance information are consistent with the model of response activation. In the case of the benefit associated with valid predictive precue information, it can be suggested that the presentation of the cue results in the preprogramming (positive parameterization) of a response to a target in the cued location. The mechanism behind the preprogramming may be different for peripheral and symbolic cues, however. When the precue is peripheral (at or near a possible target location), consistent with action-centered theories of attention, response processes are automatically initiated to the cue because it is an action-relevant stimulus. It is hypothesized that, because the participant knows not to respond to the initial stimulus, parameterized values of inhibition in the response set are strong enough to prevent that activation from achieving threshold, but weak enough to keep the activity associated with response in an excitatory state contained within the now updated response set. Alternatively, when presented with symbolic advance information, the participant must actively preprogram the response (establish an excitatory parameterization) in the response set. These suggested mechanisms are consistent with the findings of Jonides (1981).

Regardless of the specific mechanism behind the response priming, the preprogramming of the response is represented in working memory as an expectancy for the target to appear at the cued location. This expectancy is intimately linked to the motor system and is represented by the increased, but subthreshold, activity of the neurons associated with a response (i.e., direction) (see Georgeopolous, 1991, for a review on the representation of movement direction in the motor cortex). As a result of this preprogramming, when the target stimulus appears in the cued location, the neuronal activity associated with the automatic initiation of the response to the sudden appearance of the target stimulus quickly reaches threshold and the response emerges. Conversely, if the cue is invalid (the target appears in an uncued location), the activity associated with the preprogrammed response must be inhibited, or altered, and the true target response must be programmed taking into account the partially active non-target response. The result of this reprogramming of responses leads to the increased response initiation times associated with invalid precues.

In a similar fashion, the model of response activation can account for IOR. When the cue is presented peripherally, response-producing processes are automatically initiated to the stimulus. Because the cue is non-informative, the parameterized values of inhibition against responding to the location of the first stimulus are strong enough to prevent the response from emerging and, in this case, actually rebound the activity of the neurons associated with these processes to below baseline (see also Houghton & Tipper, 1994). As such, when the target appears in the location of the cue, the target response processes will require greater time to overcome the negative bias against it and achieve activation. The greater time requirement results in the observed increased reaction times. However, when the cue is central and symbolic, there is no automatic initiation of response-producing processes to the periphery. As a result, none of the subsequent target responses are biased and IOR is not observed (Posner & Cohen, 1984; Rafal et al., 1989).

While the model of response activation can explain the temporal effects that peripheral and central precue information have on action, the model can also be used to form testable predictions about the effects that these excitatory and inhibitory processes will have on the characteristics of the target response. The purpose of the present experiment was to test these predictions by asking participants to complete rapid aiming movements to a target, located either to the left or right of fixation, following predictive (80%) or non-predictive (50%) peripheral precue information. Given the results of previous work on the effects of predictive and non-predictive precues, it was expected that participants would have shorter response initiation times following valid cues than invalid cues in the 80% condition, but shorter response initiation times following invalid cues than valid cues in the 50% condition. Predictions of the characteristics of the responses, however, require a more detailed discussion.

First, it was predicted that under conditions in which the cue is predictive of the target location (80% condition) and the target is presented at the precued location, the target response would emerge uncorrupted. This prediction was based on the assumption that the precue information elicits preprogramming of the response to that location (see also Welsh & Elliott, submitted). The second prediction was that an invalid cue would not only be associated with a longer reaction time, but also an altered response trajectory relative to the target movement that followed a valid cue. It was predicted that the movement would deviate towards the precued location because of the hypothesized preprogramming of the precued response. Specifically, because the precued response is primed, when the target appears at the uncued location, characteristics of the active (primed) non-target response would be incorporated into the target action and, hence, deviation towards the cued location (a more centrally directed response) would occur.

In the case of non-informative cues, it was predicted that movements following invalid cues would result in shorter reaction times (IOR) and deviations in the path of the movement away from the cued location relative to movements following valid cues. This pattern of results was predicted because the response to the cued location would be preinhibited (Rafal et al., 1989). Thus, consistent with the effects of preestablished inhibition on movement trajectories found in other studies (Howard & Tipper, 1997;

Sheliga et al., 1994, 1995; Welsh & Elliott, submitted), the target response to the uncued location would be biased against movement in the direction of the cued location. The difference in the directions of the movements would be reflected in valid movements being oriented more towards the centre of the environment than movements following the invalid cues.

In an attempt to further our understanding of the effects of response priming and inhibition on action, a third condition was added to the study. The third condition was one in which the target appeared in the cued location on only 20% of the trials. In essence, the cue was anti-predictive of the location of the target in that it told participants to expect the target at the uncued location. It was hypothesized that, upon presentation of the peripheral cue in the 20% condition, participants would inhibit the automatically elicited response to the cued location and also prime the response to the uncued location. For the temporal measures of movement, it was predicted that the combined response priming and inhibition would lead to faster response times following an invalid cue relative to a valid cue. Given that the response to the uncued location should be primed, it was predicted that the deviation towards the uncued location would occur following a valid cue; an effect opposite to that predicted for the 80% valid condition.

Method

Participants

There were 18 right-handed participants (8 men, 10 women; age range 19-26 yrs) involved in the present study. The participants were recruited from the undergraduate and graduate Kinesiology program at McMaster University. For inclusion into the study, each person had to have normal or corrected-to-normal vision and be naïve to the purpose of the study. Each participant was given a $10 honorarium. The methods of this study were approved by the research ethics committee of McMaster University. Informed consent was obtained from the participants prior to data collection.

Apparatus

Participants sat at a table in front of grey metal box (3 cm H X 58 cm W X 70 cm L). Embedded in the surface of the aluminum were three LEDs (1.5 cm diameter). The LEDs (Dialight, series 557) emitted green light and were arranged 18 cm apart in a row aligned perpendicular to the midline of the body (Figure 1). A piece of masking tape was placed over the middle LED and a blue, 2 cm fixation cross was marked in the middle of the tape. The other two LEDs served as the location of the cues and of the targets. Finally, a circular white sticker (3 cm in diameter with an open 1 cm circular section in the middle) was affixed to the surface of the box. The sticker was placed 18 cm from the fixation cross and served as the start position.

To record the motions of the end point of the effector (dominant index finger), participants wore an infrared light emitting diode (IRED) over the nail of the finger. The location of the IRED was recorded by Optotrak™ motion recording system at a frequency of 500 Hz. The LEDs and the Optotrak™ were interfaced with a Lafayette Four-bank Millisecond Timer (model 52010) such that the onset/offset of the cue and target stimuli, as well as the beginning of movement recording, could be controlled.

Procedure and Task

Data for each participant were collected in a single session that lasted approximately 1 hr. Upon arrival at the session, the participant was given task instructions and a demonstration of the task. The participant was told to begin each trial by placing the dominant index finger on the start position and then fixating on the cross in the middle of the board. When the participant had fixated the cross, the experimenter gave a verbal "Ready" cue indicating the beginning of a 1000-2000 ms foreperiod. At the end of the foreperiod, one of the two possible target locations was cued by a brief 300 ms illumination of the LED. The participant was told that the validity of this cue would range from 80% to 20% across blocks and was told, at the beginning of each block of trials, the specific predictive value of the cue (i.e., 80%, 50%, or 20%) for that block of trials. Participants were also told that, when the cue was predictive (80% and 20% conditions), that they could use this information to their advantage. A further 700-1400 ms variable foreperiod followed the cue ending with the illumination of one of the target LEDs. The target LED remained illuminated for a further 2000 ms. Participants were instructed not to move (saccade or otherwise)[2] to the cue (first green light) but to move as quickly as possible to the target LED (second green light). Finally, to simplify data reduction, participants were told to remain on the target until the LED was turned off, after which they could return to the start position.

Participants completed 10 practice trials in the 80% valid condition prior to beginning the experimental phase of the study. During the experimental phase, trials were blocked according to the predictability of the precue and participants completed 2 blocks of trials in each of the three predictability conditions (6 blocks of trials in total).

The number of trials in each block varied depending on the validity of the cue for that block. Participants completed 50 trials in each of the 80% and the 20% valid blocks and performed 24 trials in the 50% valid block (258 total trials; 10 practice and 248 experimental). Within each block, the validity and target location for a particular trial was randomized with the constraint that a particular type of trial (e.g., valid movement to the left LED) could not be presented more than three times in a row. Order of experimental block presentation was randomly assigned. Finally, participants were offered a short break at the end of each block.

Data Reduction and Analysis

Recorded movement trajectories were filtered using a second-order dual-pass Butterworth filter with a low-pass cutoff frequency of 12 Hz. These filtered displacement profiles were then differentiated twice using a 2-point central finite difference algorithm to calculate instantaneous velocity and acceleration. All dependent variables were obtained from these profiles using custom software (see Chua & Elliott, 1993).

Temporal Dependent Variables. Movement initiation was defined as the first sample in which the velocity of the movement in the primary axis of movement (y axis) reached a threshold of 30 mm/s and remained above the threshold for more than 72 ms (36 consecutive samples). Similarly, movement termination was defined as the first sample in which the movement velocity in each axis fell below 30 mm/s and remained there for 50 ms (25 consecutive samples). As such, reaction times and total responses times were calculated by multiplying the number of samples from the beginning of movement recording (target stimulus presentation) to movement initiation or movement termination, respectively, by the sampling rate (2 ms/sample). Movement time was calculated by subtracting reaction time from total response time.

Kinematic Dependent Variables. The kinematic measures of peak acceleration (PA), peak velocity (PV), and peak deceleration (PD) were analyzed. PA and PD were defined as the maximum and minimum values of the instantaneous acceleration profiles of that particular trial, respectively. Likewise, PV was defined as the maximum velocity achieved during a particular movement. These specific kinematic markers were examined because they are thought to reflect the preprogrammed (PA and PV) and corrective (PD) portions of rapid aiming movements (see Elliott, Helsen, & Chua, 2001 for a review).

Trajectory Dependent Variables. In order to examine the effects of preprogrammed response priming and/or inhibition on the movement trajectory, the displacements along each axis were first separated from the resultant 3D displacement profiles. Next, these separated displacement profiles were divided into the four sections according to the specific kinematic markers. The four sections and their markers were: 1) Section 1 - the first sample after movement initiation until the sample immediately prior to PA; 2) Section 2 - PA until the sample immediately prior to PV; 3) Section 3 - PV until the sample immediately prior to PD; and, 4) Section 4 - PD until the sample immediately prior to movement termination (instantaneous velocity <30 mm/s). Finally, using the home position as the origin (0, 0, 0), average displacements within each section for each axis were calculated. Average displacement values were calculated by dividing the sum of all the displacement values recorded at each sample from the beginning to the end of each section by the number of samples taken during that section.

Inferential Statistics. Prior to the statistical analysis, data for trials on which the participant initiated a movement upon cue presentation (<1 % of trials) or had a RT of <100 ms (<2% of trials) were eliminated from the set. Recording errors (e.g., IRED lost from view of cameras) resulted in the elimination of a further 1-9% of trials depending on the participant. The data from one participant were completely removed from the analysis due to excessive recording (19% of total trials) and movement errors (3% of total trials).

Mean values of each temporal and kinematic dependent measure were submitted to separate 2 Side of target (Left, Right) by 3 Predictability (80, 50, 20) by 2 Validity (Valid, Invalid) repeated measures ANOVAs. The analysis of the measures of movement trajectory consisted of submitting mean values for each axis to separate 2 Side of target (Left, Right) by 3 Predictability (80, 50, 20) by 2 Validity (Valid, Invalid) by 4 Section (1, 2, 3, 4) repeated measures ANOVAs. For the analysis of the Y and Z (height) axes, the actual recorded displacement values were analyzed. In order to decrease the systematic error due to the differences in left vs. rightward movement, the absolute displacement values in the X axis were submitted to the analysis. Post hoc analysis of all significant effects involving more than two means was performed using Tukey's HSD ($p < .05$).

Results

Temporal

The analysis of TT revealed a main effect for Side, $F(1, 16) = 43.90$, $p < .001$. Consistent with previous work (see Elliott & Chua, 1996 for a review), TTs were shorter for movements into right (ipsilateral) space (579 ms) than into left (contralateral) space (626 ms). Although the main effect for Validity, F (1, 16) = 9.88, p < .01, revealed that TTs were shorter following Invalid (597 ms) than Valid cues (604 ms), post hoc analysis of the Predictability by Validity interaction, F (2, 32) = 16.80, p < .001, revealed that this Invalid cue advantage depended on the Predictability of the cue. As predicted, TTs were shorter following Valid cues than Invalid cues in the 80% condition (see Figure 2). Although, there was a trend in TT for an Invalid advantage in the 50% condition (IOR), a significant Invalid advantage was only found for movements in the 20% condition (see Table 1).

In contrast to TT, but consistent with the literature on movement laterality, the main effect for Side in the RT analysis, F (1, 16) = 5.56, p < .05, revealed that RTs were shorter when moving into left space (236 ms) than right space (246 ms) (Carson, 1996). The main effect for Validity, F (1, 16) = 19.72, p < .001, indicated that, as in TT, movement initiation times were shorter following Invalid (234 ms) than Valid (246 ms) cues. Again, this effect was superceded by a significant two-way interaction between Predictability and Validity, F (2, 32) = 17.37, p < .001. Post hoc analysis of the two-way interaction revealed a pattern of effects that was slightly different from that of the TT analysis. For RT, there a was only trend for a Valid advantage in the 80% condition, whereas significant Invalid advantages were found in both the 50% (IOR) and 20% conditions.

Finally, the MT analysis revealed only a main effect for Side, F (1, 16) = 78.87, p < .001. It was found that movements into ipsilateral (right) space (333 ms) were completed in less time than movements into contralateral (left) (391 ms) space. The

Validity of the cue did not affect MT; the main effect for Validity, F (1, 16) = 1.20, $p > .28$, and Predictability by Validity interaction, F (1, 16) = 2.25, $p > .12$, were both not significant. The absence of a Validity effect for MT suggests that the advantage associated with the validity of the cue was restricted to response initiation.

Kinematic

Consistent with the finding of a shorter MT for movements into right space, peak accelerations, F (1, 16) = 57.36, $p < .001$, peak velocities, F (1, 16) = 79.34, $p < .001$, and peak decelerations , F (1, 16) = 8.60, $p < .01$, were greater for movements into right space than into left space (see Table 2). Although no other effects reached conventional levels of significance in PA, there were significant Side by Predictability by Validity interactions found for PV, F (2, 32) = 3.71, $p < .05$, and PD, F (2, 32) = 4.10, $p < .05$. Post hoc analysis of these effects revealed identical effects for both PV and PD. Specifically, the only significant difference was that movements had higher PVs and PDs following Valid cues than Invalid cues in the 50% condition, and only when movements were made into right space. No other comparisons were significant.

Trajectory

AveY. Not surprisingly, the main effect for Section in AveY, F (1, 16) = 102.73, $p < .001$, revealed that the participants moved further from the starting position with each section (see Table 3). This overall effect was qualified by a significant interaction between Section and Side, F (3, 48) = 22.17, $p < .001$. Post hoc analysis of the interaction revealed that the average distance covered in Section 1 was not different between right and left movements. As the movements progressed, however, leftward movements achieved higher AveY values for Section 2 and 3, but ended with a shorter AveY in the last segment of the movement (Section 4).

As with the results of the Temporal and Kinematic analyses, the Validity of the cue was found to affect displacement in the Y axis (Predictability by Validity interaction for AveY, F (2, 32) = 6.30, p < .01). Post hoc analysis of this two-way interaction revealed that movements following Valid cues were shorter than movements following Invalid cues, but only in the 80% condition.

AveH. Movements were found to increase in height from Section 1 to Section 3 before decreasing in Section 4 (main effect for Section, F (1, 16) = 102.73, p < .001) (see Table 4). There was also a main effect for Side in AveH, F (1, 16) = 11.39, p < .005, revealing that participants moved higher when moving to the left target than to the right target. The main effect for AveH was qualified by a significant interaction between Section and Side, F (3, 48) = 25.46, p < .001. Post hoc analysis of this interaction revealed that movements to the left target were higher than those to the right, but only in Section 2.

The Validity of the cue was also found to affect the height of the movement trajectories. The Validity effect, however, was dependent on the predictability of the precue information as shown through significant Predictability by Validity, F (2, 32) = 8.13, p < .005, and Section by Predictability by Validity, F (6, 96) = 5.08, p < .001, interactions. Post hoc analysis of the three-way interaction revealed that movement trajectories were lower following Valid cues than Invalid cues in the 80% condition. In contrast, trajectories were lower following an Invalid cue than a Valid cue in 20%

condition. Both of these trajectory effects were only present in Sections 2 and 3 of the movements. Consistent with predictions, it seems that when there was information about the location of the target, participants took a more direct (efficient) route to the target.

AveX. As with AveY, it was not surprising that the main effect for Section in AveX, F (3, 48) = 3341.77, p < .001, revealed that the participants moved further away from center with each Section of movement (see Table 5). There were also a main effect for Side, F (1, 16) = 52.49, p < .001, revealing that participants moved farther away from center when moving to the left target than to the right target. As with the displacements in the Y and Z (height) axes, these overall effects were qualified by significant interactions between Section and Side in AveX, F (3, 48) = 24.00, p < .001. Post hoc analysis of the interaction revealed that left- and right-directed movements were not different from each other in Section 1, but as the movement continued (Sections 2-4) rightward movements were biased towards the center compared to leftward movements.

The Validity of the cue was found to affect movement trajectory. Again, the effect of the validity of the cue on displacement in the X axis was dependent on the predictability of the precue information as shown through significant Predictability by Validity, F (2, 32) = 11.88, p < .001, and Section by Predictability by Validity, F (6, 96) = 2.21, p < .05, interactions. Of theoretical interest were the results of the post hoc analysis of the three-way interaction. This analysis revealed that no differences existed between the displacements early in the movement (Section 1). As the movements progressed, however, displacements started to differ. Consistent with predictions, movements following Valid cues in the 50% condition were more central than following Invalid cues in Section 2, 3, and 4 (Figure 3). This effect indicated that participants were repelled from the cued location in this condition. In contrast to predictions, however, in the 80% condition, it was found that movements were more central for Valid cues than Invalid cues in Section 2 and 3. Likewise, in the 20% condition, Invalid cues were found to be associated with more central trajectories than Valid cues in Section 3.

Discussion

The present experiment was designed to test the model of response activation by exploring the effects of response priming and inhibition on movement planning and execution. Specifically, we examined how the temporal and kinematic characteristics of the target movement change when the possible target locations are informatively or non-informatively precued. Based on the response activation model, it was predicted that all processes hypothesized to involve the establishment of inhibition (i.e., IOR and inhibitory priming) would result in longer response times and deviation away from the inhibited location, whereas response priming would result in shorter response times and deviation towards the primed target location. Although the temporal predictions were realized, some of the trajectory predictions were not. These results are discussed in relation to the model of response activation and action-based theories of visual attention.

Response Priming and Movement

The finding that response times were lower following valid precues than invalid precues in the 80% condition is consistent with the prediction that participants would prime or preprogram their responses to the cued location in that condition (Rosenbaum & Kornblum, 1982). It also appears that participants primed the response to the uncued location and inhibited the response to the cued location in the 20% condition as this condition was associated with the largest response time advantage. It must be noted that these total time effects were mainly the result of a decrease in reaction time, as opposed to in movement time, suggesting that these effects result from the enhancement of motor programming processes and not online corrective processes. Moreover, trajectories were lower for movements under these conditions suggesting that the priming of the response was associated with a more efficient movement. This latter effect suggests that the movement processes, not just detection processes, were primed. Further evidence for response priming comes from the pattern of trajectory deviations that was observed when the target appeared in the unexpected location.

It was predicted that the direction of the movement trajectory alterations in the 80% and 20% valid conditions would be opposite to each other. Specifically, it was predicted that the movements would deviate towards the cued location on invalid trials in the 80% condition and towards the uncued location following valid cues in the 20% condition. However, the opposite pattern of deviations occurred. That is, movements were found to deviate away from the cued location on invalid trials in the 80% condition and away from the uncued location on valid trials in the 20% condition. Contrary to what we expected, participants may have adopted a programming strategy to compensate for the activity associated with the primed response. That is, to solve the problem associated with a preprogrammed non-target response and ensure that the movement did not terminate at the primed location, the participant may have programmed the target movement in a direction that was beyond the true target direction. In this way, the programmed response would compensate for the erroneous primed activity. Such a strategy would likely be more time and energy efficient than attempting to inhibit the primed response prior to programming and initiating the target response. However, as often happens in corrective systems, the correction may have been too large resulting in a vector sum beyond the true target vector (see Figure 4b).

IOR and Response Processing

In the 50% condition, it was found that response initiation times were longer following a valid than an invalid peripheral cue. This result (IOR) is what is typically found under these conditions and has been associated with an inhibitory coding against the reorientation of attention to the cued location and against programming a response to the cued location (Abrams & Dobkin, 1994; Klein, 2000). Consistent with action-based theories of attention and the model of response activation, it was also found that the trajectory of the movement to the uncued location deviated away from the location of the cue, relative to the movement on a valid trial (see also Howard &Tipper, 1997; Sheliga et al., 1994 for similar trajectory deviations using a different methodology). It is suggested that this pattern of effects is the result of the lasting, but deteriorating, inhibition of the automatically initiated response to the presentation of the cue.

To elucidate, when the response to the cue was inhibited, the activity in the motor system associated with that response was temporarily reduced to below a baseline level. If the target then appeared in the cued location, the time required for the response-producing processes to achieve the activity needed to surpass threshold levels and allow the response to emerge increased. However, because it was the coding of that specific response that was inhibited, the movement trajectory in the valid trial was unaffected (see

Figure 4c). Alternatively, when the target was presented at the uncued location, because the neurons associated with that response were not directly inhibited, the response to a target presented at the uncued location was not impeded temporally. However, because the activity of the response to the cue was below baseline, overall activity associated with the response to the uncued location was affected, resulting in a contaminated response that deviated away from the cued location (see Figure 4d) (see also Howard & Tipper, 1997).

The results of the present study conflict somewhat with the results of a study by Howard et al. (1999). They were also investigating the effect of processes associated with IOR on the trajectory of rapid, goal-directed pointing movements. Under very similar conditions they found temporal IOR effects but no trajectory effects, whereas the results of the present study revealed both temporal and trajectory effects. There were two essential differences between the studies that may have caused the difference. First, there were six possible target locations in the Howard et al. experiment, but only two in the present work. Thus, it may be that the larger number of possible locations caused the response inhibition to be more diffuse and less potent, resulting in inhibition of insufficient strength to noticeably affect movement trajectories. This possibility is unlikely for two reasons. The first reason is that IOR is often observed in multi-target (>2) environments. Indeed, IOR has even been observed when there were 441 possible target locations (Bennett & Pratt, 2001). Moreover, if the inhibition was too diffuse to have an effect on response programming, then a temporal IOR effect should not have been observed.

The second difference between the two studies that could have accounted for the differing results is that Howard et al. employed a cue-target onset asynchrony (CTOA) of 600 ms. The CTOA employed in the present study varied from 700-1400 ms. As Welsh and Elliott (submitted) found movement deviations away from a non-target location (which was a stimulus similar to the cue in the present study) when the stimulus was presented 750 ms prior to the target stimulus, it is suggested that the differences in the trajectory effects between the two studies is likely the result of the increased CTOA. This difference is suggested to arise because of the time required to develop inhibition in the manual movement system. We propose that inhibition is an independent process (command)[3] that cascades through various response-oriented systems until it reaches the motor system. Thus, there is a time delay between the initiation of the independent inhibition process and the coding of the inhibitory command in the movement system.

The proposal that there is a separate time course for inhibitory processes that affect the initiation of the response and the coding of the response is consistent with a dual-mechanism system behind IOR - one that affects the orientation of attention/detection of the stimulus and one that affects response production (Abrams & Dobkin, 1994). This suggestion, however, is incongruent with a strict interpretation of action-centered theories of attention where the response programming should be affected along the same time course as the orientation of attention. However, there is often a dissociation between shifts of attention and movement. Specifically, in typical movement situations the orienting of attention to the target occurs before movement initiation; saccadic eye movement being a major indicator of the orienting of attention in these situations (e.g., Helsen, Elliott, Starkes, & Ricker, 2000). As eye movements (shifts of attention) to the target often precede the hand movement (are programmed on a different time course), perhaps eye movement deviations would be affected at smaller CTOAs. Thus, the time course of effects is not due to separate attention and action systems, but instead the different effects of inhibition on two types of action. Consistent with this proposal, Briand, Larrison, and Sereno (2000) found that IOR develops over a shorter time period in eye than in manual responses (see also Maylor, 1985). Thus, we propose that the orienting of attention, overt or covert, is an action in and of itself. As such, attentional orientation is affected by inhibition like an overt response. However, because shifts of attention are initiated with greater speed (in less time) than overt responses such as hand movements, the effects of inhibition should be apparent sooner on shifts of attention than overt movements. Although these ideas are speculative, there is evidence to suggest that as the task difficulty increases (in this case, attention shifting to a manual response), the crossover between facilitation and inhibition occurs later (Briand et al., 2000; Klein, 2000).

Summary

The results of the present study favour the model of response activation. Specifically, it seems that the priming of a response decreased response initiation times for that response (80% condition), whereas inhibition of a response resulted in increased response initiation times (50% condition). Indeed, the greatest temporal advantage was found conditions were such that participants likely primed the target response and inhibited the competing response (20% condition). Further support for the model and for the notion of response-based mechanisms underlying IOR came from the finding that movements in the 50% condition deviated away from the cued location. Although the findings that movement trajectories in the 80% condition and the 20% condition deviated away from the cued location following an invalid cue and away from the uncued location following a valid cue, respectively, it may have been that the participants were adopting a overcorrective strategy to ensure successful movement termination. Future work will be aimed at investigating the effects and time course of processes associated with IOR on eye and hand movements.

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Acknowledgements

This research was supported by a NSERC grant to Digby Elliott and a NSERC scholarship to Timothy N. Welsh. Digby Elliott's contributions are also supported by the Canada Research Chair Programme. The authors would like to thank Luc Tremblay and John Moroz for their technical assistance. The authors would also like to thank Timothy D. Lee, Bruce Milliken, and Janet Starkes for their comments on earlier versions of this paper.

Footnotes

1. For the purposes of the present paper, the following definitions apply to the descriptors of the precue information and their relationship to the target location that followed: valid precue - target is presented at the precued location; invalid precue - target appears at the uncued location; informative/predictive precue - the target is, more often than not, presented in the same location as the cue; non-informative precue - location of precue has no relationship to the location of the target; and, anti-informative/anti-predictive precue - the target is, more often then not, presented in the uncued location.

2. Eye movements were monitored by the experimenter. All trials on which overt eye movements were made were noted and eliminated from the analysis (1-3 % of the total trials per participant).

3. A similar process has been suggested to be involved in the phenomena associated with the go/no-go paradigms (e.g., De Jong, Coles, Logan, & Gratton, 1990; McGarry & Franks, 1997).

Table 1. Mean and Standard Deviation () of total response time (TT), reaction time (RT), and movement time (MT) in ms as a function of Side, Predictability, and Validity.

DV/		Left			Right	
Validity	80	50	20	80	50	20
TT						
Valid	615 (68)	637 (76)	646 (82)	573 (49)	589 (57)	593 (61)
Invalid	629 (71)	629 (82)	605 (71)	587 (53)	574 (61)	558 (60)
RT						
Valid	228 (40)	241 (44)	261 (63)	240 (41)	257 (38)	260 (46)
Invalid	239 (49)	231 (46)	219 (44)	246 (43)	241 (40)	230 (41)
MT						
Valid	388 (55)	397 (57)	385 (55)	332 (45)	332 (50)	333 (42)
Invalid	390 (57)	398 (57)	386 (55)	342 (54)	333 (46)	328 (48)

Table 2. Mean and Standard Deviation () of peak acceleration (PA), peak velocity (PV), and peak deceleration (PD) as a function of Side, Predictability, and Validity. The values shown are in cm/s^2 for PA and PD and mm/s for PV.

DV/	Left			Right		
Validity	80	50	20	80	50	20
PA						
Valid	1645 (744)	1570 (684)	1539 (629)	3097 (1259)	3109 (1351)	2967 (1134)
Invalid	1621 (668)	1484 (592)	1526 (643)	2994 (1196)	3042 (1223)	30519 (1183)
PV						
Valid	1015 (287)	1010 (320)	1011 (280)	1436 (450)	1429 (440)	1405 (409)
Invalid	1041 (306)	1000 (290)	1001 (246)	1421 (444)	1399 (418)	1423 (406)
PD						
Valid	1458 (1159)	1437 (1211)	1462 (1016)	1775 (1474)	1790 (1492)	1676 (1270)
Invalid	1475 (1019)	1440 (1045)	1396 (865)	1795 (1515)	1721 (1373)	1728 (1250)

Table 3. Mean and Standard Deviation () of average displacement in the Y axis in mm as a function of Side, Predictability, Section, and Validity.

Section/		Left			Right	
Validity	80	50	20	80	50	20
1						
Valid	7.17 (4.1)	7.12 (4.1)	7.38 (4.4)	5.37 (4.1)	5.27 (4.3)	5.29 (4.3)
Invalid	7.85 (4.1)	7.79 (5.6)	7.20 (4.4)	5.21 (4.2)	5.17 (4.2)	5.34 (4.2)
2						
Valid	49.19 (11.6)	50.59 (12.2)	49.90 (12.4)	40.25 (8.2)	40.13 (7.0)	39.97 (8.1)
Invalid	50.57 (13.2)	51.05 (13.7)	49.61 (11.1)	40.31 (9.1)	39.76 (7.6)	40.53 (7.5)
3						
Valid	131.46 (15.2)	134.44 (16.4)	135.39 (13.2)	127.55 (15.2)	128.55 (13.1)	130.10 (11.1)
Invalid	133.97 (15.2)	132.73 (14.7)	133.71 (14.1)	128.97 (16.6)	128.17 (14.6)	129.40 (13.6)
4						
Valid	175.99 (8.6)	176.57 (9.1)	178.05 (8.9)	186.81 (9.1)	187.03 (8.4)	187.46 (8.4)
Invalid	177.40 (9.7)	176.15 (8.9)	177.10 (8.8)	188.10 (10.4)	186.70 (9.6)	187.33 (9.2)

Table 4. Mean and Standard Deviation () of average displacement in the Z axis in mm as a function of Side, Predictability, Section, and Validity.

Section/		Left			Right	
Validity	80	50	20	80	50	20
1						
Valid	2.29 (2.7)	3.21 (2.5)	3.05 (2.9)	2.24 (2.5)	2.45 (2.6)	2.54 (3.0)
Invalid	2.93 (3.0)	3.31 (2.6)	2.57 (2.7)	2.40 (2.4)	2.53 (2.7)	2.35 (2.8)
2						
Valid	29.34 (9.1)	31.18 (10.4)	30.73 (8.1)	16.72 (8.0)	17.56 (8.5)	18.26 (7.9)
Invalid	31.67 (10.3)	30.88 (9.7)	29.34 (8.1)	18.48 (9.1)	17.67 (8.0)	17.08 (7.5)
3						
Valid	36.71 (9.0)	37.06 (8.6)	37.64 (7.0)	37.15 (12.3)	38.17 (12.0)	39.11 (12.2)
Invalid	37.81 (9.4)	36.81 (8.2)	36.27 (7.8)	39.67 (13.0)	38.21 (11.7)	36.87 (11.3)
4						
Valid	14.32 (5.7)	14.30 (6.2)	13.65 (4.0)	15.27 (5.2)	15.52 (5.2)	14.86 (4.0)
Invalid	14.35 (6.0)	14.75 (5.6)	13.64 (5.4)	15.43 (5.5)	15.23 (5.4)	14.76 (5.4)

Table 5. Mean and Standard Deviation () of average displacement in the X axis in mm as a function of Side, Predictability, Section, and Validity. Absolute values reported.

Section/		Left			Right	
Validity	80	50	20	80	50	20
1						
Valid	7.97 (5.0)	7.85 (3.7)	8.87 (4.6)	2.98 (2.4)	2.85 (2.6)	2.32 (1.4)
Invalid	9.75 (6.4)	9.00 (5.7)	8.20 (3.8)	2.92 (2.8)	2.75 (1.8)	2.45 (1.5)
2						
Valid	63.02 (17.2)	63.95 (17.4)	65.24 (15.1)	31.02 (9.7)	30.75 (9.2)	30.66 (8.9)
Invalid	68.80 (21.6)	67.54 (21.0)	63.72 (13.1)	32.45 (11.9)	31.52 (9.8)	30.63 (9.0)
3						
Valid	149.52 (18.7)	151.32 (19.6)	154.89 (11.7)	113.56 (15.4)	113.75 (13.8)	117.85 (13.9)
Invalid	152.66 (22.9)	152.61 (19.4)	152.12 (14.7)	116.32 (15.8)	116.52 (14.3)	116.26 (14.3)
4						
Valid	186.58 (7.2)	186.25 (7.6)	188.27 (6.5)	170.95 (8.2)	170.13 (7.7)	172.18 (7.6)
Invalid	187.93 (10.8)	187.07 (7.4)	187.24 (6.7)	171.87 (6.9)	172.55 (7.6)	171.15 (7.8)

Figure Captions

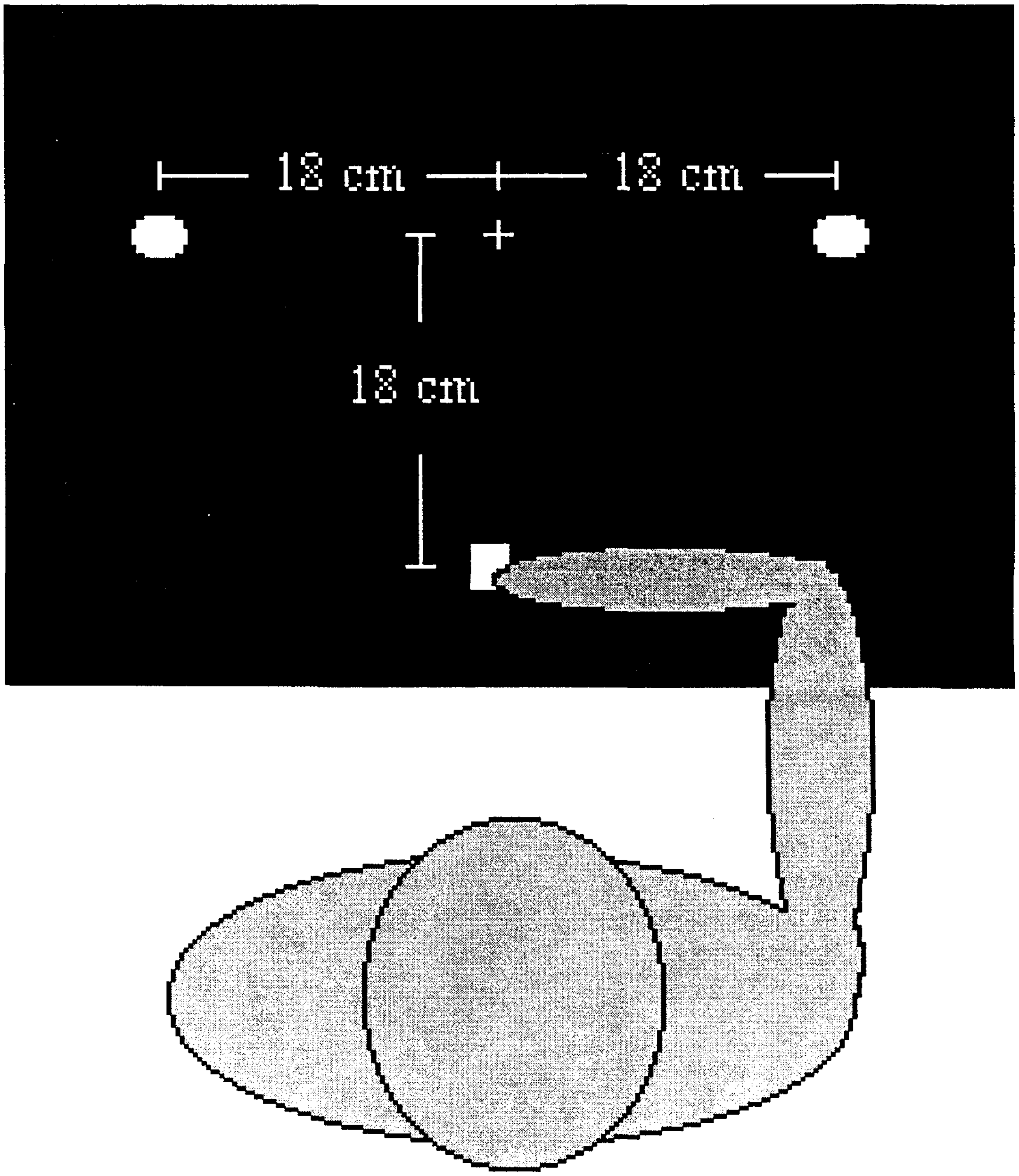
Figure 1. Schematic of movement environment.

Figure 2. Mean total response time as a function of Validity and Predictability. (Square symbols and solid lines represent total response times for movements following Valid cues. Triangle symbols and dashed lines represent total response times for movements following Invalid cues.)

Figure 3. Mean average displacement in the X (left/right) axis as a function of Section, Predictability, and Validity. Values plotted represent the difference between the mean average displacement under the specific movement conditions (e.g., movement to a Validly cued target under the 80% predictability condition) and the mean average displacements across all conditions per Section of movement. Thus, a positive value on the Y axis reflects a movement deviation away from centre relative to the average of all movements, whereas a negative value reflects a movement deviation towards centre relative to the average of all movements. (Square symbols and solid lines represent the values for movements following Valid cues. Triangle symbols and dashed lines represent the values for movements following Invalid cues.)

Figure 4. Response vector diagrams of the hypothesized activity in the motor system under the different movement conditions: A) activity associated with movements to the left and right targets independently; B) activity associated with a movement to the left target with a preprogrammed response to the right target - hypothesized to occur following an invalid cue in the 80% condition or a valid cue in the 20% condition; C) activity associated with a movement to the right target following a valid cue in the 50% condition; and, D) activity associated with a movement to the left target following an

invalid cue in the 50% condition. For comparative purposes, also diagrammed in B) and D) is direction of the uncontaminated response vector. Diagrams adapted from Tipper, Howard, & Jackson (1997).


18 cm
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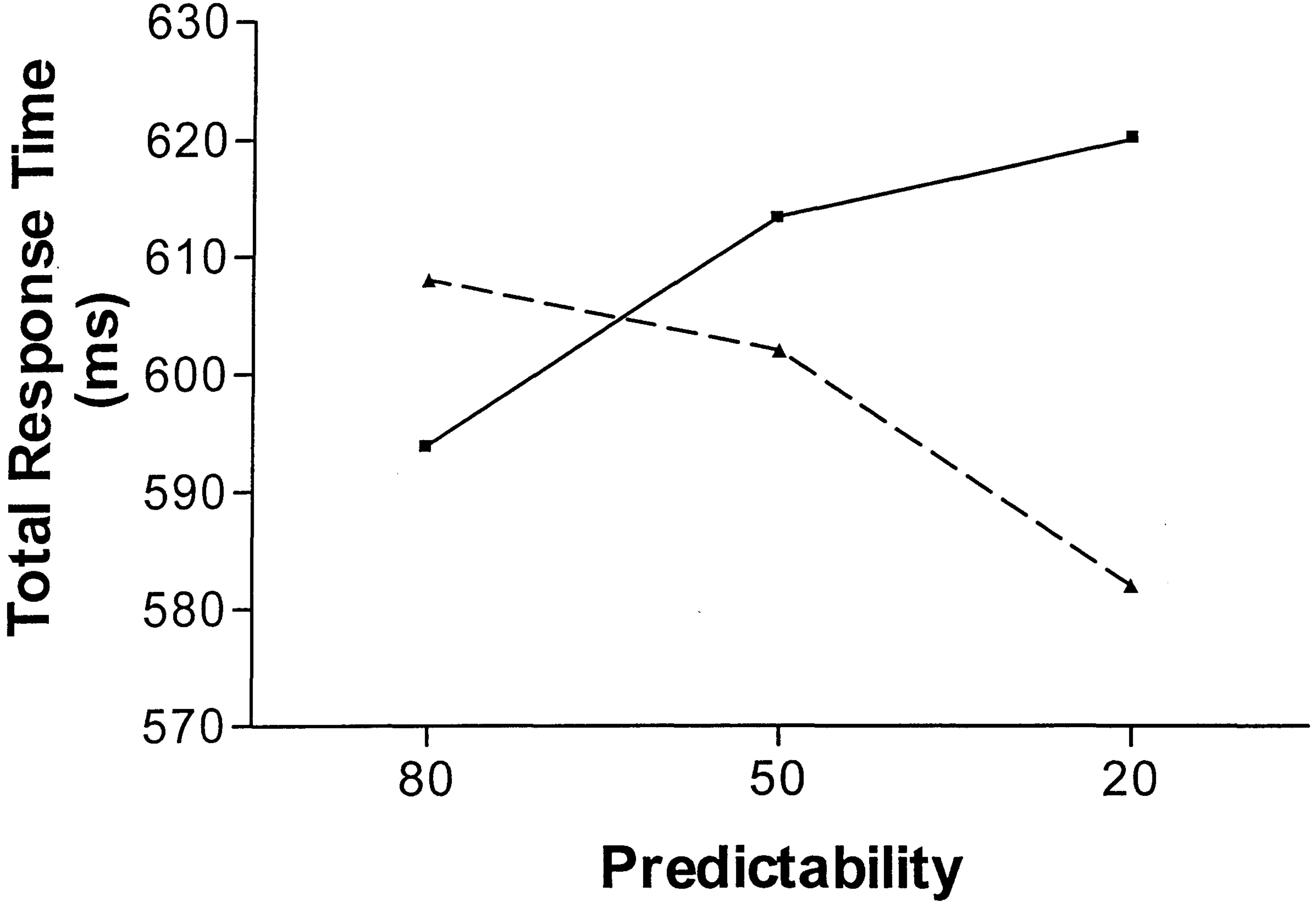
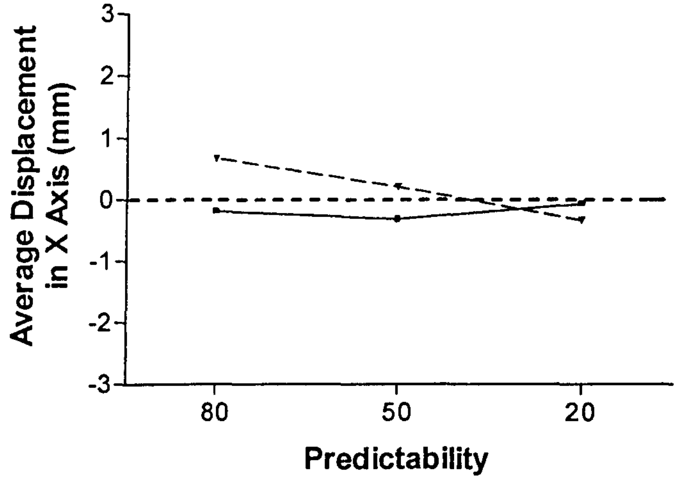
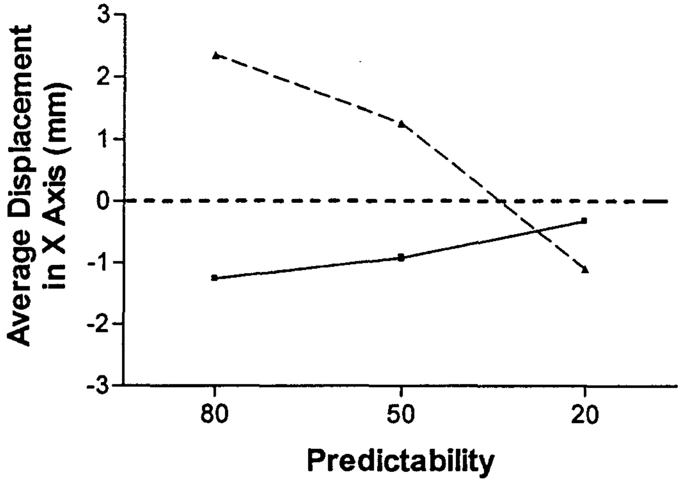
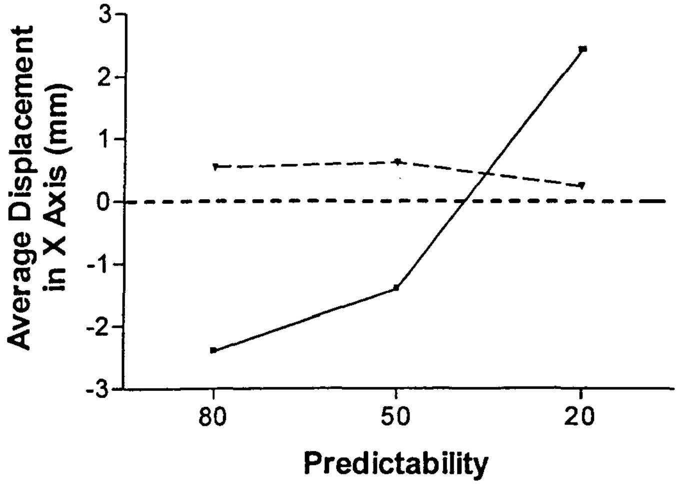
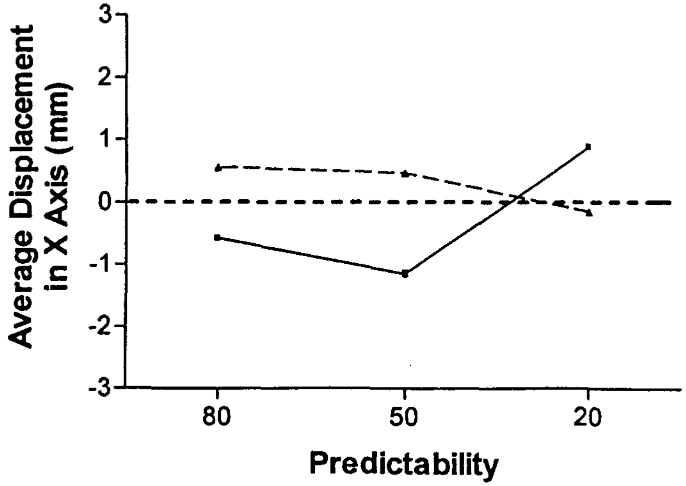
18 cm

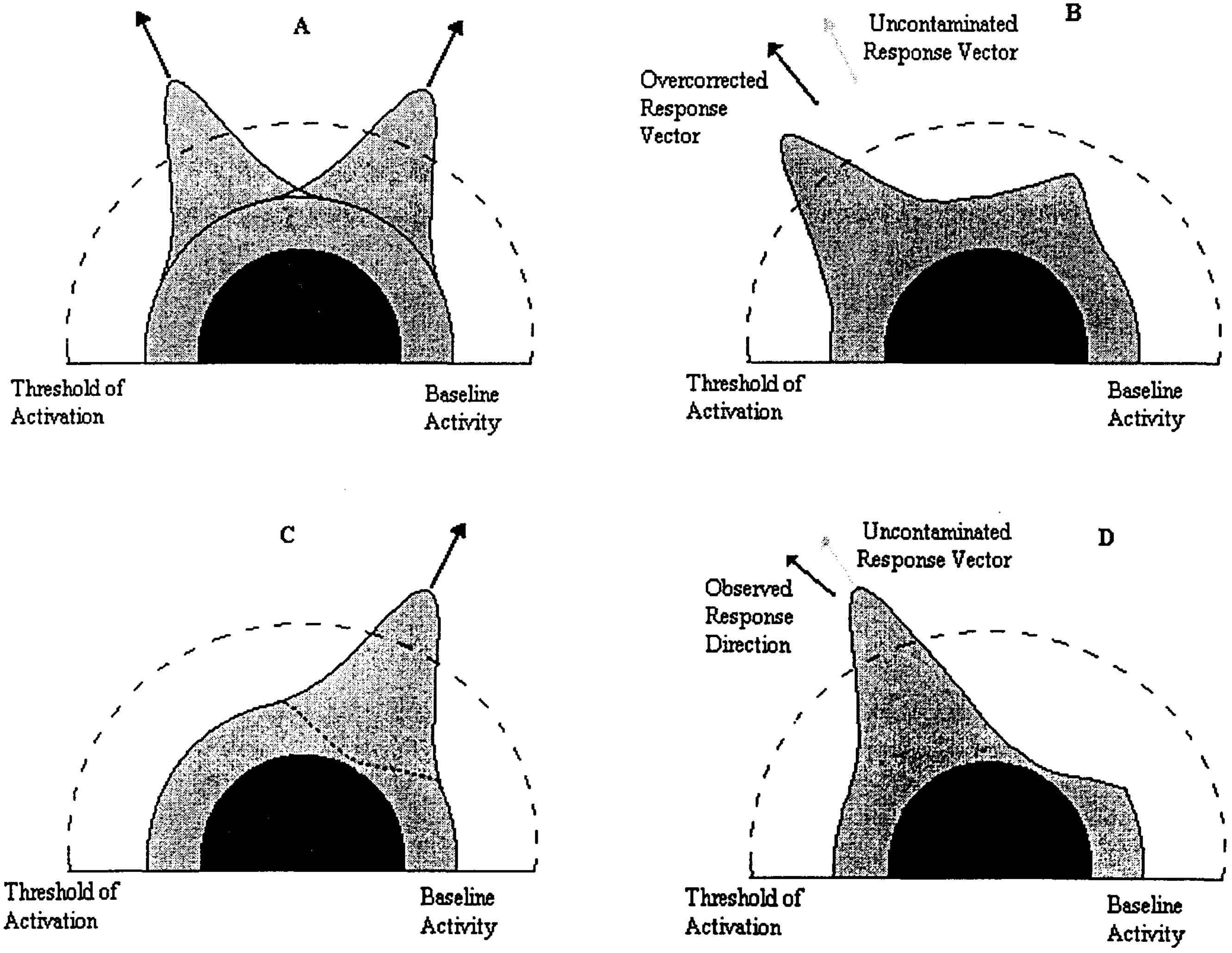

Total Response Time (ms)
630
620
610
600
590
580
570
80
50
20
Predictability


Section 1


Section 2


Section 3


Section 4


A
Threshold of Activation
Baseline Activity
B
Uncontaminated Response Vector
Overcorrected Response Vector
Threshold of Activation
Baseline Activity
C
Threshold of Activation
Baseline Activity
D
Uncontaminated Response Vector
Observed Response Direction
Threshold of Activation
Baseline Activity

STUDY 3

I was the major contributor to every aspect of this research project including experimental design, data collection and analysis, and write-up of the study. This paper has yet to be submitted for publication.

On The Relationship Between Distractor Interference, Response Inhibition, and Inhibition of Return

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Abstract

The purpose of the present study was to attempt to integrate recent proposals about the mechanisms underlying negative priming and inhibition of return (Milliken, Tipper, Houghton, & Lupiáñez, 2000) with a model of selective action (Welsh & Elliott, submitted). Specifically, the notion of a common inhibitory process underlying inhibition of return and negative priming was tested by examining the temporal and trajectory characteristics of the movements on probe trials that followed prime trials in which a target was presented alone, a distractor was presented alone, or a target and a distractor were presented simultaneously. Despite finding significant distractor interference and response inhibition effects in reaction time following the Distractor-Alone prime trials, deviations in the trajectory of the movements were found only for Competitive prime trials. Further, negative priming and inhibition of return effects were not found. These results are discussed relative to the interaction between the facilitation of return effect for colour, and the inhibition of actions.

On The Relationship Between Distractor Interference, Response Inhibition, and Inhibition of Return

Traditional studies of visual attention have been concerned with the abilities of humans to rapidly identify and respond to a target stimulus within simple and complex environments. Much of the research examining how attention can be focused or distributed throughout the environment has made use of either the precue (i.e., Posner, Nissen, & Ogden, 1978) or competition (i.e., Eriksen & Eriksen, 1974) paradigms. In the typical precuing experiment, the participant is given predictive advance information about the location of the target within the environment. This information can come in the form of either a brief peripheral cue presented at or near the location of the target, or a brief symbolic cue presented at or near fixation. Peripheral cues are thought to bring about an exogenous (automatic) shift of attention to the probable target location, whereas the symbolic cues are associated with endogenous (controlled) shifts of attention (Jonides, 1981). In support of the notion that attention has been shifted/directed to the probable target location, the time taken to initiate a response (reaction time or RT) to a target appearing at the cued location is shorter than at an uncued location.

Similar to the effects of a predictive precue, it has been demonstrated that the time taken to initiate a response is shorter for a target presented at a cued location following a non-informative (the location of the target is random with respect to the location of the cue) exogenous cue. The facilitation effect, however, is only apparent when there is close temporal proximity between the cue and the target (cue-target onset asynchrony, or CTOA, of less than 200 ms) and is hypothesized to occur as the result of the orienting of attention to the location of the cue (Posner & Cohen, 1984). When the CTOA is greater than 200 ms, however, the facilitation effect dissipates until responding to the target at the cued location is actually impeded (Posner & Cohen, 1984). The increased RT associated with valid non-informative precue information has been termed the inhibition of return effect (Posner, Rafal, Choate, & Vaughan, 1985). The inhibition of return effect has been thought to be caused by a decaying inhibitory code placed on the cued location resulting from the reorientation of a shift of attention from the cued location back to the fixation point. In order to respond to a target presented at the cued location, the actor must overcome the inhibitory code. This process of responding to the cued location requires more time to complete than that of responding to an uninhibited location. These inhibition of return effects have been reported across a variety of response modes [e.g., saccadic eye movements (Briand, Larrison, & Sereno, 2000) and simple manual button press responses (Rafal, Calabresi, Brennan, & Sciolto, 1989)] and tasks [e.g., colour discrimination (Law, Pratt, & Abrams, 1995) and responding to successive targets without an intervening cue (Maylor & Hockey, 1985)]. Based on the demonstrated universality of the inhibition of return effect, it has been suggested that there are both response-based and detection-based mechanisms that underlie in this phenomenon (Abrams & Dobkin, 1994; Klein, 2000).

The effects of lasting inhibitory processes on action have also been observed following successful selection in competitive tasks. In a typical competitive (a.k.a., visual search) task, a target is placed amongst a series of competing, non-target stimuli and the participant's task is to identify and respond to the target by either an arbitrary key press (e.g., Eriksen & Eriksen, 1974) or an aiming movement (e.g., Tipper, Lortie, & Baylis, 1992b). Facilitatory and inhibitory processes are thought to be involved in achieving successful selection of the target stimulus/response under these conditions. That is, it has been proposed that, in order for the target response to emerge, the activity associated with the target stimulus is selectively enhanced while the activity associated with the competing, non-target stimuli is selectively inhibited (Houghton & Tipper, 1994).

The strongest evidence in support of the hypothesis that inhibitory processes are operating during selection has come from the discovery of the negative priming effect (Neill, 1977; Tipper, 1985). Negative priming is the term given to the phenomenon associated with an increased RT to a target stimulus on trial n+1 (probe trial) when that target stimulus was the non-target or distractor stimulus on trial n. Similar to inhibition of return, negative priming has been thought to occur because the excitatory activity associated with the target stimulus must overcome the lasting, but temporary inhibitory code that the actor has placed on the location or response associated with the distractor stimulus (Tipper, 1985; Tipper et al., 1992b) as the result of selection on trial n (cf., Neill, Valdes, Terry, & Gorfein, 1992).

The notion that there may be a relationship between the mechanisms that cause inhibition of return and negative priming is not new. In recent theorizing about the origins of the inhibition of return and negative priming phenomena, some investigators have suggested that a common mechanism may cause the inhibition of return and negative priming phenomena (Milliken, Tipper, Houghton, & Lupiáñez, 2000; see also Houghton & Tipper, 1994). That there is a common inhibitory mechanism behind inhibition of return and negative priming makes intuitive and theoretical sense because, in events leading to both inhibition of return and negative priming, attention has been distributed to a particular location/stimulus and then withdrawn (inhibited). Further, from an evolutionary perspective, both inhibition of return and negative priming could be phenomena related to processes developed to ensure the successful search of the environment. Specifically, if, while searching for food, a particular location has been attended to and found to be void of the target stimulus (i.e., empty) or found to contain a distractor (e.g., a rotten apple), the organism would place an inhibitory code on that location impeding the return of attention to either the empty space or the distractor.

Inhibition of Return, Negative Priming and Theories of Action-Based Attention

Consistent with the common mechanism hypothesis, descriptions of the processes underlying both negative priming and inhibition of return include response-based components (see Klein, 2000 for a review of inhibition of return) and action-based frameworks (negative priming - Tipper et al, 1992b; inhibition of return - Welsh & Elliott, in preparation). Proponents of action-based theories of attention suggest that there is an intimate link between perceptual, attentional, and response-producing systems such that they form a unified system (Rizzolatti, Riggio, & Sheliga, 1994). In this way, attending to an object automatically initiates response-producing processes designed to interact with that object.

In support of action-based theories of attention, it has been repeatedly shown that non-target stimuli in the movement environment that do not present a physical barrier to the movement cause alterations in the trajectory of the path of the movement (e.g., Howard & Tipper, 1997; Welsh, Elliott, & Weeks, 1999). Welsh and Elliott (submitted) have proposed a response activation model of selective action to explain these alterations.

In short, it was proposed that the observed response is a product of the activation levels achieved by each competing response at the moment of initiation. Thus, a competing non-target response that is active at the moment of response initiation will cause a deviation towards that location because characteristics (e.g., direction, velocity) of the active non-target response will be incorporated into the target response. On the other hand, if the non-target response is inhibited at the moment of response initiation, then deviation away from the non-target location will occur because anti-characteristics of the response will be incorporated into the target response (see Welsh & Elliott, submitted; in preparation, for more detail).

Based on the tenets of the response activation model and the notions of response-based contributions to the inhibition of return and negative priming phenomena, some very specific predictions can be made about the path of a goal-directed movement that immediately follows another target movement under competitive and non-competitive conditions. It was predicted that if inhibition of return and negative priming arise from the same set of processes, then they should not differ in terms of their effects on the temporal and trajectory characteristics of aiming movements. Specifically, if a response is made (inhibition of return) or inhibited (negative priming) to a particular location on trial n, then response initiation times should be slower if that location is the target on trial n+1. Further, if inhibition of return and negative priming arise from a common inhibition process, then a movement to a target on trial n+1 should deviate away from the location that was ignored/responded to on trial n.

To test these predictions, participants were asked to complete pairs of rapid aiming movements to one of three targets. On the first of the two trials (prime), the participant could be presented with either a target stimulus alone (Target-Alone prime), a distractor stimulus alone (Distractor-Alone prime), or both a target and a distractor stimulus (Competitive prime). In all cases, the participant was asked only to move to the target location. Thus, if a distractor appeared alone, then no response was to be made. On the second (probe) trial, a target stimulus was always presented in isolation and randomly at any of the three possible locations. Each prime-probe combination was designed to test a different aspect of the common mechanism hypothesis and the model of response activation.

First, Competitive prime trials were included to attempt a replication of distractor interference effects on movement planning and execution. Although temporal distractor interference effects in selective reaching tasks have not always been observed (e.g., Meegan & Tipper, 1998 vs. Welsh et al., 1999), trajectory deviations towards the location of the non-target seem to be more reliable (e.g., Welsh & Elliott, submitted). As such, it was predicted that the presence of the distractor would cause a deviation towards that location, while it may or may not result in longer reaction times relative to a condition in which only the target is present. Further, because it has been hypothesized that the corrections of the deviations in the movement trajectory are the result of inhibition of the non-target response (Welsh & Elliott, submitted), it was predicted that longer RTs would occur when the Competitive probe target was presented in the location of the distractor on the Competitive prime trial relative to when the Competitive probe target appeared in a location that was neither a target nor distractor in the Competitive prime trial (negative priming effect).

Second, as inhibition of return has been found when responding to a target in the same location as the target on the preceding trial (e.g., Maylor & Hockey, 1985), it was predicted that response initiation times would be longer for Target-Alone probe trials when the Target-Alone probe target was in the same location as the Target-Alone prime target relative to when the Target-Alone prime target was in one of the other two locations. This prediction is based on the assumption that in returning to the start position, the participant establishes an inhibitory code against returning to a recently occupied location. Further, because it was hypothesized that this inhibitory code is represented in the movement system as a depression in the activity of the neurons associated with a response to that previously responded-to location, it was predicted that movements to the probe target would deviate away from the previously responded-to location (see Welsh & Elliott, in preparation).

Third, because it was hypothesized that there is a common inhibitory mechanism behind inhibition of return and negative priming (namely an inhibitory code against responding to the previously-ignored/responded-to location represented in the movement system), it was predicted that there would be no differences found between the Target-Alone probe and Distractor-Alone probe movement effects.[1] Specifically, as predicted for the movements following a Target-Alone prime, there would be an increased RT on the Distractor-Alone probe response when moving to the location of Distractor-Alone prime stimulus and deviation away from the location of the Distractor-Alone prime stimulus when moving to one of the other locations.

Finally, it was predicted that an inhibition of return effect would also be observed in the Competitive probe trials. That is, RTs would be longer when the Competitive probe target appeared in the same location as the Competitive prime target than when the

Competitive probe target appeared in the location that was neither a target nor a distractor in the prime trial. Although movement trajectories should deviate away from the location of the Competitive prime target when moving to one of the other locations on the Competitive probe trial (Welsh & Elliott, in preparation), Competitive probe trajectories were not analyzed due to the potential coexistence of inhibitory codes associated with inhibition of the distractor response.

Methods

Participants

The participants were twelve (6 women, 6 men; age range 20-29 yrs.) undergraduate and graduate Kinesiology students at McMaster University. All were right-handed, had normal or corrected-to-normal vision, and were naïve to the purposes of the study. Each participant was tested individually and financially compensated for their time. The methods of this study were approved by the research ethics committee of McMaster University. Informed consent was obtained from the participants prior to data collection.

Apparatus

The possible target/distractor locations were 3 light-emitting diodes (LEDs) (1.5 cm diameter) that were embedded in a grey metal box (3 cm H X 58 cm W X 70 cm L). These LEDs (Dialight, series 557) could emit either red or green light and were arranged in a row parallel to the frontal plane of the participant. The centre LED was 18 cm from each of the flanking LEDs and a circular, white sticker (3 cm in diameter with an open 1 cm diameter circular section in the middle) that served as the home position for each pointing movement.

Throughout the data collection session, the participant sat at a table on which the grey box was placed and wore a ringed metal guitar pick with an infrared light-emitting diode (IRED) fixed to its upper surface. The pick was worn such that the IRED was located above the nail of the index finger of the dominant (right) hand. The location of the IRED was recorded by an Optotrak™ 3D motion-analysis system at a frequency of 500 Hz. The Optotrak™ system was triggered to begin recording each movement by a Lafayette Four-bank Millisecond Timer (model 52010). The timer also controlled the timing of illumination of the LEDs. This arrangement of equipment allowed for the initiation of the recording of the location of the IRED to be simultaneous with the illumination of the LED(s).

Procedure and Task

Participants were screened for handedness using an adaptation of a handedness questionnaire (Bryden, 1977) prior to the first data collection session. Upon arrival at the first session, the participant was seated at the table and fitted with the guitar pick. The participant was then given instructions and a demonstration of the task. Participants were told that each experimental trial consisted of a pair of movements that originated from the white sticker. An experimental trial began when the tip of the finger of the participant was placed on the centre of the white sticker. When the finger was on the sticker, the experimenter gave a verbal "Ready" cue and initiated a 1-3 s variable foreperiod that ended with the illumination of the specific target/distractor combination for the first (prime) movement. This LED(s) remained illuminated for 1.8 s. There were three possible arrangements of illuminated LED(s) on the first of the two stimulus presentations: 1) a green LED only (Target-Alone prime); 2) a red LED only (Distractor-Alone prime); and, 3) a green and red LED illuminating simultaneously (Competitive prime) (see Figure 1). For all presentations, the task of the participant was to move as quickly as possible to the green LED and ignore a red LED should one appear. Hence, if a red LED was presented alone, no movement was to be made. Following target acquisition, the participant was to remain on the target until it was extinguished. When the target LED was turned off, the participant was asked to quickly return the finger to the centre of the home position and await the presentation of the second target location. The second target location was always a green LED, presented randomly in relation to the preceding target/distractor combination, and illuminated 1 s after the previous LED(s) were extinguished. The participant was told to remain on the second target location until it was turned off (2 s after it was turned on). After the second target was turned off, the participant was free to return to the starting location and begin the next experimental trial at their own pace.

Subsequent to the instructions, the participant completed a brief familiarization phase that consisted of 5-10 randomly selected experimental trials. The familiarization trials were followed by 288 experimental trials (576 stimulus presentations in total). These experimental trials were completed over two sessions that lasted 40-50 min. Whereas three participants chose to complete both sessions in the same day with a minimum 30 min break between sessions, the remaining nine participants completed the sessions on separate days no more than 4 days apart. During each session the participant began with the familiarization trials and then completed 4 blocks of 36 experimental trials (144 trials per session). The order of the trials within each block was random with the constraint that each combination of target-distractor/target was presented once. Eight such orders were created and were presented in random order to the participants.

Data Reduction

The raw displacement profiles were filtered, using a second-order dual-pass Butterworth filter with a low-pass cutoff frequency of 12 Hz. The filtered displacement profiles were then differentiated twice, using a 2-point central finite difference algorithm, to obtain instantaneous velocity and acceleration. All dependent variables were calculated from these profiles using custom software. Temporal measures included reaction time (RT), movement time (MT), and total response time (TT), and were calculated in the following manner. Movement initiation was identified as the first sample in which the instantaneous velocity in the Y axis surpassed 30 mm/s and remained there for the following 36 samples (72 ms) (see Chua & Elliott, 1993). Likewise, movement termination was identified as the first sample in which instantaneous velocity in all three axes fell below 30 mm/s and remained there for the following 25 samples (50 ms). RT and TT were calculated by counting the number of samples from the beginning of the recording of the IRED until movement initiation and termination, respectively, and then multiplying that number by the rate of data acquisition (2 ms/sample). MT was calculated by subtracting RT from TT.

The kinematic variables of peak acceleration (PA), peak velocity (PV), and peak deceleration (PD) in the Y axis were also determined. PA and PD were defined as the maximum and minimum values of the acceleration profiles, respectively. Similarly, PV was defined as the maximum velocity achieved during a particular trial. The identification of the kinematic variables aided in the determination of the trajectory variables. Using the starting location as the origin (0, 0, 0), each resultant movement trajectory was first dissected into its component X (left(-)/right(+)), Y (midline), and Z (height (H)) axes. These profiles were then divided into 4 sections. The Section 1 was defined as the first sample after movement initiation (instantaneous velocity >30 mm/s) until the sample immediately prior to PA. Section 2 and 3 were defined as PA until the sample immediately prior to PV and PV until the sample immediately prior to PD, respectively. Finally, Section 4 was identified as PD until the sample immediately prior to movement termination (instantaneous velocity <30 mm/s). Average displacements within each section for each axis were calculated by dividing the sum of all the displacement values recorded at each sample from the beginning to the end of each section by the number of samples recorded during that section.

Prior to the statistical analysis, trials on which a movement error (less than 1% of trials) or a recording error (less than 3% of trials) occurred were identified. A movement error was considered to have occurred when the participant initiated a movement (instantaneous velocity was greater than 30 mm/s) to the distractor location on the Distractor-Alone prime trial or when the RT was less than 100 ms. At no time did a participant complete a movement to the distractor location on a Competitive prime trial. Recording errors occurred when the IRED was lost from view of the cameras. If the movement or recording error occurred in the first of the paired trials, then the data from both of the trials were eliminated from the data set. If the error occurred in the second of the two trials, then data from the first trial remained in the data set whereas the data from the second was eliminated.

After the errors were removed from the data set, mean values of each dependent variable were calculated. Based on the hypotheses (outlined earlier), a series of specific statistical questions were addressed. Particular portions of the data were analyzed separately to answer these questions. The specific questions posed and the analyses performed to answer these questions are described in the results section. Post hoc analysis of all significant effects involving more than two means was conducted using Tukey's HSD ($p < .05$).

Results

1) Were the movements to the target different from each other in the simplest (Target-Alone prime) condition?

The purpose of this analysis was to identify the different characteristics of the movements themselves. As such, only the data for the movements for the prime trials in the Target-Alone prime condition were analyzed. Mean values of each temporal dependent measure were submitted to a repeated-measures ANOVA with Location (Left, Middle, Right) as the single factor. Consistent with previous work on movement laterality, TTs were shorter when the participant moved to the middle and right target than when moving to the left target, $F(2, 22) = 64.48$, $p < .001$ (Elliott & Chua, 1996).[2] The effects for Location found for RT, $F(2, 22) = 22.16$, $p < .001$, and MT, $F(2, 22) = 88.90$, $p < .001$, are also congruent with previous work on movement laterality (Carson, 1996) and movement amplitude (Fitts & Peterson, 1964). Response initiation times were found to be shorter for movements to the middle target than to both the left and the right target, with a trend towards shorter RTs for left- than right-directed movements. MTs were found to be shorter for movements to the right target than both the middle and left target, and shorter for middle targets than left targets (Table 1).

For the analysis of the trajectories, a 4 Section (1, 2, 3, 4) by 3 Location (Left, Middle, Right) repeated measures ANOVA was conducted on the mean values of each variable. As movements were made to targets in different directions, it is not surprising that the analysis for AveX revealed main effects for Section, $\underline{F}$ (3, 33) = 22.97, $\underline{p} < .001$, and Location, $\underline{F}$ (2, 22) = 3415.08, $\underline{p} < .001$, and a significant interaction between Section and Location, $\underline{F}$ (6, 66) = 2237.81, $\underline{p} < .001$. Post hoc analysis of the interaction revealed that values of AveX increased (the effector moved further away from centre) with each Section for movements to both the left and right target, while displacement in the X axis did not differ across Sections for movements to the middle target (Table 2). The analysis of AveY and AveH also revealed main effects for Section, $\underline{F}$ (3, 33) = 6753.13, $\underline{p} < .001$, and, $\underline{F}$ (3, 33) = 134.0, $\underline{p} < .001$, and Location, $\underline{F}$ (2, 22) = 7.07, $\underline{p} < .005$, and, $\underline{F}$ (2, 22) = 25.22, $\underline{p} < .001$, and significant interactions between Section and Location, $\underline{F}$ (6, 66) = 11.02, $\underline{p} < .001$, and, $\underline{F}$ (6, 66) = 22.74, $\underline{p} < .001$, respectively. Post hoc analysis of the interactions in AveY and AveH revealed that movements to the targets did not differ in these displacement values in the first (1) and final (4) sections of the movement, but did in the middle two sections (2 and 3). In Section 2, movements to the left target had a greater AveY displacement than movements to the middle target, which in turn had a greater AveY displacement than movements to the right target. In Section 3, movements to the left target still had greater AveY values than movements to the middle or right target, which in this section did not differ. For AveH, it was found that movements to the left target were higher than those to the middle target in both Section 2 and 3, but only higher than those to the right target in Section 2. Movements to the right target were also higher than those to the middle target, but only in Section 3.

Summary. The results of the analysis of the Target-Alone prime trials revealed that participants initiated their responses more quickly to the middle target than to either peripheral target, but completed their movements more quickly to the target in right space. Although the latter MT effect replicates the results of studies of movement laterality (e.g., Fisk & Goodale, 1985), RTs being shortest for movements into central space, with only a trend for a left space advantage, is likely the result of an interaction between amplitude (Fitts & Peterson, 1964) and laterality effects (Carson, 1996). Movements to the targets also differed in terms of their trajectories. Apart from the inherent left/right displacement differences, movements to the left target were generally higher and extended into the Y axis more quickly than movements to either the middle or right target. Given the longer MTs to the left target, it is possible that movements to the left target were less efficiently planned and executed - likely the result of both laterality (Carson, 1996; Elliott & Chua, 1996) and biomechanical [e.g., single (rightward) vs. multi-joint (leftward) movement] issues.

2) Did the distractor interfere with movement programming and execution?

This analysis was conducted to examine whether or not the presence of a simultaneously presented non-target stimulus affected the temporal and trajectory measures of movement. To test for these effects in the temporal measures of movement, separate single-factor, repeated-measures ANOVAs were conducted on mean values of RT and MT for movements to each target, with No Distractor (Target-Alone prime), Competitive prime 1, and Competitive prime 2 as the three levels. For example, for movements to the left target, the data for the Target-Alone-left prime movements would be compared to the data for the left-target/middle-distractor (Competitive prime 1) and left-target/right-distractor movements (Competitive prime 2).

Although the presence of the distractor did not affect MT, significant distractor interference effects were found in RT for movements to the left, F (2, 22) = 34.32, $p <$ .001, middle, F (2, 22) = 6.10, $p <$ .01, and right targets, F (2, 22) = 13.10, $p <$ .001. For movements to the left target, a distractor in the middle and right locations were found to significantly increase RT, with a middle distractor being associated with a greater increase in RT than a right distractor (Figure 2A). When movements were made to the middle or right target, a right and middle distractor were found to significantly increase RT, respectively (Figures 2B and 2C). Left distractors did not reliably increase RTs for movements to middle or right targets.

To investigate the effects of the distractor on the movement trajectories, separate 4 Section (1, 2, 3, 4) by 2 Distractor Location (1, 2) repeated measures ANOVAs were conducted on the mean difference values for AveX, AveY, and AveH for movements to each target. These difference values were calculated by subtracting the displacement value for the Target-Alone prime movement from the displacement value for each Competitive prime movement. The results of the analysis of AveX revealed that the presence of the distractor altered the movement trajectories for movements to the left target (Section X Location interaction, F (3, 33) = 3.18, $p <$ .05) and the middle target (main effect Location, F (1, 11) = 12.70, p < .001; Section X Location interaction, F (3, 33) = 14.63, p < .001). For movements to the middle target, it was found that a distractor in right space was associated with a rightward (positive) deviation, whereas a distractor in left space was associated with a leftward (negative) deviation in the movement trajectory in Sections 3 and 4 (Figure 3). Similar effects were found for movements to the left target as a right distractor was associated with a rightward deviation in the movement relative to a middle distractor in Section 3 only. Movement trajectories to the right target were not affected by a distractor.

The presence of a distractor was also found to affect the height of the movement to the middle target. Post hoc analysis of the significant Section by Location interaction in AveH, F (3, 33) = 4.56, p < .01, revealed that movements were higher when the distractor was to the left than when the distractor was to the right. This effect, however, was only present in Section 2 (Figure 4). No significant effects were found in AveH for movements to the left target or right target. Finally, none of the analyses for AveY revealed effects that achieved conventional levels of significance.

Summary. In contrast to previous work from our lab (e.g., Welsh et al., 1999; submitted), the presence of a distractor was found to significantly increase the time required to initiate a response. Furthermore, consistent with the notion of a hand-centred frame of reference (Tipper et al., 1992b), a distractor in central or right space was associated with significant interference, whereas a distractor in left space was not. Although left distractors were not associated with temporal interference, they still affected the movement trajectories in movements to the middle target. Congruent with predictions based on the model of response activation, characteristics of the non-target response seemed to be incorporated into the target response resulting in deviation towards the non-target location. On a final note, the finding that there was significant distractor interference in both temporal and trajectory measures of the movement speaks against a simple speed-accuracy trade-off interpretation of the trajectory effects (see also Welsh & Elliott, submitted).

3) Was movement planning and execution affected when moving to a recently responded-to or not-responded-to location?

The purpose of this analysis was to test whether or not the mechanisms that cause the inhibition of return effect are the same as those involved in inhibiting a response to an ignored location (as reflected in the negative priming effect). As such, mean values of RT and MT from the Target-Alone and Distractor-Alone probe trials were submitted to separate 2 Previous Action (Respond, Ignore) by 3 Location (Left, Middle, Right) repeated measures ANOVAs for movements to each location. The results of the analysis for RT revealed that the main effects for Previous Action and Location, as well as the Previous Action by Location interaction were significant for movements to each target (Table 3). Post hoc analysis of these interactions revealed that response initiation times were significantly longer when participants returned to the location of the prime stimulus, but only when the participant had ignored the response to the prime stimulus (Distractor-Alone probe trials) (Figure 5A-C). The Location of or Action required by the prime stimulus did not affect MT.

Although participants were not slower to return to the location of a previously responded-to location, evidence of inhibition associated with withdrawing attention from a previously responded-to location may be found in the movement trajectories. To explore this possibility, a series of $\underline{t}$-tests were conducted that contrasted the average displacement value for the Target-Alone prime movement to the average displacement value for each Target-Alone and Distractor-Alone probe movement. Significant effects revealed in this set of analyses were small and inconsistent (only 28 of the 216 (13%) comparisons were significant). However, when an effect was present, it was found that the movements deviated away from the location of the previous stimulus whether it was responded-to or ignored. For example, Target-Alone probe movements completed to the middle target following Target-Alone prime movements to the right target veered to the left relative to the Target-Alone prime middle movement in Sections 1, $\underline{t}\,(11) = 3.83$, $\underline{p} < .005$, Section 2, $\underline{t}\,(11) = 2.38$, $\underline{p} < .05$, and Section 3, $\underline{t}\,(11) = 2.29$, $\underline{p} < .05$ (Table 4, 5, 6).

Summary. Although it was found that movements to the location of a previously ignored stimulus were associated with increased response initiation times, a significant increase in response initiation time when returning to the previously responded-to location was not found in the present study. Also incongruent with predictions were the modest trajectory effects. This result was surprising given the robust nature of the temporal effects in the Distractor-Alone conditions. It should be noted, however, that when there were significant deviations in the path of the movement, the deviations were away from the location of the previous stimulus.

4) Did negative priming occur?

According to the model of response activation, alterations in the path of the movement that are caused by the activity associated with the non-target response are corrected through non-target response inhibition as opposed to through the use of afferent feedback loops. One way to test this hypothesis is to look for evidence of negative priming (Tipper et al., 1992b). The analysis conducted to test for the negative priming effect consisted of a series of planned comparisons. For these planned comparisons, mean RTs and MTs for Competitive probe movements in which the target location was the same as the distractor location on the Competitive prime trial were compared to Competitive probe movements in which the target was presented in the location that was neither a target nor a distractor on the Competitive prime trial. The only significant effect in these analyses was for MT for movements to the left target, $\underline{F}$ (1, 11) = 5.77, $\underline{p} < .05$. Probe movements were completed more quickly if the target appeared in the same location as the distractor (326 ms) on the prime trial than if it appeared at a location that was not a target or a distractor on the Competitive prime trial (334 ms) (Table 7).

Summary. Negative priming was not evident.

5) Was inhibition of return evident in the movement following a competitive prime trial?

As one of the purposes of the study was to test the idea that negative priming and inhibition of return result from the same mechanisms, a planned comparison analysis similar to the one for negative priming was conducted on the mean RTs and MTs for movements to each target. Similar to the preceding planned comparison analysis, the means from Competitive probe movements that were completed to the same location as the target location on the preceding Competitive prime trial were compared to the means for Competitive probe movements that were completed to a location that was neither the target nor distractor on the preceding Competitive prime trial. The only significant effect for this series of analyses was for RT to the left target, F (1, 11) = 6.75, $p < .05$, revealing that movements were actually initiated more quickly if the left target was also the location of the target on the prime trial than if the left location was neither the target nor the distractor on the Competitive prime trial (208 ms vs. 220 ms).

Summary. Inhibition of return was not evident in the probe trials following a competitive trial.

Discussion

Inhibition of return and negative priming are the terms given to the phenomena of increased response initiation times to targets appearing at recently attended and ignored locations. As both effects are hypothesized to be the result of temporary inhibitory codes against responding to a particular stimulus/location (cf., Neill et al., 1992), it has been suggested that negative priming and inhibition of return arise from the same mechanism (see Milliken et al., 2000). The purpose of the present study was to test the common mechanism hypothesis and the ability of a model of selective action to explain the negative priming and inhibition of return phenomena. In this context we examined the temporal and trajectory characteristics of target-directed aiming movements that followed responses to a target location and/or inhibition of a response to a non-target location. Although significant temporal and trajectory distractor interference and temporal response inhibition effects were found, inhibition of return and negative priming effects were not found. These results are discussed with reference to current theories of selective action and competing explanations of negative priming.

Competition in Selective Reaching

Analysis of the Competitive prime movements revealed that the presence of action-relevant non-target stimuli increased response initiation times and altered the trajectories of the movement. Consistent with the notion of a hand-centred frame of reference, a distractor in right space was associated with significant temporal interference whereas a distractor in left space was not (ipsilateral effect - Meegan & Tipper, 1998; Tipper et al., 1992b). Interestingly, a distractor in central space was associated with greater interference than a distractor in right space. That the participants were likely fixating the centre target before stimulus presentation suggests that a retinal-centred reference frame (Eriksen & Eriksen, 1974) may have also been employed. Alternatively, because the middle target was also closer to the starting location of the movement than either of the flanking targets (18 cm vs 25.5 cm), it may be that the relative proximity of the centre target to the home position (proximity-to-hand effect - Tipper et al., 1992b) may have caused this increase in interference. Unfortunately, the methodology employed does not allow us to distinguish between these two explanations.

Consistent with the model of response activation, the trajectories of the movements in the Competitive prime condition were found to deviate towards the location of the distractor. The pattern of results was not perfectly congruent with previous work, however. Whereas movements to the right target were unaffected by a distractor, movements to the middle target were affected by both a left and a right distractor. The finding that the left distractor affected the middle target movement is not consistent with the findings of Welsh et al. (1999) in which only central or right distractors were associated with altered movement trajectories. Perhaps the difference in the results between the two studies may be the sensitivity of the measures. Specifically, Welsh et al. (1999) looked only at peak displacement in one axis of the movement, whereas the whole movement was examined in the present experiment. It should also be noted that the effect of the left distractor was only found for movements to the middle target in the present study. When the movements were to the right target, the left distractor caused neither temporal nor trajectory interference. Thus, the subtle effect of the left distractor on the movement trajectories to the middle target may have resulted from the effects of the interaction between a retinal and hand-centred frame of reference.

On a final note, it has previously been questioned whether the alterations in the movement trajectories in our previous work were the result of concurrently represented responses or of the participants adopting a speed-accuracy strategy that emphasized speed. It was suggested that participants were choosing to initiate a response based on the first perceived change in the environment (thus, no temporal interference) and planned the response such that it was an average of the two responses (thus, deviation towards the distractor). Once the movement was initiated, the participant then relied on online corrective processes to successfully complete the movement to the target location. Such an argument could be used to explain the trajectory effects on the movements to the middle target with a left distractor (deviation towards the left distractor despite the absence of temporal interference). However, because both temporal and trajectory interference effects were found for the same movements when the distractor was in right space, and when movements to the left target were accompanied by a right distractor, this strategy explanation does not hold. Instead, the altered movement trajectories appear to be the result of competing response-producing processes (see also Welsh & Elliott, submitted). In sum, the results support theories and models of action-based attention (Rizzalotti et al., 1994; Tipper et al., 1992b; Welsh & Elliott, submitted) and the idea that multiple frames of reference may be employed to complete a particular movement task (Bekkering & Pratt, 2001).

Response Inhibition and Repetition Priming

Recently, Milliken et al. (2000) suggested that the two phenomena of negative priming and inhibition of return could arise from a common inhibitory mechanism. They further described two possible mechanisms through which these effects are generated. The first hypothesis focuses on the retrieval and updating of episodic memory traces as the source of the increased response initiation times (Neill et al., 1992; see also Kahneman, Treisman, & Gibbs, 1992).[3] According to the retrieval hypothesis (Neill et al., 1992), processes that result in negative priming and (by extension) inhibition of return occur after the onset of the probe stimulus. It is suggested that when you have experience with a particular set of conditions/stimuli, you create an episodic memory trace for that set of stimuli. Contained within that trace is information regarding the type of response that was made on the previous interaction with that set of stimuli. Specifically, in that trace, "tags" are established for or against responding to a particular stimulus based on the action previously taken. When presented with a similar set of stimuli on a second occasion, the established response tag is retrieved as part of the memory trace of the actor's previous experience with that set of stimuli. If the response information that is retrieved with the trace is appropriate for the task, then the target response quickly emerges. However, if the retrieved trace has a "do-not-respond-to" label on the now target stimulus, then reprocessing of the stimulus and reprogramming of the response must occur. This reprocessing/programming is time consuming and is what is thought cause the increased RTs associated with the previously to-be-ignored non-target stimulus now being the to-be-responded-to target stimulus (negative priming).

The second hypothesis, based on a model proposed by Houghton and Tipper (1994), emphasizes a neural network, response-based account of attention. The basis of this model is that a selection-for-action template is maintained in working memory and is intimately linked to response (motor) systems. This template contains property (e.g., shape, location) values that describe the to-be-selected stimulus. When the properties of the stimulus match the template, the stimulus receives excitatory feedback and the response is activated. If the stimulus does not match, it receives inhibitory feedback and the response to the stimulus is withheld. It has been suggested that when a response to a stimulus is inhibited - by either inhibiting the response to a non-target stimulus or by the reorientation of attention to a central fixation point - a lasting, but temporary inhibitory code is incorporated into the selection-for-action template and placed on the non-target (mismatched) properties of that stimulus. Thus, negative priming effects arise because of the additional time required for the activation levels of the target stimulus to overcome the inhibitory codes placed on its previously non-target properties in the template before stimulating activity in the response systems.

It was thought that due to the similarities between the Houghton and Tipper model and the model of response activation (Welsh & Elliott, submitted), the latter could be used as a guide to distinguish between the above accounts due to the emphasis that the model of response activation places on the effects and time course of inhibitory processes. The major difference between the Houghton and Tipper (1994) and the Welsh and Elliott (submitted) accounts is that, in the latter, inhibitory codes are not only maintained in a template (response set) in working memory, but are also simultaneously represented in the motor system as below-baseline activity associated with a response to that stimulus. As both negative priming and inhibition of return are hypothesized to be associated with inhibition against responding to a stimulus, in conjunction with the intimate link this inhibition is thought to have with the motor system (Rizzolatti et al., 1994; Welsh & Elliott, submitted), predictions based on the model of response activation would be that negative priming and inhibition of return are associated with movement trajectories that deviate away from the location of the previously ignored/responded to stimulus. Unfortunately, the methodology employed, although designed to examine the movement trajectories predicted to be associated with negative priming and inhibition of return in isolation, failed to produce significant temporal negative priming and inhibition of return effects. As such, it is not surprising that predicted deviations were not realized. The remainder of this section is dedicated to explaining why the methodology failed to replicate the inhibitory aftereffects, and how these results relate to the competing frameworks.

Increased Response Initiation Times Following Distractor-Alone, but not Target-Alone, Primes. Based on previous work reporting inhibition of return effects for repeated responses to target locations (e.g., Maylor & Hockey, 1985; Spence, Lloyd, McGlone, Nichols, & Driver, 2000), it was expected that response times to Target-Alone probe targets that were in the same location as the Target-Alone prime target would be longer than if the Target-Alone probe target was in a different location from the Target-Alone prime target. Such was not the case. A significant inhibition effect was found for response on the Distractor-Alone probe trials, however. Although the discrepancy between the two effects seems to suggest that inhibitory processes were not at work following the Target-Alone prime responses, we suggest another possibility. What was not considered in the design of the study was the facilitating effects of colour repetition.[4]

For example, Tanaka and Shimojo (1996; Experiment 1) required participants to indicate the detection of a red or green rectangle on successive trials by a left or right mouse button press, respectively. They found that if the rectangle was the same colour on successive trials, a facilitation of return effect for colour occurred. Thus, it is likely that the facilitation of return (a.k.a., repetition priming) for colour offset the effects of the inhibitory processes associated with inhibition of return for spatial location in the present study (see also Milliken et al., 2000; Pratt, 1999). That inhibition of return has been found for nearly identical target-target (Elliott, Tremblay, & Welsh, 2002) and cue-target tasks (Welsh & Elliott, in preparation) in which the colour of the stimuli did not change from trial n to trial n+1 (hence, no discrimination required) supports this notion. At what processing locus these repetition priming effects are manifested is unknown. As there was significant slowing of initiation of the response when returning to the location of a previously ignored stimulus that was not associated with reliable trajectory changes, it is suggested that these codes may not be represented in the motor system. Tanaka and Shimojo (1996) speculated that the opposing repetition effects for spatial and non-spatial action-relevant information may reflect differences between dorsal and ventral visual stream processing (see Milner & Goodale, 1995 for a discussion of the different visual streams). More work is required to sort these effects out. An initial investigation could consist of putting the facilitation of return for colour (ventral) into conflict with the inhibition to respond to the location of a previously ignored stimulus (dorsal) to examine which would dominate in the programming of action.

For example, a task could require participants to respond to the green light and ignore the red light on trial n, but then to always respond to the illuminated location on trial n+1 (regardless of whether it is green or red). Much like the results of the present work, it would be predicted that responses would be initiated faster in the green-green location repetition condition than in the red-green location repetition condition. In the green-red location repetition condition, however, there is no longer the facilitation of return for colour, but there would be a repetition of the response to a target location. Thus, it may be predicted that an inhibition of return effect will be observed in these movements. In the red-red location repetition condition, there is direct conflict between the facilitation of return effect for colour and the inhibition to return effect based on the previously ignored stimulus. Thus, if these effects reflect the differential processing of stimulus information by independent visual streams, then it is likely that an increase in response initiation time when returning to the previously ignored location will be found because the inhibition of the response may be represented in the action (dorsal) stream. However, if the two visual streams interact to control action (cf. Milner & Goodale, 1995), then it is likely that no increase in response initiation time when returning to the previously ignored location will be found because, similar to what is hypothesized to occur in the green-green condition, the facilitation and inhibition effects wash each other out.

Although the failure to find an inhibition of return effect in the present study is consistent with the work cited earlier, Law et al. (1995; see also Taylor & Klein, 1998) found inhibition of return for repeated colour presentations. However, the task employed in the Law et al. study was different from that used in other unsuccessful attempts to find inhibition of return for colour discrimination (Kwak & Egeth, 1992) in that there was an intervening colour stimulus between the cue and the target to pull attention away from the cued colour. For example, if the task is to respond to the blue square, a sequence of "blue" - blank - "blue" would not elicit an inhibition of return effect, whereas a sequence of "blue" - blank - "magenta" - blank - "blue" would elicit an inhibition of return effect. The thought being that attention needs to be drawn from the cued colour before the inhibitory processes begin to operate. With relevance to the present study, although the participant returned their attention to the home position and fixation point, there was no intervening colour event to remove attention from that non-spatial element of the display. Again, this suggests that the facilitation of return effect for colour offset the inhibition of return effect for location, causing a null result.

Finally, the results of the present study have implications for the models of attention discussed earlier. First and foremost, the results indicate that the model of response activation (Welsh & Elliott, submitted) is perhaps too simplistic in its current form. For example, regardless of the properties of the stimulus, predictions based on the model were that when attention is drawn to a location and then reoriented to another location, increased response initiation times should result when returning to the previously attended/ignored location on the following trial. Such was not the case. Further, reliable deviations in the movement trajectories were not found when response inhibition was evident (Distractor-Alone probe condition). Thus, it is evident that in order for the model of response activation to account for the variety of repetition effects, it must be expanded to include links to perceptual systems (e.g., ventral visual pathway).

Alternatively, the response inhibition model of Houghton and Tipper (1994) does a better job of explaining the present pattern of results. Due to the requirements of selection on all prime trials, a stimulus that fits the template (a suddenly appearing green light) would receive excitatory feedback. As such, processing of the following probe target would be unaffected regardless of its location. On the other hand, when the red non-target light suddenly appeared, the associated properties (e.g., location) would receive inhibitory feedback along with the red property. This temporary inhibition would be incorporated into the selection-for-action template and affect any processing associated with the subsequent target presentation at that location only.

Similarly, the retrieval hypothesis (Neill et al., 1992) would do well to explain the null inhibition of return effect. Specifically, because the appearance of the green stimulus on the Target-Alone prime afforded a "respond-to" action, when the green stimulus subsequently appeared in the same location on the Target-Alone probe trial, the retrieved trace would contain a "respond-to" tag on the green stimulus at that location. As such, the tag would be appropriate to the Target-Alone probe task and the response would be programmed without delay. Although this initial explanation is consistent with the retrieval hypothesis, that the "respond-to" tag placed on the green stimulus at the location of the Target-Alone prime target was not associated with facilitation for a repeated response relative to a non-repeated response may actually be difficult to reconcile with the retrieval hypothesis. Specifically, a "respond-to" tag should facilitate response producing processes versus a situation in which the present target location does not match a recently experienced set of conditions (i.e., there is no trace to retrieve). To counter the facilitation suggestion, one might argue that the novelty associated with the target stimulus appearing at a new location may have resulted in the by-passing of the retrieval process resulting in short reaction times to the new locations as well (Milliken et al., 2000). Hence, it could be that there would be no differences in the processing times between repeated and novel sets of stimuli despite the different mechanisms associated with response production in each case.

The increased response initiation times found when returning to the location of the Distractor-Alone prime stimulus can also be conceptualized within the framework of the episodic retrieval hypothesis. Specifically, instead of a "respond-to" tag being placed on the location of the target on the Target-Alone prime, a "do-not-respond-to" tag could have been attached to the location of the red (distractor) stimulus. As such, retrieval of the trace and the "do-not-respond-to" tag on the location of the Distractor-Alone prime stimulus on the Distractor-Alone probe trial would have slowed the processing of the response to that location relative to the untagged locations.

In sum, although the response activation model has been able to account for the effects of competing responses on the current movement (Welsh & Elliott, submitted) and inhibition of return when target discrimination is not required (Welsh & Elliott, in preparation), it is too simplistic to handle more complex interactions of selection and repetition effects. It seems that the Houghton and Tipper (1994) model and the retrieval hypothesis (Neill et al., 1992) are better able to explain these effects. Distinguishing between these two hypotheses, however, is not possible with the present data.

<u>Negative Priming and Inhibition of Return.</u> Contrary to predictions based on the

model of response activation, negative priming and inhibition of return following the Competitive primes was not found in the present study. That negative priming and inhibition of return were not found may still be informative, however, because these null effect may have resulted for a particular reason. First, it may be that the response system can not maintain inhibition against more than one response concurrently. Although there is no direct evidence against this suggestion from the present work, a number of researchers have reported that inhibitory codes can be maintained on at least four locations (Abrams & Pratt, 1996; Tipper, Weaver, & Watson, 1996). Instead, it is suggested that the failure to find an inhibition of return effect in Competitive probe movement was due to colour repetition priming (see earlier discussion; see also Milliken et al., 2000).

Second, and more specifically related to the failure to replicate the negative priming effect, it might have been that participants did not inhibit the competing response on the Competitive prime trial. Instead, they might have corrected their altered movement trajectories using afferent feedback. Although there is no direct evidence from the present study against this explanation, given the literature on negative priming and aiming movements (Tipper et al., 1992b; 2002) and other spatial detection tasks (e.g., Milliken et al., 2000; Tipper, Brehaut, & Driver, 1990) showing that inhibition is associated with tasks similar to that utilized in the present study, it is suggested that participants did correct the movements through inhibition of the competing response.

Finally, it may be that negative priming was not observed because there was no discrimination requirement (competition between target and distractor) in the probe task. As was done in the section on inhibition of return, an examination of the experimental design within the context of the alternative hypotheses is needed to explain this null effect. The specific issue of concern here is whether or not, and why, competition in the probe task is required for the negative priming effect to be present.

In some of the original work on negative priming it was noted that the negative priming effect disappeared whenever there was no conflict (competition) in the probe trial (e.g., Lowe, 1979). In one such study, Tipper and Cranston (1985; Experiment 3) required all participants to name the red letter that overlapped with a green, to-be-ignored letter on the prime trials. On the probe trials, however, half the participants were presented with a similar task (name red letter, ignore green letter) while the other half were presented with only a single black letter that required naming. The results revealed that participants in the selection group demonstrated negative priming, whereas the participants of the non-selection group were actually facilitated by the repeated distractor. Tipper et al. (1990) replicated the dissociation between negative priming in competitive and non-competitive probe trials in a spatial task.

To explain the seeming necessity of selection in the probe task to observe negative priming, Tipper and Cranston (1985) suggested that when an actor approaches a task in which selection is known to be required, a "selection state" is maintained in which inhibitory and excitatory mechanisms of selection are primed. When the prime trial selection occurs, the connection between the perceptual processing of the distractor and its response is inhibited allowing the coupling between target stimulus and the target response to be completed. It was hypothesized that if the actor knows that selection is required on the following trial, then the inhibition related to the distractor is incorporated into the selection state. If selection on the probe trial is not required, then inhibition is overridden or allowed to decay and subsequent responding is not impaired. Houghton and Tipper (1994) have developed and modeled the notion of the "selection state" into their template model. Based on this proposed mechanism behind negative priming, it is not surprising that negative priming was not observed in the present study as there was never competition on the probe trial.

However, there are conflicting views as to whether competition is necessary for negative priming to be observed. Neill, Terry, and Valdes (1994) provided evidence that it is not necessary to have competition. They pointed out that Tipper and colleagues used an all-or-none manipulation of competition on the probe trials. That is, either the participants always had a distractor on the probe, or never had a distractor on the probe trials. To investigate whether or not this all-or-none procedural manipulation was the cause of the failure to find the negative priming effects, Neill et al. (1994) treated competitive/non-competitive probe trials as a within-subject variable and randomly presented an equal number of each type of trial to participants. Consistent with their hypothesis, negative priming effects were found on both types of trials. Indeed, the negative priming on the non-competitive trials was almost twice the size (29 ms vs. 16 ms) of the negative priming on the competitive trial (though this difference only approached significance).

Neill et al. (1994) interpreted this finding as evidence against a "selection state" (response inhibition/template) hypothesis. If, according to Tipper and Cranston (1985), the attentional set was dropped and the inhibition was allowed to decay on the trials on which selection was not required, then there should not have been negative priming on the non-competitive trials in the Neill et al. (1994) study. They argued, on the other hand, for their retrieval hypothesis suggesting that the reason for the negative priming on the non-competitive trials was the result of discordance between the current set of stimuli and the memory trace of the set of stimuli for the preceding prime trial. Further, because the discordance would be greater when there is only one stimulus available, even slower retrieval processes would occur leading to increased negative priming effects in this non-competitive probe condition (i.e., the trend described earlier).

We do not interpret the findings of the Neill et al. (1994) study to be contradictory with the response inhibition theory. In fact, the response inhibition theory may be equally, if not better, able to explain these results and those of the present study. The key, as astutely pointed out by Neill et al (1994), was the intermixing of the competitive and non-competitive probe trials. By failing to mix in competitive and non-competitive trials, the participants in the studies of Tipper and colleagues, as well as in the present study, likely adopted the strategy of overriding the automatically induced inhibition or allowing it to decay. Thus, they were freely able to respond to whatever stimulus first appeared in the probe trial. When the trials were mixed as in the study by Neill et al. (1994), the participants likely adopted the safer strategy which was to maintain the inhibition in the selection state (a.k.a., template) on all trials. Thus, they may have behaved as though there was always going to be competition on the probe trial and maintained the inhibition to aid in the selection.

The above description would apply to an example situation in which two people are sorting different types of wine bottles from a box to store on different shelves. In this situation, there is one person who takes the bottles from the box and puts them on a table, while the other one takes the bottles from the table and places them on the correct shelf.

If the shelver takes one of two different bottles from the table and puts it on the shelf, he/she will likely not be sure where the loader has placed the next bottle on the table nor which type of wine was placed on the table. Thus, if the shelver is trying to put all of one type of wine away before shelving the other, an inhibitory code could be maintained against selecting the bottle that was previously left on the table. This inhibition would facilitate the acquisition of the bottles that are to be shelved first whether or not the bottles on the table are the same or different. However, near the end of the shelving process when there is only one type of wine left, careful searching and established inhibition would not be required and the shelver can take any bottle that is available.

Indeed, we feel that the lack of negative priming when a discrimination task on the probe trial is not incorporated into the design actually presents a problem for the retrieval hypothesis. As described by Neill et al. (1994), the retrieval of the episodic trace and the tag that accompanies it, should always cause longer response times to a non-Competitive probe that follows a competitive prime because of the greater discrepancy between the past and present contextual information. A trend towards that effect was found. However, when the requirements of the task are such that selection is never required, it is often found that no negative priming effect is found (e.g., Tipper et al., 1990; the present work). To account for this discrepancy, Neill et al. (1994) suggested that the effectiveness of the current set of stimuli in a non-competitive probe task to retrieve a related prime trial may vary with the experimental circumstances. When the probe is effective, a strong negative priming effect will be observed. If the probe is not effective, then negative priming will be diminished. No details were given about under what circumstances the probe will be effective and when it will not be effective.

Finally, the model of response activation must be given consideration. Although it was predicted that negative priming should occur whether there is competition in the probe trial or not, because of the hypothesized series of processing events, such was not the case. As discussed in the preceding subsection on inhibition of return, it seems that the model is in need of development. However, given the correspondence between the Houghton and Tipper (1994) model and the model of Welsh and Elliott (submitted), a post hoc explanation similar to that of the selection state strategy can be forwarded. That is, the participants were adopting a strategy to override any inhibition established in the Competitive prime trial, and as such, the response set was cleared and activation levels in the motor systems were returned to baseline following the Competitive prime movement. This clean slate explanation, however, is challenged by the findings of the significant increase in reaction times on location repeated in the Distractor-Alone probe condition. If the participants were allowing all inhibition to decay because selection was not required in the probe trial, then the increased reaction times when moving to the location of the ignored stimulus should not have been observed. Again, it is more likely that another layer of description is necessary for the development of the model to account for this dissociation.

Summary

Overall, although the model of response activation correctly predicted the deviation in the movement trajectories when competition between responses was involved, it is apparent from the results of the analyses of the probe trial movements that it is in need of development to be able to account for all perception-action coupling effects. As recently suggested by Tipper (2001) in reference to the (Houghton & Tipper, 1994) population coding model of selective action, it seems that consideration of perceptual and retrieval processes (Neill et al., 1992) and a more integrative approach to selective action is required. The results of the present work support this proposition as no one hypothesis could perfectly account for all of the results. Future work will investigate why response competition in the probe trial seems to be a necessary condition of negative priming as well as examining the role of facilitation of return for colour movement tasks with reference to dorsal-ventral visual stream interaction.

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Acknowledgements

This research was supported by a NSERC grant to Digby Elliott and a NSERC scholarship to Timothy N. Welsh. Digby Elliott's contributions are also supported by the Canada Research Chair Programme. The authors would like to thank Luc Tremblay and John Moroz for their technical assistance. The authors would also like to thank Timothy D. Lee, Bruce Milliken, and Janet Starkes for their comments on earlier versions of this paper.

Footnotes

1. Although negative priming is typically associated with the processes involved in the selection of the target from the non-target responses, we suggest here that the processes involved in inhibiting the response to the distractor when it is presented alone are not different from those involved when selection must occur. Tipper, Eissenberg, and Weaver (1992a) conducted a study using a very similar protocol to that of the present study and found negative effects of response inhibition in a non-competitive condition (their Response Inhibition condition, our Distractor-Alone condition). Interestingly, these response inhibition effects dissipated with increasing practice while negative effects (negative priming) of the inhibition in a competitive condition (their Ignored Repetition condition, our Competitive probe condition) did not. Rather than suggesting different mechanisms for the two effects, they proposed that participants discovered the probabilistic relationship between the location of the distractor-alone stimulus and the location of the probe stimulus (on 50% of the trials, the target appeared in the location of the sole distractor while appearing in one of the other three locations on only 16.7% of the trials) and used this knowledge to override the reflexive inhibition. The probabilistic relationship between the location of the prime distractor and the probe target for the Ignored Repetition trials was more subtle. As such, it was likely that participants did not recognize the relationship and did not strategize to override the reflexive inhibition on these trials. We agree with this interpretation and likewise propose that the processes involved in inhibiting the response to the distractor in our Distractor-Alone and Competitive prime trials are one in the

same (see also Park & Kanwisher, 1994). Hence, we used the Distractor-Alone condition to test our ideas about the effects of negative priming on movement and of the common mechanism behind inhibition of return and negative priming.

That said, it is acknowledged that a truer (more traditional) measure of negative priming would have been to examine the characteristics of the trajectories in the Competitive probe trials. However, because participants also moved to a location on these trials, inhibition associated with inhibition of return would be coexistent with codes associated with negative priming. Thus, it would not be possible to assess the effects of the inhibition associated with negative priming in isolation.

2. Apart from this effect of Location in Target-Alone prime trials, the significant effects and the directions of these effects for TT only differed from those of RT in terms of effect size. As such, TT effects will not be reported for the remainder of the text.

3. In the paper by Milliken et al. (2000), an explanation based on the ideas of the Kahneman et al. (1992) was emphasized over those of Neill et al. (1992) as an alternative to the Houghton and Tipper (1994) explanation. This alternative explanation was based on assumptions about how the relative efficiencies of two parallel and independent stimulus identification processes (one that identifies repeated stimuli and another that identifies novel stimuli) are reflected in response initiation times. If the target stimulus is one that was either a distractor

or target on the prime display (a repeated stimulus), then the identification of that stimulus and of the response is based on retrieval/reviewing processes in which the current target is compared to and integrated with a recently experienced set of stimuli. This set of stimuli are sustained in what are termed object files - hypothesized representations of the environment, presumably maintained in working memory, that have characteristics that are similar to the episodic traces of Neill et al. (1992). Alternatively, if the target stimulus is novel (neither a target nor distractor on the prime display), then a process of creating a new object file and programming of a response is initiated. The idea behind the proposal of Milliken et al. (2000) is that a response will be programmed based on the more efficient identification process. If conditions are such that the processing of a repeated stimulus (through integration with an object file) is more efficient than the processing of a novel stimulus, then a facilitatory repetition effect would be observed. In contrast, if conditions are such that the processing of the novel stimulus information is more efficient than the integration of the repeated information, then negative priming or inhibition of return would be observed (see Milliken et al., 2000, for greater detail). Although the explanation of the priming effects based on the hypotheses of Kahneman et al. (1992) and Neill et al. (1992) are rooted in the notion that the priming effects are the result of processes that occur after probe stimulus presentation, only certain ideas of the Kahneman et al. explanation are incorporated into the current discussion for the following reasons.

First, the many similarities between the notions of episodic traces and object files and the retrieval/reviewing processes that lead to the priming effects preclude the necessity of discussing both. Second, where these similarities exist, the hypothesis of Neill et al. is more comprehensive in terms of response processing (a main theme of the present work). For example, Kahneman et al. proposed that contained within the object file for a particular stimulus is "...information predicting ...the responses it should appropriately evoke..." (p. 178). However, this response-coding idea was not developed in terms of the "respond-to"/"do-not-respond-to" tags of Neill et al. (1992). Such coding was likely not discussed in the paper by Kahneman et al. (1992) because participants were not required to select or respond a target in the prime display. Thus, coding the responses in terms of "do" or "do not" was never at issue in the Kahneman et al. studies. Consistent with the idea that priming or tagging did not occur in the Kahneman et al. work was that no effect of colour repetition was found (see Study 6). That a facilitation of return effect for colour was not found underscores the lack of utility the Kahneman et al. hypothesis has for explaining the present data.

4. We thank Dr. Bruce Milliken for pointing this out to us.

Table 1. Mean and standard deviation () total response times (TT), reaction times (RT), and movement times (MT) in ms of movements to the Left, Middle and Right target as a function of the Distractor Location on the Target-Alone prime and Competitive prime trials.

Target/ DV	Distractor Location None	Left	Middle	Right
Left				
TT	592 (73)	N/A	624 (72)	610 (73)
RT	260 (30)	N/A	294 (34)	279 (38)
MT	332 (51)	N/A	330 (49)	332 (47)
Middle				
TT	531 (63)	539 (67)	N/A	537 (70)
RT	242 (26)	245 (30)	N/A	252 (30)
MT	289 (45)	294 (47)	N/A	286 (49)
Right				
TT	545 (67)	549 (75)	563 (68)	N/A
RT	269 (33)	274 (38)	290 (29)	N/A
MT	276 (48)	275 (49)	274 (49)	N/A

Table 2. Mean and Standard Deviation () of the average displacements in X, Y, and Z axes as a function of Target, Distractor Location, and Section in mm on the Target-Alone prime and Competitive prime trials.

DV/	Left Target			Middle Target			Right Target		
Sec	No	Middle	Right	No	Left	Right	No	Left	Middle
AveX									
1	-6.9 (3.9)	-7.0 (4.1)	-8.2 (4.7)	-4.1 (2.1)	-4.0 (2.1)	-1.5 (1.9)	-1.4 (1.9)	-8.2 (4.7)	-7.0 (4.1)
2	-52.4 (12.8)	-52.8 (13.0)	-53.2 (12.4)	-4.6 (3.4)	-4.8 (4.0)	23.0 (7.2)	22.6 (6.1)	-53.2 (12.4)	-52.8 (13.0)
3	-129.8 (13.2)	-131.8 (9.9)	-128.8 (10.8)	-1.9 (4.0)	-3.0 (4.8)	97.0 (12.1)	97.5 (9.9)	-128.8 (10.8)	-131.8 (9.9)
4	-160.6 (5.1)	-163.2 (2.7)	-161.7 (2.9)	-2.6 (1.9)	-3.9 (2.5)	154.4 (4.6)	154.8 (3.2)	-161.7 (2.9)	-163.2 (2.7)
AveY									
1	7.1 (1.8)	7.2 (1.9)	7.4 (1.9)	6.6 (1.5)	6.6 (1.8)	6.2 (1.6)	6.2 (1.6)	7.4 (1.9)	7.2 (1.9)
2	44.5 (6.2)	44.9 (6.5)	44.8 (6.7)	38.9 (5.3)	39.5 (5.2)	36.1 (4.4)	35.8 (4.4)	44.8 (6.7)	44.9 (6.5)
3	120.5 (9.4)	121.3 (6.2)	120.7 (6.5)	113.7 (6.1)	114.4 (7.0)	110.3 (6.0)	111.3 (6.2)	120.7 (6.5)	121.3 (6.2)
4	160.9 (4.1)	161.3 (1.8)	161.8 (1.7)	161.2 (2.2)	161.3 (2.3)	163.3 (3.4)	163.9 (3.2)	161.8 (1.7)	161.3 (1.8)
AveH									
1	0.9 (1.4)	1.0 (1.5)	1.5 (1.7)	0.6 (1.6)	0.5 (1.5)	1.4 (1.6)	1.5 (1.5)	1.5 (1.7)	1.0 (1.5)
2	23.1 (7.2)	23.4 (7.0)	23.8 (7.1)	12.7 (5.8)	13.2 (5.6)	13.3 (4.9)	13.3 (4.8)	23.8 (7.1)	23.4 (7.0)
3	32.9 (8.2)	35.1 (8.3)	35.2 (8.4)	29.3 (6.8)	29.5 (7.0)	32.3 (6.9)	31.8 (7.2)	35.2 (8.4)	35.1 (8.3)
4	12.7 (3.6)	12.8 (2.2)	13.3 (2.5)	12.4 (2.6)	12.4 (2.7)	14.1 (2.5)	13.3 (2.2)	13.3 (2.5)	12.8 (2.2)

Table 3. Mean and standard deviation () total response times (TT), reaction times (RT), and movement times (MT) in ms of movements to the Left, Middle and Right target as a function of previous Target or Distractor Location on the Target-Alone probe and Distractor-Alone probe trials. Also shown are the F ratios and p values (<) for the main effect of Previous Task and Location and the Previous Task by Location interaction.

Target/	Previous Target Location			Previous Distractor Location					
DV	Left	Middle	Right	Left	Middle	Right	Task	Loc.	T x L
Left									
TT	559 (64)	546 (71)	549 (69)	619 (90)	570 (78)	560 (75)	38.3 (.01)	20.6 (.01)	6.54 (.01)
RT	216 (36)	216 (32)	211 (33)	289 (47)	236 (40)	232 (34)	39.9 (.01)	35.9 (.01)	13.7 (.01)
MT	343 (41)	330 (49)	338 (51)	330 (52)	334 (50)	328 (55)	2.69 (.13)	0.54 (.55)	2.41 (.12)
Middle									
TT	490 (67)	495 (65)	498 (72)	498 (77)	535 (84)	509 (83)	5.84 (.05)	3.90 (.05)	2.64 (.10)
RT	193 (27)	193 (31)	200 (38)	214 (31)	242 (40)	217 (36)	25.7 (.01)	7.92 (.01)	10.8 (.01)
MT	297 (51)	302 (48)	297 (50)	284 (53)	293 (48)	292 (53)	3.57 (.09)	0.62 (.55)	0.27 (.77)
Right									
TT	501 (59)	503 (70)	496 (75)	508 (94)	522 (63)	548 (94)	39.9 (.01)	35.9 (.01)	13.7 (.01)
RT	216 (29)	221 (35)	218 (37)	233 (42)	241 (33)	278 (55)	17.9 (.01)	10.6 (.01)	16.8 (.01)
MT	286 (44)	282 (50)	278 (56)	275 (61)	281 (42)	270 (46)	2.55 (.14)	2.81 (.09)	0.42 (.66)

Table 4. Mean and Standard Deviation () of the average displacements in X, Y, and Z axes in mm as a function of Previous Location and Section for movements to the Left Target on the Target-Alone probe and Distractor-Alone probe trials.

DV/		Previous Target Location			Previous Distractor Location		
	Section	Left	Middle	Right	Left	Middle	Right
AveX							
	1	-7.2 (3.2)	-8.8 (4.2)	-9.1 (4.1)	-7.4 (5.0)	-8.0 (5.9)	-7.2 (4.4)
	2	-53.6 (8.4)	-54.1 (10.0)	-53.3 (10.7)	-53.0 (10.4)	-55.6 (10.6)	-52.4 (11.8)
	3	-133.3 (7.9)	-128.4 (10.2)	-130.6 (9.8)	-133.7 (4.8)	-133.0 (10.7)	-132.0 (10.5)
	4	-163.7 (4.6)	-158.7 (10.7)	-163.3 (4.1)	-163.0 (2.7)	-160.2 (12.5)	-162.3 (4.1)
AveY							
	1	6.3 (2.3)	6.1 (2.7)	6.3 (3.7)	7.3 (2.1)	7.8 (3.1)	7.2 (2.0)
	2	45.2 (5.6)	43.8 (7.0)	43.1 (8.4)	45.7 (3.9)	46.5 (5.6)	43.5 (5.9)
	3	125.5 (5.3)	121.9 (7.2)	121.2 (6.8)	124.6 (5.0)	123.7 (5.3)	121.2 (6.8)
	4	165.1 (3.6)	162.4 (2.7)	162.2 (3.6)	163.8 (3.4)	163.2 (3.4)	160.3 (3.7)
AveH							
	1	0.7 (1.5)	1.1 (1.8)	1.1 (2.0)	0.9 (1.7)	1.3(2.0)	0.7 (1.7)
	2	22.7 (7.8)	23.5 (8.5)	22.7 (6.6)	24.0 (8.7)	24.5 (8.4)	23.4 (7.9)
	3	31.9 (7.8)	33.1 (7.2)	33.1 (6.2)	33.6 (7.9)	34.3 (7.8)	32.6 (8.3)
	4	11.4 (1.9)	12.0 (1.7)	12.3 (2.9)	11.7 (1.9)	12.4 (1.8)	12.0 (2.4)

Table 5. Mean and Standard Deviation () of the average displacements in X, Y, and Z axes in mm as a function of Previous Location and Section for movements to the Middle Target on the Target-Alone probe and Distractor-Alone probe trials.

DV/	Previous Target Location			Previous Distractor Location		
Section	Left	Middle	Right	Left	Middle	Right
AveX						
1	-4.5 (1.9)	-4.7 (2.3)	-5.4 (2.2)	-4.1 (2.3)	-4.5 (2.1)	-4.3 (2.1)
2	-5.2 (4.3)	-5.7 (3.4)	-6.3 (3.8)	-4.4 (4.4)	-4.7 (3.8)	-4.6 (4.0)
3	-3.7 (7.2)	-3.5 (3.0)	-3.9 (3.5)	0.9 (4.9)	-1.1 (2.8)	-1.7 (3.4)
4	-3.8 (7.6)	-3.2 (2.6)	-2.8 (2.5)	-2.0 (3.1)	-1.2 (2.4)	-2.5 (2.1)
AveY						
1	5.7 (2.5)	6.0 (1.9)	5.9 (1.8)	6.7 (2.0)	7.2 (2.3)	6.8 (2.4)
2	39.8 (5.3)	39.3 (4.9)	39.4 (5.1)	38.0 (6.3)	40.5 (6.5)	39.9 (6.1)
3	117.4 (5.4)	116.0 (6.8)	117.4 (6.2)	107.8 (10.2)	114.1 (8.6)	115.6 (6.5)
4	165.6 (4.6)	163.9 (3.7)	164.5 (2.9)	157.4 (8.7)	162.2 (4.8)	163.0 (4.1)
AveH						
1	0.6 (1.5)	0.6 (1.7)	0.8 (1.8)	0.5 (1.4)	0.5 (1.5)	0.5 (1.5)
2	11.8 (4.5)	12.2 (4.4)	12.2 (4.6)	11.8 (5.5)	12.3 (5.1)	12.4 (4.8)
3	27.4 (6.0)	28.5 (6.5)	28.1 (4.7)	28.1 (7.6)	29.4 (6.1)	29.0 (7.2)
4	11.7 (3.0)	11.8 (2.5)	11.7 (2.5)	12.4 (3.3)	12.5 (2.9)	11.6 (2.1)

Table 6. Mean and Standard Deviation () of the average displacements in X, Y, and Z axes in mm as a function of Previous Location and Section for movements to the Right Target on the Target-Alone probe and Distractor-Alone probe trials.

DV/	Previous Target Location			Previous Distractor Location		
Section	Left	Middle	Right	Left	Middle	Right
AveX						
1	-1.9 (2.4)	-2.1 (2.5)	-2.9 (1.9)	-1.3 (2.0)	-1.2 (2.1)	-1.4 (2.3)
2	22.4 (7.2)	23.0 (6.5)	21.2 (5.5)	23.4 (7.2)	24.4 (7.7)	22.6 (7.4)
3	93.2 (14.7)	97.0 (14.8)	93.2 (12.3)	94.8 (11.5)	95.9 (10.5)	93.3 (13.9)
4	151.3 (11.8)	154.6 (4.8)	153.7 (6.6)	149.8 (5.8)	153.1 (5.8)	150.2 (4.8)
AveY						
1	4.9 (1.7)	4.3 (2.1)	5.4 (2.3)	6.3 (1.2)	6.5 (2.1)	6.2 (1.9)
2	36.5 (3.9)	35.6 (3.7)	37.0 (4.0)	35.6 (3.8)	36.6 (5.4)	36.0 (4.5)
3	112.3 (7.8)	112.1 (9.2)	112.5 (7.8)	107.8 (6.6)	108.3 (8.7)	107.7 (8.6)
4	165.0 (4.2)	163.9 (5.1)	164.3 (4.1)	160.1 (7.7)	162.4 (5.9)	161.1 (4.1)
AveH						
1	1.1 (1.5)	1.1 (1.7)	1.0 (1.6)	1.4 (1.7)	1.7 (1.7)	1.5 (1.7)
2	11.6 (5.3)	11.4 (4.7)	11.4 (4.3)	13.0 (5.7)	13.7 (6.2)	13.1 (4.0)
3	29.3 (7.6)	30.1 (7.5)	30.2 (7.7)	30.4 (8.9)	31.5 (8.6)	30.3 (6.5)
4	13.3 (2.8)	14.2 (3.4)	13.7 (2.7)	13.2 (3.6)	13.4 (3.2)	13.8 (3.3)

Table 7. Mean and Standard Deviation () total response time (TT), reaction time (RT), and movement time (MT) in ms as a function of previous Target/Distractor Location and Target on the Competitive probe trials.

	Target/Distractor Location					
Target/ DV	Left/Middle	Left/Right	Middle/Left	Middle/Right	Right/Left	Right/Middle
Left						
TT	542 (69)	535 (64)	546 (59)	556 (64)	554 (59)	550 (64)
RT	208 (34)	208 (24)	225 (23)	218 (29)	222 (21)	221 (30)
MT	334 (44)	327 (50)	321 (44)	338 (49)	331 (48)	329 (51)
Middle						
TT	489 (60)	491 (64)	504 (69)	475 (62)	489 (66)	495 (58)
RT	193 (30)	195 (28)	197 (33)	190 (30)	195 (26)	200 (26)
MT	296 (48)	295 (51)	307 (49)	285 (41)	294 (48)	296 (47)
Right						
TT	505 (63)	500 (67)	493 (62)	516 (66)	492 (68)	510 (76)
RT	225 (29)	221 (36)	210 (27)	227 (31)	213 (25)	223 (38)
MT	279 (41)	280 (45)	283 (50)	288 (51)	279 (53)	287 (50)

Figure Captions

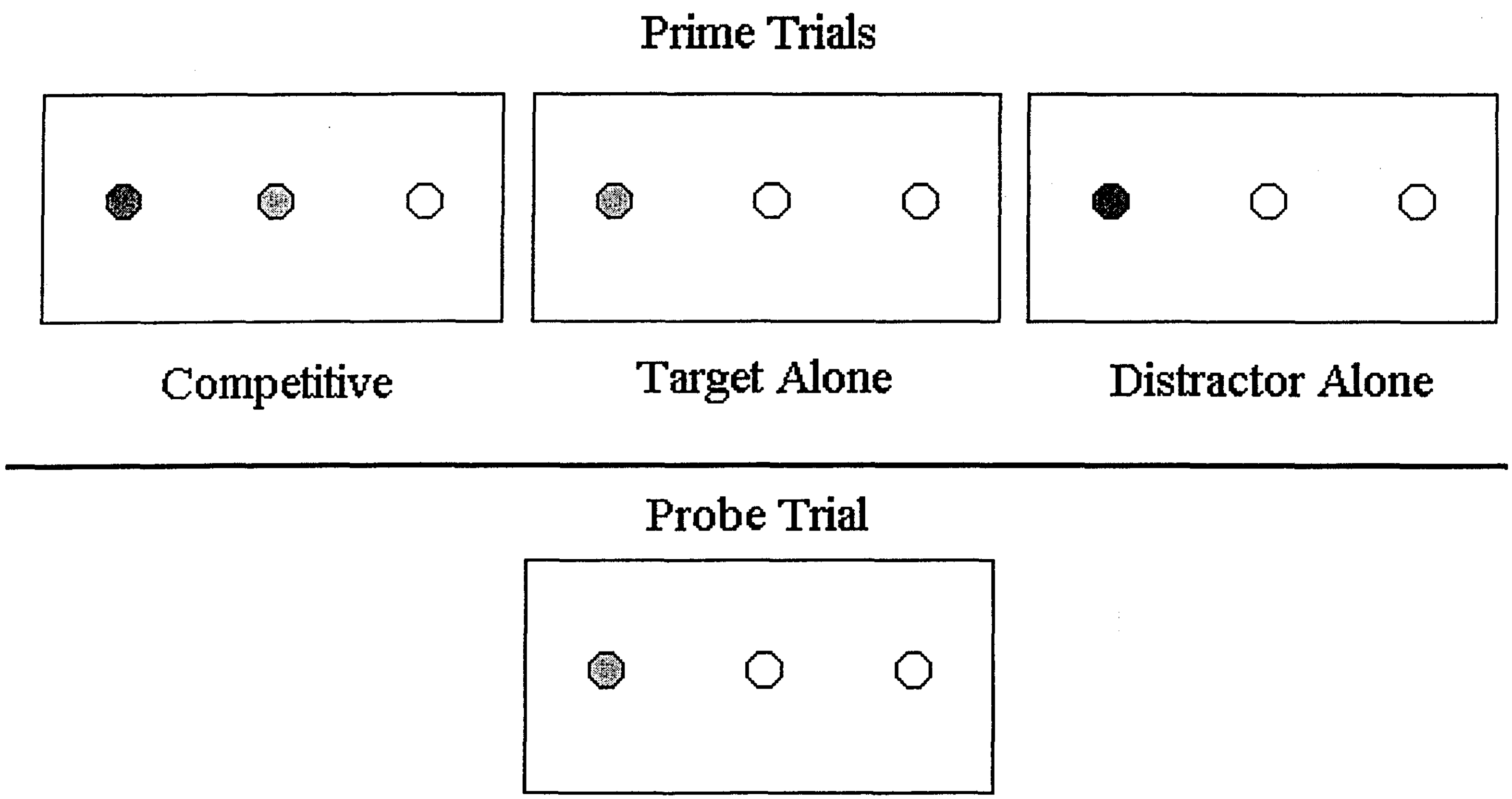
Figure 1. Diagram of prime/probe trials in relation to left location as the probe target.

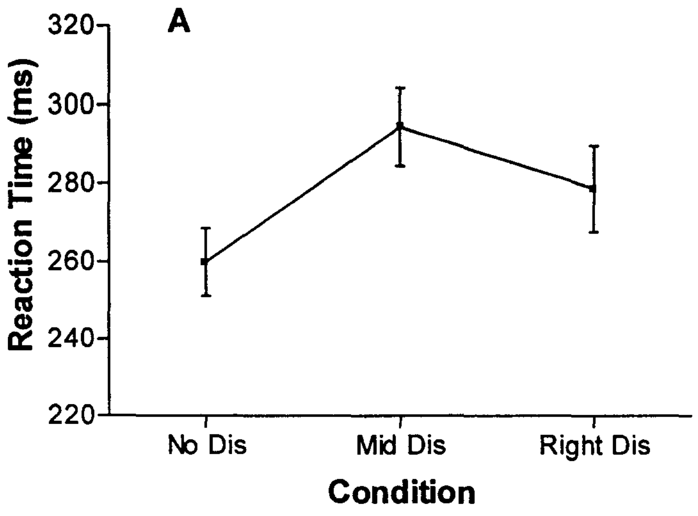
Figure 2. Mean reaction times as a function of Distractor Location for movements in the Competitive prime trials to the: A) Left Target; B) Middle Target; and, C) Right Target. Standard error bars are shown.

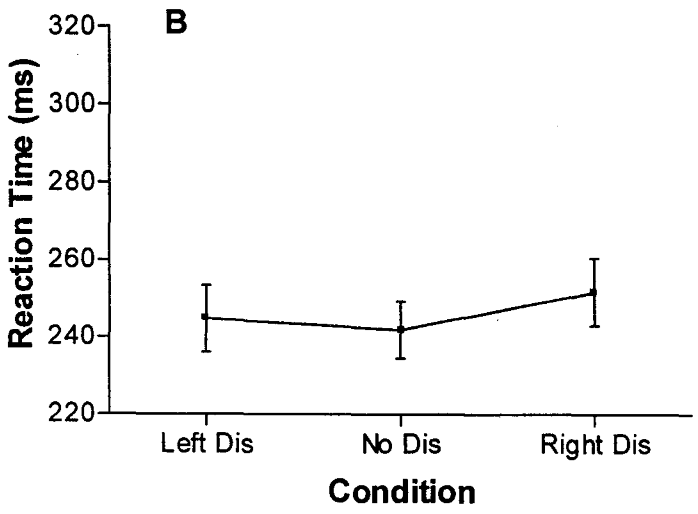
Figure 3. Mean difference deviations in X (leftward (-)/rightward (+)) axis during the Competitive prime trials for movements to the Middle Target as a function of Distractor Location. The square symbol represents movements with a Left Distractor. The triangle represents movements with a Right Distractor. Standard error bars are shown.

Figure 4. Mean difference deviations in Z axis during the Competitive prime trials for movements to the Middle Target as a function of Distractor Location. A positive deviation represents a movement that was higher than the control movement, whereas a negative deviation represents a movement that was lower than the control movement. The square symbol represents movements with a Left Distractor. The triangle represents movements with a Right Distractor. Standard error bars are shown.

Figure 5. Mean reaction times for the Target-Alone probe (square symbol) and the Distractor-Alone probe (triangle symbol) as a function of the previous stimulus location for movements to the: A) movements to left target; B) movements to middle target: and, C) movements to right target. Standard error bars are shown.


Prime Trials
Competitive
Target Alone
Distractor Alone
Probe Trial


A
320
300
280
260
240
220
Reaction Time (ms)
No Dis
Mid Dis
Right Dis
Condition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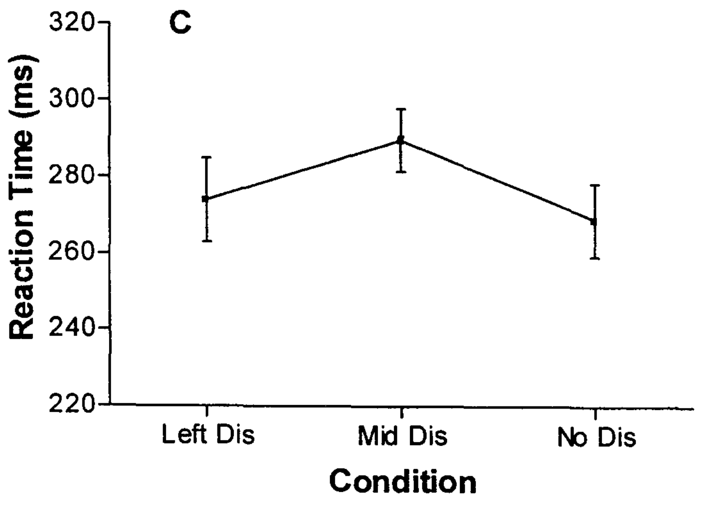
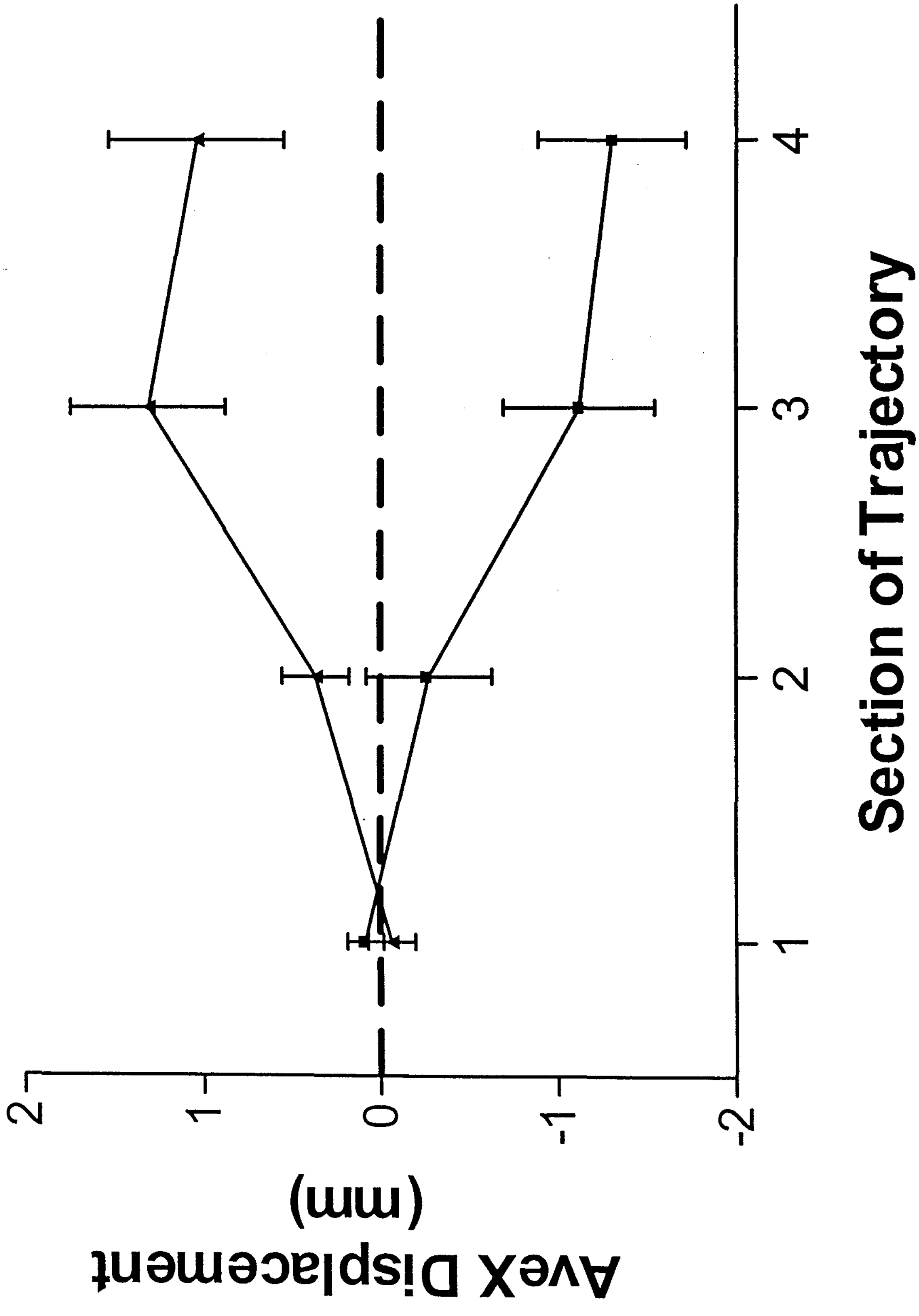
300
280
260
240
220
Reaction Time (ms)
Left Dis
No Dis
Right Dis
Condition


C
320
300
280
260
240
220
Reaction Time (ms)
Left Dis
Mid Dis
No Dis
Condition


AveX Displacement
(mm)
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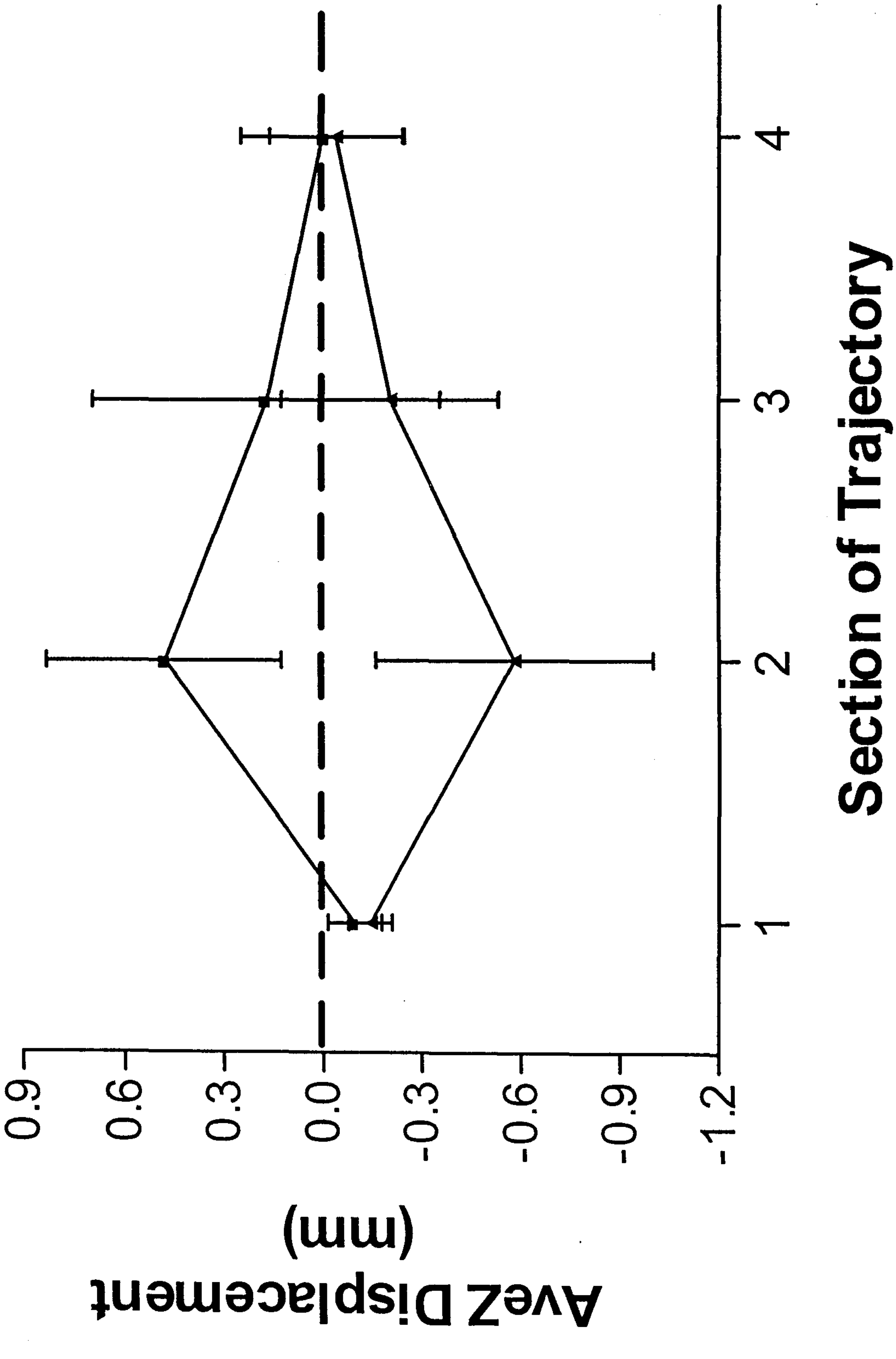
0
-1
-2
1
2
3
4
Section of Trajectory


AveZ Displacement
(mm)
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0.0
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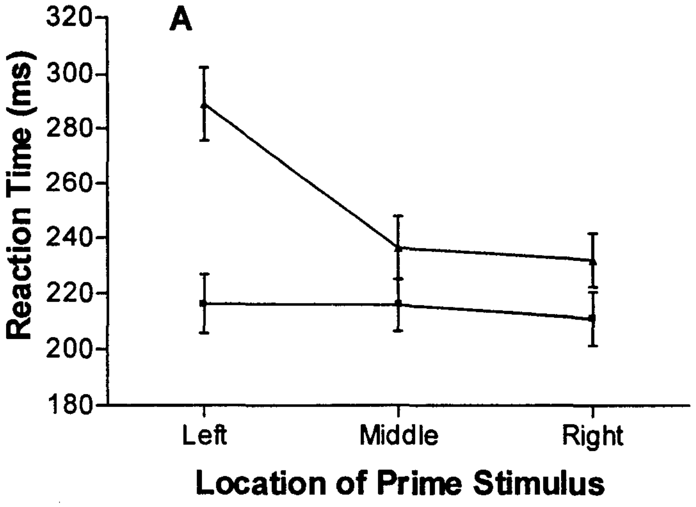
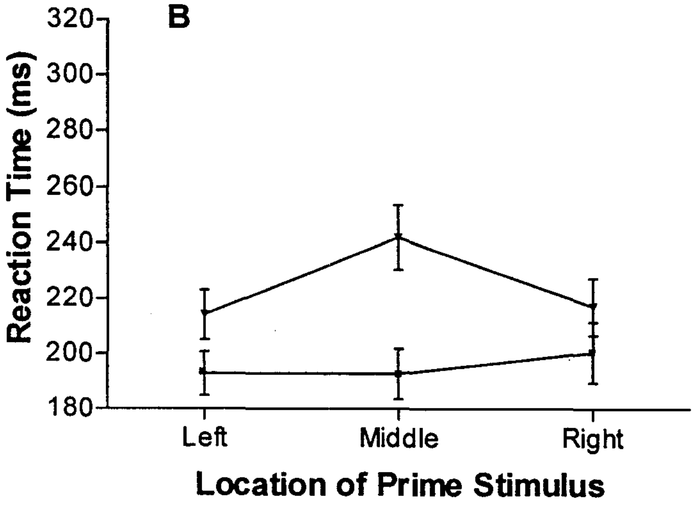
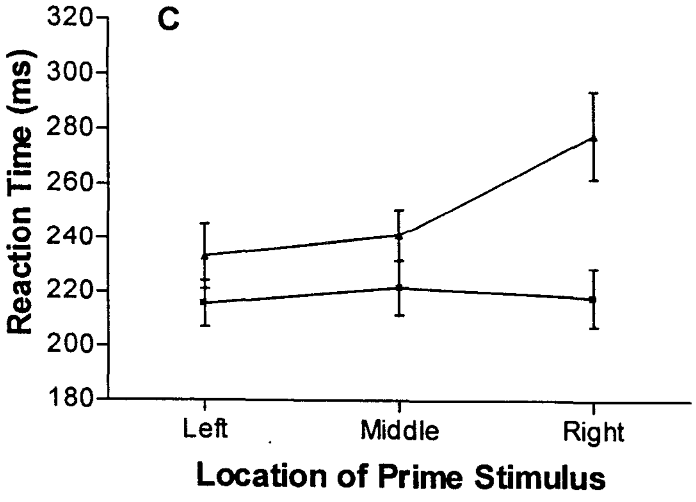
-0.6
-0.9
-1.2
1
2
3
4
Section of Trajectory


A
Reaction Time (ms)
320
300
280
260
240
220
200
180
Left
Middle
Right
Location of Prime Stimulus


B
Reaction Time (ms)
320
300
280
260
240
220
200
180
Left
Middle
Right
Location of Prime Stimulus


C
Reaction Time (ms)
320
300
280
260
240
220
200
180
Left
Middle
Right
Location of Prime Stimulus

GENERAL CONCLUSION

Previous investigations of the relationship between selective attention and action have indicated that the presence of a non-target stimulus in the movement environment affects both the temporal (Tipper, Lortie, & Baylis, 1992) and kinematic (Pratt & Abrams, 1994; Welsh, Elliott, & Weeks, 1999) characteristics of the movement. For example, Tipper, Howard, and Jackson (1997) found that a non-target block caused an increase in reaction time and deviations in the trajectory of the movement to the target block relative to when the target block was presented in isolation. To explain these effects, a model of selective action was proposed in which responses activated to target and non-target stimuli compete for activation. The purpose of the present series of studies was to test this model by measuring the direction of temporal and trajectory interference effects in the target movement relative to when inhibition of the competing responses was hypothesized to occur. Five experiments were conducted. These experiments were reported in three manuscripts.

The first paper reported three experiments whose results helped to define the parameters of the model of response activation. As the task in the original study that found deviations towards the location of the distractor employed a computer-based movement task (Welsh et al., 1999), it might have been that the results were due to a breakdown in the natural perception-action coupling (see earlier arguments). Thus, the first experiment in this paper was an attempt to replicate these results when participants completed a similar task that involved real movements in 3D space. Consistent with the results of Welsh et al. (1999), the distractor was found to cause deviation in the path of the movement towards its location while not affecting the time to plan or execute the goal-directed movement. These results were interpreted as evidence that the responses to both the target and non-target stimulus were initially corepresented in the motor system before inhibitory processes acted to suppress the non-target response.

Because deviation towards the location of the distractor was also found in real 3D movements, the second experiment was designed to test the hypothesis that deviation away from the non-target location in the studies by Howard and Tipper (1997) and Sheliga, Riggio, and Rizzolatti (1994; 1995) was due to successful inhibition of the competing response. In this experiment, the onset of a distractor relative to the onset of the target was varied. As predicted, when the participant was given enough time between the onset of the distractor and the onset of the target to inhibit non-target response, movement deviation away from the non-target location was found. If there was insufficient time between the distractor and target onset to inhibit the response, movement deviation towards the distractor occurred. It is important to note these results are consistent with the notion that both inhibitory and excitatory mechanisms are involved in the selection process (Houghton & Tipper, 1994).

In the final experiment reported in the first paper, the interaction between response priming and distractor interference was examined. Given the results of the first two studies and those of Welsh et al. (1999), it was hypothesized that if the target response was primed, then distractor interference would not be observed in the temporal or kinematic measures of movement. The null effect under these conditions was predicted because it was thought that if the target response was primed, the processes associated with that response would have a "head start" in the race for activation. As a result of this head start, the target response would have emerged before the activity associated with the non-target response would reach the motor system. The results were consistent with these predictions as the movements completed following a valid cue did not demonstrate evidence of interference. Further, when the distractor appeared at the cued location, significant interference effects were found in both temporal and trajectory characteristics of the movement that were parallel to the findings of the earlier studies. Overall, the results of the first three experiments were supportive of the model of response activation.

The experiment reported in the second paper was designed to further investigate the effects that response priming and inhibition have on both temporal and trajectory measures of movement. For this study, the precuing technique was utilized. Participants were given either predictive (80% valid), non-predictive (50% valid), or anti-predictive (20% valid) precue information about the target location. Consistent with the hypothesis that inhibition of return is caused by an inhibitory code placed on the response to a location that was previously attended to, movement deviations were found to deviate away from the cued location in the 50% valid condition. However, although response priming and inhibition were evident in the temporal measures of the movements in the 80% and 20% valid conditions, respectively, the direction of the trajectory effects was opposite to what was predicted. A strategy of overcompensation was suggested as the explanation for these incompatible results.

Finally, the third paper is a report of an attempt to discover the effects that processes hypothesized to cause inhibition of return and negative priming would have on goal-direct aiming movements. If both the inhibition of return and negative priming are associated with inhibition of the responses to a particular stimulus, then it was predicted that the trajectories of movements to a location should deviate away from the location of either the target or the distractor on the previous trial. Despite replicating significant temporal and trajectory distractor interference effects, inhibition of return and negative priming effects were not observed. These results are discussed with reference to other competing explanations of the negative priming effect and the need for future development of the model of response activation.

In sum, although not all aspects of selective action were accounted for by the model of response activation, the model does have predictive power for movements when competition between alternative response locations is current. Based on the results of the present work, it appears that there is an intimate link between perception, attention, and action. Indeed, consistent with the affordance theories of perception-action coupling (Gibson, 1979) it seems that the appearance of action-relevant stimuli within the movement environment automatically initiate response-producing processes to those stimuli. Furthermore, given the results of Study 2 and others (e.g., Sheliga et al., 1994; 1995), it also seems that orientation of attention is coded in the motor systems suggesting that attention could be conceived of as an action. Although the results of the earlier studies of the dissertation suggest a direct connection between perception, attention, and action, the results of the final experiment indicate that identification and memory processes can still affect the perception-action link (Milner & Goodale, 1995). It is evident that more research is needed to uncover the complex links between perception and action systems (see also Tipper, 2001).

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