REACHING INTO CLUTTERED VISUAL ENVIRONMENTS: EVIDENCE FOR ACTION REPRESENTATIONS OF NON-TARGET OBJECTS

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ABSTRACT

Among the most important behavioural abilities possessed by humans and other animals is the ability to act selectively in complex sensory environments that afford a large number of potential actions. A common example of such selective action used by experimental psychologists is picking a ripe (red) apple among unripe (non-red) apples. In the laboratory, this selection problem is usually examined using colour visual search tasks, in which subjects have to make a spatially-arbitrary response when they detect a red target among yellow non-targets. Typically selective processes handle such a selection problem very efficiently - measured by no increase in response time when non-targets are present. But such search tasks are poor analogues of the apple picking problem, because in order to pick the red apple one must direct a reaching response to its spatial location. The experiments in this thesis instead used a selective reaching task in which subjects responded to a red target, in the presence of a yellow non-target, by reaching to its location. In the selective reaching task, unlike in the search task, selective processes do not handle the selection problem with optimal efficiency - measured by an increase in response time when non-targets are present (i.e., interference).

The experiments in the thesis were designed to show that this suboptimal selection efficiency was related to the fact that reaching responses were used. The hypothesis was informed by physiological evidence that visuomotor information and colour information are processed by parallel pathways in the visual system. The need for visuomotor processing leading to reaching distinguishes the selective reaching task from the search task. The experiments provided support for the hypothesis that this visuomotor processing led to the concurrent activation of subovert reaching responses associated with the target and non-target, creating a response competition. The results have implications for theories of selection that purportedly apply to real-world situations such as picking a ripe among unripe apples, but that do not take into account the act of picking itself. Applications of the results to real-world situations in which people reach for the wrong object in multiple-object visual displays are also discussed.

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CHAPTER I

INTRODUCTION

Among the most important behavioural abilities possessed by humans and other animals is the ability to act selectively in complex sensory environments that afford a large number of potential actions. Consider the relationship between two species which have evolved in the same environment - a large predatory fish and a smaller prey fish. The next time you watch a documentary on aquatic wildlife, notice that prey fish do not scatter in reaction to the appearance of a predator, they quickly come together in schools. The prey fish incurred an evolutionary advantage when they developed schooling behaviour because of its utility for thwarting the killing ability of the predator. A school of 200 prey fish contains sensory information that affords 200 possible actions whereas a single scattering prey fish affords a single action. The predator faced with the former sensory environment would go hungry unless she possessed the ability to act selectively. That such predators continue to thrive attests to the fact that they have evolved selective abilities which have struck a balance with the behavioural adaptations of their prey.

Picking a single apple from a tree containing many apples is another common example used by contemporary experimental psychologists who study selective behaviour in humans and other primates. For the purposes of this thesis, I will further specify this example to the problem of picking a ripe (red) apple from a branch when an unripe (green) apple is nearby on the same branch. Although this selection problem may seem trivially easy compared to the one faced by the predator fish, and other selection problems faced by humans, it still requires neural computations of enormous complexity (see Allport, 1987; Jeannerod, 1994, p.230; Van der Heijden & Bridgeman, 1994; Wise & Desimone, 1988).

It is interesting to see how the study of such real-world problems has been translated into the modern experimental laboratory. I will provide a hypothetical example of what would be considered an experimental analogue of the apple picking problem - a colour visual search task. Human subjects sit in front of a personal computer and view the monitor. The subjects are instructed to press a button on the keyboard as quickly as possible when they see a red circle (a target) appear on the screen, and the time it takes for them to do so is measured. To ensure that subjects do not make this response until they see a target, some trials, on which subjects are to respond by pressing a different button, do not contain a target. Two types of target trials are seen: (1) a red circle appearing alone, or (2) a red circle and a green circle (a distractor) appearing together. The latter poses a selection problem that is not present in the former. Imagine looking from branch to branch on an apple tree and responding in a certain way when you see a red apple - some branches have a lone red apple, others have a single red apple among green apples, and the rest have only green apples.

If the time to respond to the red circle is longer when the green circle is present, then the increase in response time is considered a measure of how long selective processes took to operate. This type of measure could then be used to study the selection processes more closely. For example, if several green circles were present instead of one, would response time increase? If so, then one could conclude that increasing the number of irrelevant objects compromises the efficiency of the selection system being studied. Similarly, if a green circle at one location caused a greater increase in response time than a green circle at another location, then one could conclude that the spatial location of irrelevant objects influences the efficiency of the selection system.

Experimental psychologists have run very similar experiments to this hypothetical search example. The typical finding is that there is little, if any, increase in response time when targets and distractors are discriminated by colour, provided the colours are easily discriminable (see Carter, 1982; Duncan, 1989; Duncan & Humphreys, 1989; Treisman & Gelade, 1980; Treisman & Gormican, 1988). Also, excepting pre-trial location biases due to fixation position or location cueing, the absolute spatial position of a colour distractor does not seem to influence response time. These findings lead selection theorists to conclude that the selection system operates very efficiently when the target differs in colour from surrounding distractors. In fact, some theories have stated that selective processes are not even utilized when targets and distractors are discriminated by colour (e.g., Treisman & Gelade, 1980).

How do these experimental findings translate back to the real-world analogue of picking a red apple in the presence of a green apple? Selection theory suggests that the presence of the green apple would likely not compromise the efficiency of the selection system. However, one could argue that there are many differences between the real-world and experimental situations that call into question the validity of the analogy, and hence the validity of the application of selection theory to the real-world situation. In order to address such an argument, one must design an experimental situation that does a better job at bridging the translational gap to the real-world situation. Before I arrived at McMaster University my supervisor, Steve Tipper, had designed such an experimental situation - the selective reaching task.

Figure 1 (see Chapter II) is a schematic drawing of the visual display used in the selective reaching task. At each of the nine locations, there was a response button, a red LED, and a yellow LED. A red and yellow LED would light at different locations, and subjects were instructed to reach for and press the button at the location of the red LED (target) as quickly as possible while ignoring the yellow LED (distractor).

There were several fundamental differences between the selective reaching task and the search task described earlier, and these differences made the selective reaching task a closer analogue to the real-world situation. Many of these differences were related to the fact that the search task did not consider how visual information was used by motor systems in the real-world situation (Eriksen, 1995; Neisser, 1976; Stelmach, 1982):

1. Targets and distractors appeared at locations which differed in three dimensions in the selective reaching task rather than the two dimensions of the computer screen in the search task. Apples on a tree differ in three, rather than two, dimensions.

2. Targets were responded to by reaching to the location of the red light in the selective reaching task rather than pressing a button at a different location (on the keyboard) than the red circle (on the screen). When you want an apple on a tree, you reach for the location where the apple is rather than an arbitrary location at the base of the tree.

3. To correctly respond in the selective reaching task, and in the apple picking task, information concerning the location of the target must be available. However, in the search task, it is possible to detect the presence of a target without knowing its location (see Treisman & Gelade, 1980).

4. In the selective reaching task, targets at different locations required unique responses

whereas in the search task, targets at different locations required the same response. When you want to pick a second apple, you don't reach to the same location where you picked the first.

5. Distractors in the selective reaching task, like targets, were associated with unique responses because there was a response button at each distractor location. In the search task, no response could be made to distractors. When reaching for apples, it is possible that you could unintentionally reach for an unripe apple.

It was possible that these differences were irrelevant. The search task could have been considered a comparable analogue of the real-world situation if the selective reaching task produced the same results. In other words, there should have been negligible influence of yellow distractors on response time to red targets and distractor location should have been irrelevant. On the contrary, Tipper, Lortie, and Baylis (1992) found distractor interference in the selective reaching task, and interference was clearly determined by distractor location. This thesis represents my efforts to explain why distractor interference occurs in the selective reaching task, and why distractor location is important. In other words, my goal was to determine why the efficiency of the selection system is compromised in this case of selective action.

A Preview

The selective reaching task is a very simple task compared to many cognitive selection tasks (e.g, Stroop, 1935). But given the complex processes involved in even the simplest of tasks, the simplicity of the selective reaching task gives researchers an advantage in terms of the potential for understanding the underlying processes. Now that materialism is the accepted solution of the mind-body problem, the ultimate reductive explanation for any behaviour is how it is accomplished by the brain. From this perspective, the simplicity of the selective reaching task is particularly advantageous because it can be accomplished by non-human primates. The neurophysiology underlying the behaviour of these closely-related animals can be explored with more invasive, and informative, techniques. Thus our understanding of the processes involved in selective reaching can be informed by neurophysiological studies of related tasks.

In the search task, although targets and distractors differed in colour and in spatial location, responding to targets only required colour discrimination; targets could be detected without reference to their spatial location. In the selective reaching task, targets and distractors also differed in colour and in spatial location, but responding to targets required target localization in addition to colour discrimination. There is abundant evidence suggesting that colour and location information are processed independently and in parallel in the ventral and dorsal streams, respectively, of the primate visual system (Ungerleider & Mishkin, 1982; see Ungerleider & Haxby, 1994 for human findings). Thus, the search task relied primarily on processing occurring in the ventral stream, and the selective reaching task relied on processing in both streams (and on the integration of information between streams).

One must be careful when attributing the processing of object properties (e.g., colour) to the ventral stream or location to the dorsal stream, because object information is available to the dorsal stream (Goodale & Milner, 1992), and coarse coding of location occurs in the ventral stream (Desimone & Duncan, 1995). Goodale and Milner (1992) presented convincing evidence that object properties which are relevant to action, such as object shape for grasping actions, are processed in the dorsal stream. However, colour is probably one of the least important object properties for determining the form of an action. Also, the location coding in the ventral stream is not sufficient for completing the selective reaching task, because an arm movement must bring the hand to a visual target location, and the spatiomotor processing required to do so is the domain of the dorsal visual stream and its anterior projections (Milner & Goodale, 1993).

There are two properties of visuomotor processing which are relevant to the current discussion (both are discussed in greater detail in Chapter V). First, spatiomotor processing in the dorsal stream is remarkably fast and efficient. For example, there are numerous examples of rapid adjustments of reaching movements to changes in location of visual stimuli without subjects being consciously aware of the changes or adjustments (e.g., Castiello, Paulignan, & Jeannerod, 1991; Goodale, Pelisson, & Prablanc, 1986). This visuomotor efficiency ensures that spatially-directed reaches are quickly made to visual stimuli. The second relevant property is that visuomotor systems are capable of representing movements to more than one visual object in parallel (Eriksen & Schultz, 1979; Goldberg & Segraves, 1987). This is counter to many selection theories which assume that selective processes must single out one visual object for action before any visual information is passed on to motor systems.

The aforementioned properties of visuomotor and colour processing lead us to the following suggestions regarding selective reaching interference. We suggest that when two stimuli are presented, visuomotor processing in the dorsal stream (and beyond) leads to the rapid and parallel formation of premotor representations of movements to both stimuli. In parallel, colour information is processed in the ventral stream. By the time selective processes, which require integrated colour and location information, can operate, distractors have achieved some degree of visuomotor representation. The fact that distractors have achieved such advanced representations increases the burden on selective processes which must filter out distractor representations from influencing action to the target. Hence the cost in selection efficiency shown by distractor interference in selective reaching.

Why is distractor location an important determinant of the degree of interference in selective reaching? Visuomotor processing is more efficient at producing reaching movements to stimuli appearing at some locations than at others. In other words, after a set period of time following stimulus presentation, the level of premotor representation achieved by that stimulus depends on its spatial location. Hence the faster a reaching movement can be made to a location, the greater the advancement of the premotor representation of a distractor appearing at the location (when information becomes available for selection), and the greater the interference caused by the distractor. The experiments in the thesis directly test this hypothesis: Does an increase in visuomotor processing efficiency (a decrease in response time) to a target location correspond to an increase in interference from a distractor at the same location?

Alternatively, the location interference effects in selective reaching may be due to visual-spatial biases to certain locations resulting from some aspect of the selective reaching procedure. Search theory (e.g., Treisman & Gelade, 1980; Treisman & Gormican, 1988) might suggest that interference in general in the selective reaching task would be due to the fact that the target and distractor colours were not easily discriminable and thus "attention" was required to process the colour of each stimulus in a serial fashion. Castiello (1996) suggested further that "attention" must be focused on a stimulus in order for an action to be made to that stimulus. On target and distractor trials the target would be processed first 50% of the time, and the distractor would be processed first 50% of the time. On target-only trials the target would be processed first on 100% of the trials. Thus interference in general could be explained by the fact that distractor trials took longer because "attention" was delayed from focusing on the target on 50% of trials. However, this account cannot explain why distractors at certain locations caused more interference than distractors at other locations, *unless* "attention" was biased to the former locations. Thus it was crucial for our account to show that the location interference effects were due to visuomotor efficiency rather than visuospatial biases, and the experiments in the thesis were designed to this end.

CHAPTER II

The following is a single experiment paper which has recently been revised and re-submitted following peer review from *The Quarterly Journal of Experimental Psychology, Section A: Human Experimental Psychology*. The experiment in the paper is Experiment 1 of the thesis. All references, notes, tables and figures from this paper are self-contained in Chapter II. References, notes, and figures from all other Chapters are listed together at the end of the thesis. To avoid confusion, numbers referring to figures and notes in the other Chapters begin with four and two, respectively, because Figures 1-3 and Note 1 appear in Chapter II.

The introduction of the paper reviews the selective reaching results from Steve Tipper's laboratory which were found prior to my arrival at McMaster University and published in Tipper, Lortie, and Baylis (1992). Applications of selective reaching research to real-world problems outside of the experimental psychology laboratory are also discussed.

EXPERIMENT 1

Reaching into Cluttered Visual Environments: Spatial and Temporal Influences of Distracting Objects

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Running head: SELECTIVE REACHING

Abstract

Subjects reached with the right or left hand to a visual target at one of six locations from a starting position at the body midline. We measured the increase in response time to a target when a distractor was present at one of the other five locations (i.e., interference). In a similar task, Tipper, Lortie, and Baylis (1992) showed that distractors appearing at locations between the starting position and the target location caused more interference than distractors beyond the target. We replicated this finding and showed that it is due to the proximity of distractors to the starting position (the proximity effect). Tipper et al. also showed that distractors appearing in the right hemispace caused more interference than left distractors when the right hand was used, but that left distractors caused more interference when the left hand was used (the ipsilateral effect), and we replicated this finding. We examined interference in the reaction time (RT) and movement time (MT) components of the total response time measure used by Tipper et al. The proximity and ipsilateral effects were found in RT and MT, suggesting that both temporal components of movement are influenced similarly by distractors. There were also individual differences in movement initiation strategies which were predictive of the temporal locus of distractor influence - subjects with short RTs were more likely to show the spatial influence of distractors in MT. Errors occurred when the distractor location was touched, and there were proximity and ipsilateral effects in the error data. We discuss applications of these findings to real-world situations in which people reach for the wrong object in multiple-object visual displays.

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Reaching into Cluttered Visual Environments: Spatial and Temporal Influences of Distracting Objects

Reaching for objects with the aid of vision is an ability of tremendous importance to humans and other animals; it is among the most frequent behaviours that humans perform daily. In most reaching situations we encounter day-to-day, there are multiple objects in space and only one must be acted upon. Consider examples in which you reach for and grasp a single pencil in a holder containing several pens and pencils, or reach for and press a single key on a keyboard containing dozens of keys.

Despite the fact that many reaching situations involve multiple objects, the laboratory study of reaching has focused almost exclusively on single-object environments. Reaching movements to a single object appearing at a known location, or at one of several possible locations, have been extensively studied, but reaching movements to one of several possible objects have been almost completely ignored. The experimental study of reaching into multiple-object environments is clearly important for its potential to be applied to problems outside of the laboratory. For example, costly manual errors in human-machine interactions are commonly the result of reaching for the wrong object in machine interfaces containing multiple objects; the ability to minimize such errors requires an understanding of what aspects of multiple-object environments are likely to produce them.

In addition to its practical interest, the experimental study of reaches into complex visual environments is of theoretical interest to the areas of visually-guided reaching and selective attention. Often when we reach for an object, the visual field into which we reach contains objects other than the object of interest. The visual system, which at least at its earliest stages processes all stimuli in the visual field in parallel, encodes non-target objects (distractors) in addition to the target object. Until the brain is able to identify the target and filter out information about distractors, the distractors are potential targets. As potential targets, they can compete for the control of action, and influence reaching movements to the actual target.

Although visual selective attention mechanisms have likely evolved to enable motor acts such as reaching into multiple-object environments, selective attention researchers have neglected to use reaching responses in the laboratory. This would not be a problem if the conclusions drawn about the nature of selective attention mechanisms were unaffected by the nature of the motor responses used in the tasks to study these mechanisms. However, recent efforts to use reaching responses in selective attention tasks have provided novel insights into the nature of selective attention mechanisms.

Selective Reaching

Tipper, Lortie, and Baylis (1992) introduced a visual selective attention task that required a directed manual reach to a visual target that appeared randomly at one of nine locations in peripersonal space. A visual distractor, differing in colour from the target and presented simultaneously at one of the eight remaining locations, caused response time delays for reaches to the target location (i.e., interference). Interestingly, the spatial nature of the interference varied according to action properties of the task, such as the starting position of the hand and which of the hands was used to respond.

Figure 1 is a representation of the stimulus display used by Tipper et al. (1992). For reaches from the starting position shown (at the front of the display) to targets in the middle row (locations 4, 5 and 6), there was more interference from distractors in the front row (locations 1, 2 and 3) than from distractors in the back row (locations 7, 8 and 9). The starting position of the hand was then moved to the rear of the display (above the back row shown in Figure 1) while the body was maintained in the same position, so that subjects were reaching towards the body. The results were the opposite for reaches from this rear starting position to targets in the middle row - back row distractors interfered more than front row distractors. In other words, the starting position of the hand had a profound influence on the spatial nature of the interference. The hand used to respond also influenced interference. When the right (dominant) hand was used to reach for a target in the middle of the display (location 5), there was more interference from a distractor to the right of midline (location 3) than from a distractor to the left of midline (location 1). But when the left (nondominant) hand was used to reach for the same location, there was more interference from the left distractor than the right distractor.

(FIGURE 1 ABOUT HERE)

Tipper et al. (1992) interpreted these findings by suggesting that motor programs for reaches to both the target and distractor are specified in parallel, and that "the nature of the simultaneously activated responses determines the level of competition (interference) between them" (p.903). They suggested that front and back row distractors were more competitive when subjects reached from the front and back of the display respectively, because those distractors were within the path of the response to the target. They also suggested that distractors in the hemispace ipsilateral to the responding hand were more competitive than contralateral distractors. This latter suggestion was supported by findings of advantages on various dependent measures for movements directed to visual targets in the hemispace ipsilateral, relative to contralateral, to the responding hand (Fisk & Goodale, 1985; Prablanc, Echallier, Komilis, & Jeannerod, 1979).

The purpose of the present study was twofold. One purpose was to clarify the theoretical interpretations offered by Tipper et al. (1992), and others, for explaining distractor interference in selective reaching. The second purpose was to compile our present knowledge about the spatial and temporal aspects of distractor interference in selective reaching, and discuss the potential applications of such knowledge.

Spatial Aspects of Selective Reaching Interference

Although we agree with the general theoretical interpretation offered by Tipper et al. (1992), questions remain about interpreting the "competitiveness" of distractors at certain spatial locations under certain response conditions. For example, when manipulating the starting position of the hand, it is not clear that the distractor's relation to the response path is the crucial variable being influenced. Another variable that is being influenced by this manipulation is the proximity of the distractor to the starting position of the hand. Recall that for both starting positions, distractors in the row nearest the starting position interfered more than distractors in the row farthest from the starting position (Tipper et al., 1992). It is possible that distractors' proximity to the starting position of the hand, rather than their position relative to the response path, determined their competitiveness.

Like the evidence cited above for the greater competitiveness of movements directed to the hemispace ipsilateral to the responding hand, there is also evidence for advantages on various dependent measures for more proximate movements (e.g, Fitts & Peterson, 1964; Glencross, 1973; Rosenbaum, 1980). Also, infants who can perceive depth have a spontaneous reaching preference for the nearer of two objects when the two objects subtend the same visual angle (e.g., Bower, 1972), suggesting that near objects are more competitive.

The present study attempted to discriminate between the influence, on distractor interference, of (1) the proximity of the distractor to the starting position of the hand, and (2) the position of the distractor in relation to the response path. Such a discrimination allows us to further specify the theoretical account suggested by Tipper et al. (1992). They suggested that motor programs for both the target and distractor are specified in parallel, and that the nature of the responses determines the amount of response competition.

We suggest further that what determines the amount of interference from distractors is the degree to which their subovert response processes compete temporally in a race, with the subovert response processes associated with the target, for the control of overt action. Distractor interference is a measure of the processing time required to decouple the distractor premotor processes from the control of motor processes. This selection time is determined by the status of distractor processing when target identification information becomes available; the closer distractor processing gets to the output level, the greater the selection time. Any factor that influences the speed with which a response can be generated to a spatial location influences the amount of interference from a distractor at that location. For example, motoric manipulations such as the starting position of the hand and the hand used to respond influence the speed of response processing for different locations and thus the amount of interference from distractors at those locations.

Our account suggests that distractor response processes are initiated independently from, and in parallel with, target response processes. The hypothesis that interference is determined by the position of the distractor in relation to the response path is inconsistent with this account, because the response path is defined by the target location. In order for distractor interference to be determined by the target location, as the response path account suggests, the target would have to be identified prior to the influence of distractors. We suggest that it is unlikely that interference would be determined subsequent to target identification.

The distractor proximity hypothesis, however, is an alternative that is consistent with our account because the location of a distractor with respect to the starting position of the hand is independent of the location of the target. Similarly, a distractor's position relative to the body midline, and its relationship to the responding hand are independent of target location. Our account suggests that the spatial relationship of a distractor to the starting position of the hand or to the responding hand determines the speed with which distractor processing progresses and thus how much a distractor will interfere.

In the present study, evidence in favour of the response path hypothesis will be taken as inconsistent with our theoretical interpretation of selective reaching interference. Conversely, evidence in favour of the proximity hypothesis will be taken as consistent with our theoretical interpretation.

Temporal Aspects of Selective Reaching Interference

One other study of selective reaching, by Pratt and Abrams (1994), recognized the implications of the response path hypothesis, and set out to examine the influence of distractors in the response path on different temporal periods of manual movements. In the Tipper et al. (1992) study, interference was measured across the total time period from the time the stimuli appeared until the target location was reached. We will refer to this measure as Total Time (TT). Pratt and Abrams (1994) split TT into 3 components:

(1) Reaction Time (RT): from the appearance of stimuli until the onset of movement.

(2) Movement Time (MT):

- (a) ballistic (MT_b): from movement onset until peak velocity of the movement.
- (b) corrective (MT_c): from peak velocity until the end of the movement.

Pratt and Abrams (1994) replicated the Tipper et al. (1992) finding of more TT interference from distractors between the starting position and the target than from distractors beyond the target position. Furthermore, they found the same effect in both the RT and MT_c (but not the MT_b) components of the movement.

Pratt and Abrams (1994) interpreted the RT finding as follows. RT is traditionally taken to indicate the time required to plan and prepare a movement. The RT finding "suggests that at least some of the planning that takes place during the latency interval occurs in a representational system in which the starting location of the movement is important, in addition to the goal for the movement...part of the preparation to move involves some attention to the path of the movement, and the objects that may be encountered along the way" (p.253). This interpretation realizes the implications of the response path account discussed earlier; in other words, target (goal) information is required for interference to be determined by a distractor's relation to the response path.

Pratt and Abrams (1994) interpreted the MT_c result in a similar manner. The MT_c result "is consistent with the function that is believed to be served by the corrective movements: To assist in the accurate termination of the movement at the desired target - to the exclusion of other nearby potential targets. As Tipper et al. (1992) suggested, because the limb must pass over the near distractor, it becomes necessary to suppress any tendency to terminate the movement there. Such a suppression is not necessary for a far distractor - because movements to the target need not pass over it" (p.253). This interpretation also assumes the importance of the response path in determining interference.

We have already described how the response path hypothesis is inconsistent with our theoretical interpretation. An explanation for the TT findings of Tipper et al. (1992) and Pratt and Abrams (1994) which is consistent with our account would be that distractors that were between the starting position and the target were more proximate to the starting position than distractors beyond the target. However, we have not yet offered an explanation for interference in different time periods of movement.

Pratt and Abrams (1994) suggested that distractors cause interference in different time periods because they pose unique problems for movement planning and movement correction mechanisms which must be resolved for the movement goal to be achieved. We suggest, on the other hand, that a single selection problem must be resolved for the goal to be achieved. As discussed earlier, this problem is one of target-distractor competition based on processing advantages for responses to visual stimuli at certain spatial locations. The temporal locus of the resolution of this selection problem (i.e, interference) is determined by the time at which the target is identified relative to when the movement is initiated. If the target is identified (and selection occurs) prior to movement initiation, then interference (a measure of selection time) would occur in RT. Conversely, if the movement is initiated prior to selection, then interference would occur in MT. If the movement is initiated during selection, then interference could occur in RT and MT.

Selection is traditionally thought to occur prior to movement initiation. However, the methods used in the Tipper et al. (1992) and Pratt and Abrams (1994) studies (and in the present study) do not necessitate this interpretation. In these studies there was no penalty (no catch trials) in the task to force subjects to make a selection decision prior to movement initiation. Subjects were instructed to get to the target as quickly as possible once the stimuli appeared; in other words they were instructed to minimize TT rather than MT. Under these conditions subjects could have initiated a movement prior to the time when selection was resolved, and thus could show MT interference.

Our interpretation of the Pratt and Abrams (1994) RT and MT_c results is as follows. The spatial nature of the interference is the same for both time periods, and can be explained by the proximity hypothesis. That the resolution of the spatial selection problem occurred in both time periods is a function of when selection occurred relative to movement initiation. As suggested earlier, on a given trial, if the movement is initiated during selection, then interference could occur in RT and MT_c. These findings could also be due to within or between subject differences in when selection occurred relative to movement initiation, because the reported results are pooled from many trials and many subjects. In other words, a single subject may have varied from trial-to-trial, or there may have been subject-to-subject variance, in terms of when selection occurred relative to movement initiation. The reported findings of RT and MT_c interference across subjects are thus consistent with our account that the resolution of a single selection problem could take place in both time periods.

This interpretation requires an explanation for why no MT_b interference differences were found for distractors between the starting position and the target and distractors beyond the target in the Pratt and Abrams (1994) study. "Ballistic" refers to a period of the movement which is pre-programmed and not subject to modification (Carlton, 1981; Woodworth, 1899). Thus it is not surprising that in selective reaching tasks, if a movement is initiated before selection is completed, then the initial, ballistic part of that movement would not show temporal evidence of the resolution of selection.

In the present task, we did not partition MT into MT_b and MT_c, because our equipment did not allow us to do so. Pratt and Abrams (1994) also analyzed MT as a whole, and found that there was more MT interference from distractors between the starting position and the target than from distractors beyond the target. Based on the results of Pratt and Abrams, MT interference measured in the present study was more likely to have occurred during the later portion of the movement, rather than the initial portion.

The present study sought to explain temporal aspects of distractor interference by creating an experimental situation for which our account and that of Pratt and Abrams (1994) would make different predictions.

Spatial and Temporal Aspects of Selective Reaching Interference

In the Tipper et al. (1992) and Pratt and Abrams (1994) studies, only certain target-distractor conditions were analyzed. Similarly, in the present experiment only a subset of the trials were used to resolve the issues outlined above. To be sure that the conclusions of these analyses could be generalized to a larger sample of possible selective reaching situations, we analyzed all of the possible target-distractor conditions in the experiment. This analysis took into consideration what is known about spatial and temporal aspects of interference from selective reaching studies.

Individual Differences and Errors

We also took a closer look at individual differences in the way subjects responded in the experiment to see if our account accurately predicted the temporal locus of interference (RT or MT) for different response strategies. Finally, we looked at error performance. An error occurred when the distractor location was touched, and we predicted that those spatial locations at which distractors were more likely to cause interference were also more likely to be sites of errors. Following the *Results*, we discuss the implications of the present findings for theoretical models of selective attention and for applications to human-machine interactions.

Method

The task was very similar to that used by Tipper et al. (1992), although there were notable differences. Rather than the nine-location display of Tipper et al. (see Figure 1) we used six stimulus locations (see Figure 2). In addition to measuring TT, we also measured RT and MT.

(FIGURE 2 ABOUT HERE)

Subjects

Forty undergraduate students (18 males and 22 females) from McMaster University participated in the experiment for course credit. All subjects were right handed, had normal colour vision, and had normal or corrected-to-normal acuity. Twenty subjects used their right hand and twenty used their left hand for the experiment.

Reaching Apparatus

The stimulus board used in the experiment is displayed in Figure 2. The board (area = 51 square cm) was raised to an angle of approximately 30° from the horizontal and placed on a table 14 cm from the front edge. On the board were six 1.7 cm X 1.7 cm buttons arranged in 2 columns of 3 buttons each, with a distance of 13.5 cm separating buttons within a column and 29 cm separating the two columns horizontally. Two small lights, one red and one yellow, were positioned beside each other directly below each button. The start button was located 13.3 cm before the centre of an imaginary line connecting the front row buttons of each column. The board was interfaced to an Apple IIe computer which controlled stimulus lights, and recorded response times and errors.

Design

There were 36 possible target-distractor combinations on the board: one no-distractor (target only) control condition and five distractor conditions for each of the six target locations. Twenty trials of each target-distractor combination appeared randomly for each subject for a total of 720 trials.

There were three measures of response time: (1) Reaction time (RT), measured from the time the target light appeared to the time the start button was released; (2) Movement time (MT), measured from the time the start button was released to the time the target button was pressed; and (3) Total time (TT), measured from the time the target light appeared to the time the target button was pressed (RT + MT).

Procedure

The subjects sat in front of the stimulus board under dim illumination and were told to get in a position where they could comfortably reach all six keys with their designated hand. They were asked to maintain a body posture such that the body midline was in line with the start button and the shoulder line was parallel to the front edge of the board. As in the Tipper et al. (1992) experiments, no chin rest was employed because arm movements can be disrupted when the head is restricted (e.g., Biguer, Jeannerod, & Prablanc, 1985). Subjects were instructed to press the start and target buttons with the tip(s) of the index and/or middle finger. They were instructed that on each trial a red light would appear under one of the 6 buttons and that on some trials a yellow light would appear at a different location. They were instructed to press the button above the red light as quickly as possible while ignoring the yellow light. Each trial began with the subject pressing and holding the start key with the appropriate hand. A pause (approximately 600 ms) occurred between start key depression and stimulus onset. After the pause, the target and distractor (or target alone) appeared and remained on until the subject completed the response. After the response, the subject could initiate the next trial at any time. The computer gave an error tone if the subject pressed the wrong key or if the start key was released before stimulus onset. In the latter case the trial was repeated. After a 10 trial demonstration from the experimenter, the subjects completed 20 practice trials which were chosen randomly from the 36 target-distractor combinations. Following the practice trials, subjects participated in 720 experimental trials. Subjects rested for two minutes after 360 of the experimental trials had been completed, and then completed the remaining 360 trials.

Results

Interference scores for each subject in each distractor condition were calculated in the following manner. First a mean response time was calculated for each target-distractor combination (including target-only conditions). The difference between mean response times for each target-distractor combination and its respective control (response time to that target without a distractor) was then calculated. Interference scores for each subject in each distractor condition were calculated by taking a mean of all difference scores in a particular distractor condition, where each condition is pooled across several target-distractor combinations. The description of which target-distractor combinations were included in distractor conditions for each analysis use the location numbers shown in Figure 2. Front row locations on the left and right were 1 and 4 respectively, middle row locations were 2 and 5, and back row locations were 3 and 6.

The hand used to respond was analyzed as a between-subjects factor in all analyses. When examining the influence of the responding hand on hemispatial interference (Tipper et al., 1992), distractors were categorized as ipsilateral/contralateral rather than right/left, so that right distractors were ipsilateral for subjects who used the right hand and contralateral for subjects who used the left. Unexpectedly, there was a main effect of hand for all analyses - there was more interference for the subjects who used their right hands. This result is difficult to explain; there is no precedent in the literature for such a finding and it has not been replicated in any of the many other studies from our laboratory. However, hand did not interact with any other factor, and we will not discuss right or left hand as a factor in the analyses.

Spatial Aspects of Selective Reaching Interference

We first sought to replicate the Tipper et al. (1992) and Pratt and Abrams (1994) findings that distractors between the starting position and middle row targets caused more TT interference than distractors beyond the middle row targets. Interference scores were calculated for all middle row target (locations 2 and 5) trials. Mean interference scores were calculated for each subject for: (1) front row distractor (locations 1 and 4) trials and (2) back row distractor (locations 3 and 6) trials. Front row distractor interference (mean = 17.94 ms) was greater than back row distractor interference (mean = 9.01 ms) [$t(39) = 4.246$, 2-tailed, $p < .001$]. This was a replication of the previous findings.

We discriminated between the response path hypothesis and the proximity hypothesis for explaining the above result in the following manner. Tipper et al. (1992) and Pratt and Abrams (1994) combined all trials in which distractors were between the starting position and the target into a single category (i.e, distractors in the response path). We sub-categorized these trials according to differences in the distractor's proximity to the starting position and the distractor's relation to the response path. More specifically, we looked at trials in which targets were in the back row (locations 3 and 6 on Figure 2). Notice that distractors at the other locations (1, 2, 4 and 5 on Figure 2) differed in terms of proximity and relation to the response path. For a reach to a target at location 6, distractors 1 and 4 were more proximate to the starting position than distractors 2 and 5, and distractors 4 and 5 were more likely to have been in the response path than distractors 1 and 2. Similarly, for a reach to a target at location 3, distractors 1 and 4 are more proximate to the starting position than distractors 2 and 5, and distractors 1 and 2 are more likely to be in the response path than distractors 4 and 5.

These categories and the mean interference for trials in these categories are compiled in Table 1. An ANOVA that yielded a main effect of response path, or an interaction of response path with proximity, would support the hypothesis that distractors' relation to the response path plays a role in determining interference. However, the only effect was a main effect of proximity - distractors nearest to the starting position (mean = 29.55 ms) interfered more than distractors further from the starting position (mean = 10.950 ms) [$F(1,39) = 38.411, p < .0001$]. Distractors' relation to the response path had no influence on interference; in fact, mean interference was slightly higher for non-response-path distractors

(22.24 ms) than for response-path distractors (18.26 ms). This analysis supports our contention that proximity to the starting position, rather than relation to the response path, is the best explanation for why distractors between the starting position and the target interfere more than distractors beyond the target.

(TABLE 1 ABOUT HERE)

Temporal Aspects of Selective Reaching Interference

This experiment also sought to discriminate between our account and the account of Pratt and Abrams (1994) for explaining temporal aspects of distractor interference. Recall that our account holds that a single, spatial selection problem has to be resolved, and that this problem may be resolved before or after movement initiation. Thus, if there is interference in RT and MT, we predict that the spatial nature of that interference will be the same in RT and MT. Pratt and Abrams' account holds that there may be unique spatial problems that have to be resolved and that such problems may uniquely affect different temporal periods of movement. Their explanation for interference in RT and MT was that distractors between the starting position and the target caused unique problems for movement preparation (RT) and movement correction (MT).

Back row target trials, which were analyzed above for TT interference, provide an opportunity to discriminate between these accounts. When reaching to back row targets, distractors closer to the starting position (front row distractors) caused more TT interference than distractors further from the starting position (middle row distractors). The two accounts for the temporal nature of interference would make different predictions about the RT and MT components of this TT interference. Our account would predict that if there is interference in RT and MT, then the spatial nature of the RT and MT interference should be the same as the TT interference. In other words, front row distractors should cause more interference than middle row distractors in RT and MT, as they did in TT.

The Pratt and Abrams account would not make the same predictions, however. A proximity effect in MT would be inconsistent with their corrective interpretation of MT interference. If interference in MT is corrective in nature - i.e., it results from the need to exclude nearby potential targets which may affect the accurate termination of the movement at the desired target - then distractors that are closer to the target should cause more MT interference. In other words their account would predict that middle row distractors, which are closer to the target, should cause more MT interference than front row distractors. Similarly, a proximity effect in RT would be inconsistent with their account. Their account of RT interference would predict the same amount of interference from front and middle row distractors, because both types of distractors are equally likely to be encountered in a movement to the target.

Mean RT and MT interference scores for back row target trials are represented in Table 2. In RT, front row distractors interfered more than middle row distractors [$t(39) = 4.403$, 2-tailed, $p < .001$]. Front row distractors also caused more MT interference than middle row distractors [$t(39) = 4.458$, 2-tailed, $p < .001$]. Both of these findings are inconsistent with the account offered by Pratt and Abrams (1994) for explaining RT and MT interference. To be sure that our account was supported, we analyzed these findings together with time period (RT or MT) as a factor. A repeated measures ANOVA revealed that time period did not interact with proximity. In other words, the spatial nature of the interference (proximity to the starting position) was the same for both RT and MT. This result is consistent with our contention that interference in different time periods of movement is a function of when selection is resolved relative to movement initiation.

(TABLE 2 ABOUT HERE)

Spatial and Temporal Aspects of Selective Reaching Interference

There are two main findings about the spatial determinants of selective reaching interference that have come out of the present study and Tipper et al. (1992). First, the more proximate a distractor is to the starting position of the hand the more likely it will interfere (the proximity effect). Second, Tipper et al. showed that a distractor in the hemispace ipsilateral to the responding hand is more likely to interfere than a contralateral distractor (the ipsilateral effect). However, these studies only used certain trials to uncover these findings. For example, Tipper et al. only used middle row target trials to show the proximity effect, and trials with targets at a single location (location 5 on Figure 1) to show the ipsilateral effect. Similarly, thus far in the present study, we have only analyzed trials in which targets appeared at locations 3 and 6 or locations 2 and 5 (see Figure 2).

To show that these findings of spatial aspects of interference can be generalized, it is necessary to analyze reaches to all target locations. To this end, we analyzed TT interference for trials to all targets in a factorial ANOVA with relationship to the responding hand and hemispace as one factor (ipsilateral or contralateral) and proximity to the starting position as another factor (front/near, middle/medium, or back/far). Mean interference scores are shown in Table 3. As expected, there was a main effect of ipsilaterality; ipsilateral distractors (mean = 24.73 ms) interfered more than contralateral distractors (mean = 14.98 ms) [$F(1,39) = 25.458, p < .001$]. There was also an expected main effect of proximity [$F(2,78) = 32.269, p < .0001$]. Post-hoc comparisons (Tukey's HSD) revealed that front row distractors (mean = 27.88 ms) caused significantly more ($p < .01$) interference than middle row (mean = 17.23 ms) and back row (mean = 14.45) distractors, but that middle row was not significantly greater than back row interference. The interaction of ipsilaterality and proximity approached, but did not reach, significance [$F(2,78) = 2.635, p < .08$]; there was a suggestion in the data that distractors closest to the starting position *and* ipsilateral to the responding hand were particularly competitive (see Table 3), but the failure of the interaction to reach significance did not allow us to test this possibility. This analysis confirmed, in a more generalizable way, that proximity to the starting position and hemispatial relationship to the responding hand are spatial determinants of selective reaching interference.

(TABLE 3 ABOUT HERE)

Our account for temporal aspects of interference should undergo the same test for generalizability. We predict simply that if there is RT and MT interference, then the spatial nature of the interference in RT and MT should be the same as found in TT. In other words we should find the ipsilateral effect and the proximity effect in RT and MT, as we did in TT.

Mean RT and MT interference scores for reaches to all target locations are shown in Tables 4a and 4b, respectively.

In RT there was a main effect of ipsilaterality; ipsilateral distractors (mean = 8.06 ms) interfered more than contralateral distractors (mean = 3.95 ms) [$F(1,39) = 7.862$, $p < .01$]. There was also a main effect of proximity in RT [$F(2,78) = 5.140$, $p < .01$]. Tukey's HSD test revealed that front row distractors (mean = 8.60 ms) caused significantly more ($p < .05$) interference than middle row (mean = 4.78 ms) and back row (mean = 4.63) distractors, but that middle row was not significantly greater than back row interference.

The MT analysis was very similar. There was a main effect of ipsilaterality; ipsilateral distractors (mean = 16.68 ms) interfered more than contralateral distractors (mean = 11.03 ms) [$F(1,39) = 10.968$, $p < .01$]. There was also a main effect of proximity in MT [$F(2,78) = 22.851$, $p < .0001$]. Tukey's HSD test revealed that front row distractors (mean = 19.28 ms) caused significantly more ($p < .01$) interference than middle row (mean = 12.46 ms) and back row (mean = 9.82) distractors, but that middle row was not significantly greater than back row interference.

To be sure that our account was supported, we analyzed RT and MT interference together with time period (RT or MT) as a factor. A repeated measures ANOVA revealed that time period did not interact with proximity or ipsilaterality. In other words, the spatial nature of the interference was the same for both RT and MT. This result is consistent with our contention that interference in different time periods of movement is a function of when selection is resolved relative to movement initiation.

(TABLE 4 ABOUT HERE)

Individual Differences in the Tendency to Initiate Movements Prior to Selection

Our account for temporal aspects of interference also holds that interference in different time periods may be a function of between-subject differences in when movements are initiated relative to selection. Variance in initiation behaviour would not be surprising because there were no catch trials in the task to force subjects to know the target location prior to movement initiation, and the instructions were to minimize TT rather than MT. When observing subjects, the experimenter noticed that some subjects initiated movements rapidly following the onset of stimuli; these movements often lacked stimuli-based direction and required considerable correction for trial completion. Other subjects seemed to be more cautious about initiating movements before they knew the location of the target, and their movements were often directed at the target. The former subjects are more likely to show MT interference, and the latter RT interference. In either case, the spatial nature of the interference effects should be the same because the same selection problem must be resolved.

If some subjects adopted a strategy whereby they were releasing from the start key soon after detecting stimuli (early), then presumably they would have shorter RTs and longer MTs. Conversely subjects who remained at the starting location until the appropriate movement had been selected (late) would have longer RTs and shorter MTs. Thus, the ratio of RT to TT should indicate which strategy was adopted by any particular subject. In other words, late initiators should have a higher ratio of RT/TT than early initiators. Mean RTs and TTs were calculated across all trials, and RT/TT was calculated for each subject. The subjects with the ten highest ratios in each hand group were considered 'late', the subjects with the ten lowest ratios were considered 'early', and strategy was factored into RT and MT analyses as a between-subjects variable.

Because strategy was not experimentally manipulated, it is unlikely that there were equal numbers of subjects using each strategy. For example, if more than half of the subjects adopted an early strategy, then some of them would be inaccurately categorized as 'late' by our method of categorization. Nevertheless, if this were the case, then those subjects in the 'early' category would be accurately categorized. Thus we expected the RT and MT analyses to conform to one of three possibilities:

1. Both 'early' and 'late' categories were accurate because half of the subjects adopted an early strategy and half adopted a late strategy. If this were the case, then 'early' subjects should show little interference in RT and most of their interference in MT. Conversely, 'late' subjects should show little interference in MT and most of their interference in RT. This should appear in the RT and MT ANOVAs as interactions of strategy with the spatial factors. In RT for example, strategy should interact with proximity because 'late' subjects should show a proximity effect but 'early' subjects should show little interference (no proximity effect).

2. Only the 'early' category was accurate because more than half of the subjects adopted an early strategy. As with the first possibility, 'early' subjects should show little interference in RT and most of their interference in MT, and the RT ANOVA should show interactions of strategy with the spatial factors. However, because the 'late' category contains subjects who adopted an early strategy, 'late' subjects should show MT in addition to RT interference.

Thus, in the MT ANOVA, strategy would not interact with the spatial factors because the spatial nature of the interference would be the same for 'early' and 'late' subjects.

3. The third possibility is the converse of the second. In other words, only the 'late' category was accurate because more than half of the subjects adopted a late strategy. In this case, strategy should interact in the MT rather than the RT ANOVA.

Tables 5a and 5b show the component means of the strategy x spatial factor interactions for RT and MT, respectively. In the RT analysis, strategy interacted with ipsilaterality [$F(1,38) = 13.326$, $p < .002$] and proximity [$F(2,76) = 6.698$, $p < .003$]. Further analysis revealed a reliable RT ipsilateral effect for 'late' ($p < .001$), but not 'early' initiators. There was also a reliable effect of proximity in RT for 'late' initiators ($p < .002$); Tukey's HSD test showed that front row distractors interfered more than back row ($p < .01$), but not middle row distractors. Although there was an effect of proximity in RT for 'early' initiators ($p < .05$), Tukey's HSD test showed no differences among front, middle, and back distractors. In the MT analysis, strategy did not interact with ipsilaterality or proximity. The RT and MT analyses conformed to the second possibility stated above - the 'early' category accurately represented an early strategy. In other words, at least half of the subjects were initiating movements before selection was resolved, and were forced to resolve selection solely during MT.

(TABLE 5 ABOUT HERE)

The performance of 'early' initiators in RT and MT is a perfect example of how between-subject differences can account for selective reaching interference in different time periods. If all subjects adopted an early strategy, then presumably there would be little RT interference, and the converse would be true if all subjects adopted a late strategy. In the present study, because some of the subjects used an early and some a late strategy, there was both RT and MT interference. Impressively, regardless of the time period in which interference was measured or the initiation strategy used by subjects, the spatial nature of the interference was always the same.

Errors

An error was recorded when the key at the distractor location was pressed. Errors can be considered failures of selection because the incorrect movement of two competing movements was selected and executed. Distractors that cause the most selection difficulty (i.e., interference), because of temporal processing advantages in the race for selection, are more likely to cause such a selection failure. Thus we expected that more errors were made to those distractors that caused more interference - front row and ipsilateral distractors.

For the 40 subjects the number of errors for all 720 trials ranged from 0 (17 subjects) to 9 (1 subject). The average number of errors per subject for the 720 trials was 1.325 (or .184 %). All of the subjects combined made 53 errors. The number of errors for each hand at each distractor location are shown in Table 6a. Note that for the right hand more errors were made to location 4 than any other location, and for the left hand more errors were made to location 1 than any other location; for each hand these locations were near and ipsilateral to the responding hand. This finding is in agreement with the interference data. Both the proximity effect and the ipsilateral effect were examined individually using a chi-square analysis to determine whether error frequency differed across distractor conditions.

The proximity effect was examined by looking at error frequency for front, middle and back row distractors. Frequencies are shown in Table 6b. Error frequency differed across distractor rows, *chi-square* = 25.622, $p < .01$. Front distractors were the most frequent sites of errors, and middle and back row distractors caused approximately the same number of errors.

The ipsilateral effect was examined by looking at error frequency for ipsilateral and contralateral distractors, shown in Table 6c. Despite the fact that there were more errors to ipsilateral distractors, the analysis revealed no significant difference between ipsilateral and contralateral distractors, *chi-square* = 2.283, $.20 > p > .10$.

Although rare, uncorrected actions to distractors do occur; those locations that caused more interference were more likely to receive erroneous actions.

(TABLE 6 ABOUT HERE)

Discussion

In selective reaching tasks, distractors between the starting position of the hand and the target caused more interference than distractors beyond the target. Tipper et al. (1992) and Pratt and Abrams (1994) suggested that the former distractors interfered more because they were in the path of the reaching response to the target. The present study showed that these distractors interfered more because they were closer to the starting position of the hand, rather than because of their relationship to the response path. This 'proximity effect' was one of two findings about the spatial nature of selective reaching interference shown in the present study. The other finding, first shown by Tipper et al., was that distractors in the hemispace ipsilateral to the responding hand were more likely to cause interference than contralateral distractors (the 'ipsilateral effect').

Our account suggests that the amount of interference caused by a distractor is determined by the speed with which visuomotor processing of the distractor progresses. This account can explain both the proximity and ipsilateral effects because there is evidence of visuomotor processing advantages for near and ipsilateral locations. Previous findings have shown advantages for movements to near relative to far locations (e.g, Fitts & Peterson, 1964; Glencross, 1973; Rosenbaum, 1980), and ipsilateral relative to contralateral locations (Bashore, 1981; Fisk & Goodale, 1985; Poffenberger, 1912; Prablanc, Echallier, Jeannerod, & Komilis, 1979; Prablanc, Echallier, Komilis, & Jeannerod, 1979). There were also advantages for movements to near and ipsilateral locations in the present study. Figure 3 shows TT of movements to the six locations for control trials on which no distractor was present. There were clear temporal advantages for movements to locations near the starting position of the hand and locations in the hemispace ipsilateral to the responding hand.

(FIGURE 3 ABOUT HERE)

The proximity and ipsilateral effects were found in both the RT and MT periods of movements. This was consistent with our suggestion that the spatial selection problem caused by distractors can be resolved in RT and/or MT, depending on the time at which the movement is initiated relative to when the target is identified. Further evidence was provided for this account by showing that there were individual differences in movement initiation strategy that determined the temporal locus of interference for different subjects.

Finally, error performance was consistent with the proximity and ipsilateral interference effects. In other words, distractors that were more likely to cause delays in reaches to the target were also more likely to be sites for errors.

Selective Attention Theory

We suggest that distractor interference in selective reaching is caused by competition from response processes associated with a movement to the distractor location. Similar suggestions have been used to explain the influence of irrelevant information in a variety of tasks. For example, interference effects in the Stroop (1935) task (e.g., Morton & Chambers, 1973; Posner & Snyder, 1975) and the flanker task (e.g., Eriksen & Eriksen, 1974; Eriksen & Schultz, 1979) have been explained by response competition. Furthermore, psychophysiological evidence for response-based processing of irrelevant information has been found in both the Stroop (Duncan-Johnson & Koppell, 1981) and flanker tasks (Coles, Gratton, Bashore, Eriksen, & Donchin, 1985). The Simon effect has similarly been attributed to the automatic elicitation of competing response processes from irrelevant stimulus information (Simon, 1969). Walker, Kentridge and Findlay (1995) reported influences of irrelevant stimuli on eye movements to visual targets, and attributed these influences to competition from potential targets. These findings support our suggestion that response competition is a plausible explanation for interference in selective reaching.

Although our hypothesis can explain findings of selective reaching interference, the present study does not unequivocally rule out alternative hypotheses. For example, the proximity effect could be due to the fact that near distractors were closer to the viewer/eyes, rather than closer to the hand. However, this is an unlikely possibility because Tipper et al. (1992) showed that when the starting position was moved to the far side of the reaching display, and fixation was held constant, distractors farther from the viewer interfered more than distractors closer to the viewer. Furthermore, in the present study, ipsilateral distractors interfered more than contralateral distractors despite the fact that they were both equidistant from the viewer.[1] We hope to rule out any other possible alternatives to our hypothesis with future research.

Applied Issues

This study has shown that the ability to reach for an object is affected in a predictable manner by the presence of distracting objects in the reaching space. This type of knowledge could prove invaluable to our understanding of why certain manual errors occur in the real world, and how they can be avoided.

Experimental psychologists have attempted to observe and categorize error performance (Norman, 1981; Reason, 1990). Norman (1981), for example, proposed a theory of action that categorizes action slips. Action slips are a form of human error defined as the performance of an action that was not what was intended. According to Norman's (1981) theory, the type of reaching errors observed in the present study would likely be classified as slips resulting from a faulty, data-driven activation of schemas. In other words a schema for a competing action is unintentionally activated by some external stimulus. Our approach allows a greater understanding of which external stimuli are more likely to activate responses that compete with the intended response for the control of action.

Engineering psychology, human factors, and ergonomics researchers have sought to optimize the efficiency and safety of human-machine interfaces. Manual performance, particularly erroneous performance, is of obvious concern when designing such interfaces. One methodological approach is to observe performance in the interface environment under actual performance conditions. For example, Fitts and Jones (1961) analyzed 460 errors made by aircraft pilots, many of which were simple manual errors. Half of the errors were classified as substitution errors (e.g., confusing one control with another). They suggested that many of these errors were due to a lack of uniformity in the placement of controls in different aircraft. If the same control mechanism is in different locations in different aircraft, there is an increased likelihood that multiple locations are competing for the control of action and that an error will occur - especially if the pilot is under time pressure. The present results suggest that erroneous actions to competing controls could also be influenced by the spatial arrangement of the control display.

Another example of the observation of manual performance under real-world conditions was reported by Glendon (1993), who examined 52 human error incidents from the electricity supply industry. Many of these errors were examples of reaching for the wrong control on a panel containing multiple controls. Glendon (1993) suggested the use of 'near miss' reporting in addition to error reporting as an important tool in ergonomics research. In other words, because errors are rare but potentially costly, any way in which errors could be predicted, such as by examining 'near misses', could be valuable. Because there was a correspondence between errors and interference in the present study, measuring interference from a distracting object could be analogous to measuring a 'near miss'. Thus, interference from objects at certain locations could be used as a measure of the potential for an error to be made to objects at those locations.

Applied researchers have used experimentation in addition to observation to examine erroneous performance. Bradley (1969), for example, reported results that are similar to the results reported in the present study. Bradley had subjects reach, with their right hands, to a single target knob on a two-dimensional display in the vertical and horizontal planes. Surrounding the target knob was a configuration of other knobs; the number of knobs varied, with a maximum of four placed above, below, to the left, and to the right of the target. Each trial began with the subject's right hand at a starting location at the bottom of the display, located centrally in the horizontal plane and 5.5 inches toward the subject in the depth plane. The task was to reach for and turn the target knob to a certain setting as quickly as possible. Subjects were also instructed to avoid touching any of the surrounding knobs because the slightest touch would invalidate the setting of the touched knob; inadvertent touches of surrounding knobs were recorded as errors.

The effects of the positioning of the surrounding knobs nicely parallel the present findings. Because the right hand was used, the ipsilateral effect would predict more errors to the right knob than to the left. Indeed, when all four knobs were present, 177 errors were made to the right knob and 17 were made to the left, and when there were only the right and left knobs, there were 142 right errors compared to 38 left errors. Similarly, because the lower knob is closer to the starting position of the hand than the upper knob, the proximity effect would predict more errors to the lower knob. As expected, when all four knobs were present, 79 errors were made to the lower knob and 58 were made to the upper knob, and when there were only the upper and lower knobs, there were 90 lower errors compared to 35 upper errors.

There are several differences between the present study and Bradley's that make the similarity of the results impressive, and allow for greater generalizability of the conclusions that can be drawn about the spatial positioning of manually-operated objects. For instance, the nature of the action required was different in each study; his subjects were required to grasp and turn a knob, whereas our subjects were required to finger-press a button. Also, the target was always in the same position in Bradley's study whereas target location varied and targets and distractors shared locations in our study. In other words, his task was a simple RT task with surrounding objects whereas our task was a more difficult selective attention/choice task. Despite these methodological differences, the influence of the spatial location of competing objects was remarkably similar in the two studies. This gives greater weight to the possibility that these spatial relationships will have influence in a variety of human-machine interfaces that contain multiple, manually-operated controls.

Footnote

1. The proximity effect causes trouble for the "spotlight" metaphor for visual attention. Spotlight models predict that distractors closer to the target are more likely to interfere than distractors further from the target. The opposite was shown by the back row target analyses in the present study - distractors closer to the target (middle row) interfered *less* than distractors further from the target (front row). This counterintuitive finding is an example of how traditional conclusions about selective attention mechanisms cannot be trusted to generalize to all task conditions. For further examples of results that are problematic for the spotlight metaphor see Allport (1989, p.658).

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Table 1: Target-distractor locations and TT interference (in ms) on trials varying in the proximity of the distractor to the starting position (near or far), or the degree to which distractors were in the path of a reaching response to a target (response-path or non-response-path).

	Response-path	**Non-Response-path**	
Near	Trials 3-1 & 6-4 28.30	Trials 3-4 & 6-1 30.80	29.55
Far	Trials 3-2 & 6-5 8.23	Trials 3-5 & 6-2 13.68	10.95
	18.26	22.24	

Table 2: RT and MT interference (in ms) on reaches to back row targets (locations 3 and 6) in the presence of front row (locations 1 and 4) or middle row (locations 2 and 5) distractors.

	RT	**MT**
Front row	7.53	22.03
Middle row	-0.33	11.28

Table 3: TT interference (in ms) on trials varying in the proximity of the distractor to the starting position (near = front row; medium = middle row; far = back row), or the relationship between the responding hand and the hemispatial location of the distractor (ipsilateral or contralateral).

	Near	**Medium**	**Far**	
Ipsilateral	34.61	22.36	17.32	24.73
Contralateral	21.16	12.11	11.68	14.98
	27.88	17.23	14.45	

Table 4:

A: RT and MT interference (in ms) on trials varying in the proximity of the distractor to the starting position (near = front row; medium = middle row; far = back row).

	Near	Medium	Far
RT	8.60	4.78	4.63
MT	19.28	12.46	9.82

B: RT and MT interference (in ms) on trials varying in the relationship between the responding hand and the hemispatial location of the distractor (ipsilateral or contralateral).

	Ipsilateral	Contralateral
RT	8.06	3.95
MT	16.68	11.03

Table 5:

A: RT interference (in ms) for early or late initiators on trials varying in the proximity of the distractor to the starting position (near = front row; medium = middle row; far = back row), or the relationship between the responding hand and the hemispatial location of the distractor (ipsilateral or contralateral).

	Ipsi.	**Contra.**		**Near**	**Medium**	**Far**
Early	-0.54	0.02		0.92	-2.84	1.14
Late	16.65	7.89		16.29	12.39	8.13

B: MT interference (in ms) for early or late initiators on trials varying in the proximity of the distractor to the starting position (near = front row; medium = middle row; far = back row), or the relationship between the responding hand and the hemispatial location of the distractor (ipsilateral or contralateral).

	Ipsi.	**Contra.**		**Near**	**Medium**	**Far**
Early	21.49	16.30		24.55	18.88	13.26
Late	11.86	5.75		14.01	6.03	6.39

Table 6:

A: Number of errors to distractors at locations 1 to 6 for subjects using their right or left hand.

	1	2	3	4	5	6
Right hand	4	5	5	12	2	1
Left hand	14	1	2	5	0	2

B: Number of errors to distractors varying in proximity to the starting position (near = front row; medium = middle row; far = back row).

Near	Medium	Far
35	8	10

C: Number of errors to distractors varying in their hemispatial relationship to the responding hand (ipsilateral or contralateral).

Ipsilateral	Contralateral
32	21

Figure Legends

Figure 1: Reaching display used in Tipper, Lortie, and Baylis (1992).

Figure 2: Reaching display used in the present experiment.

Figure 3: Mean TT (in ms) of reaches with the left and right hand for control trials on which there was no distractor present.

Figure 1

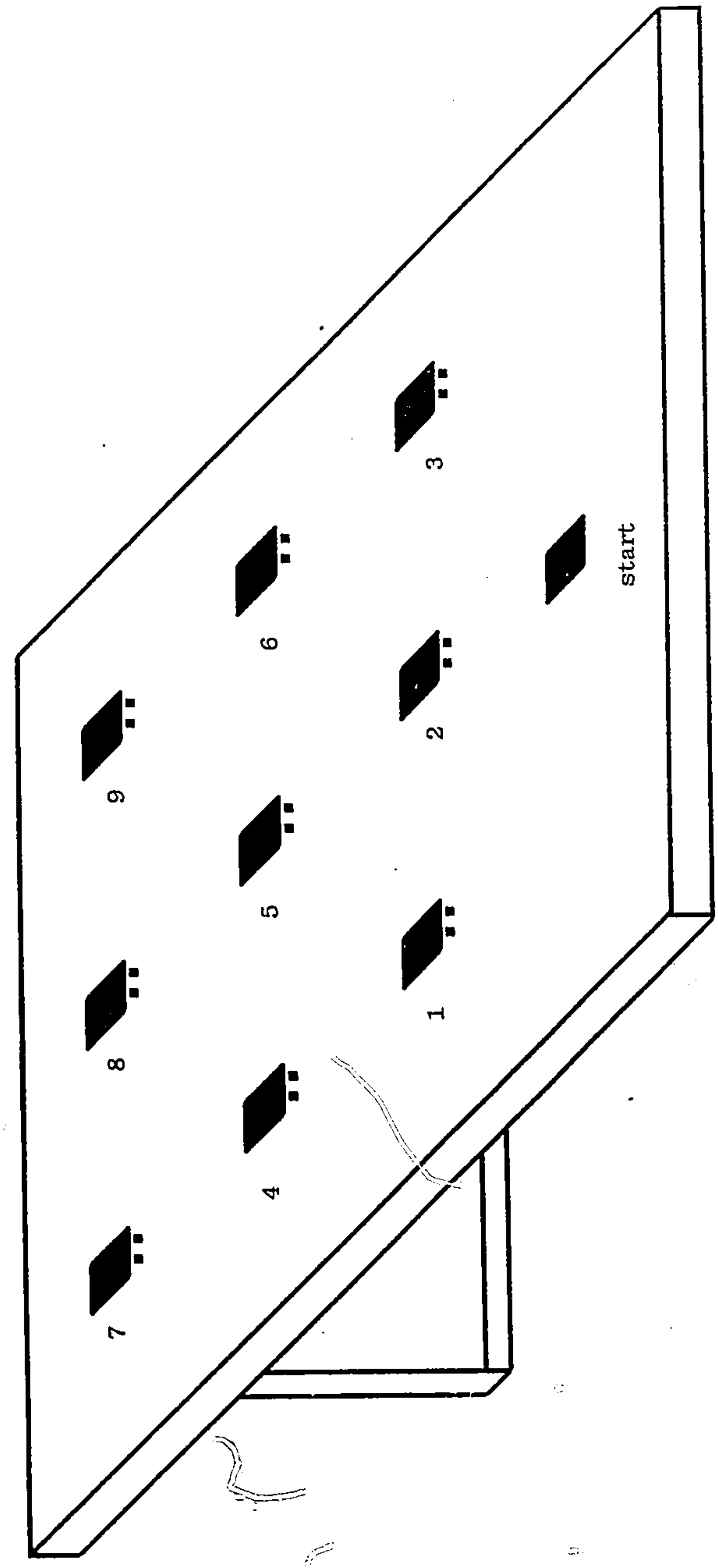


Figure 2

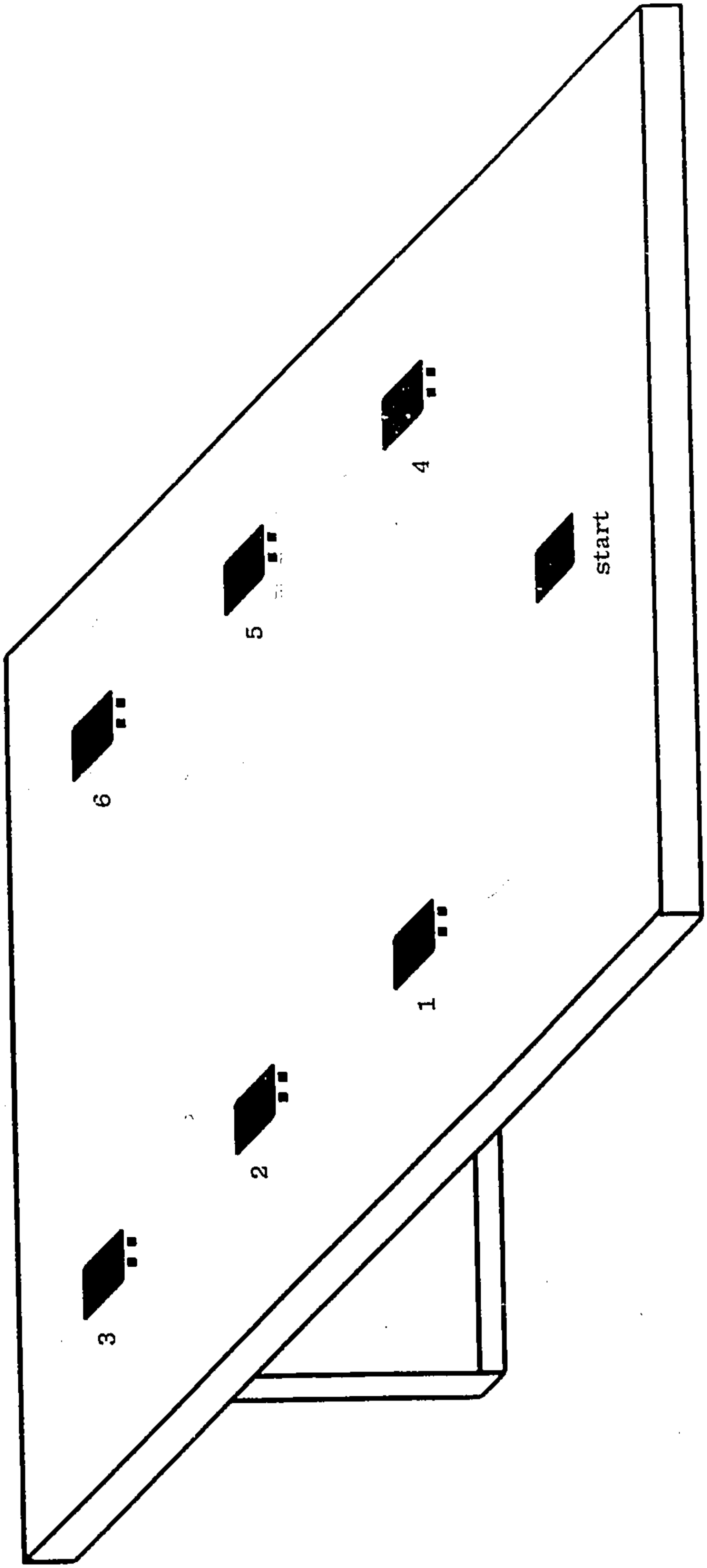
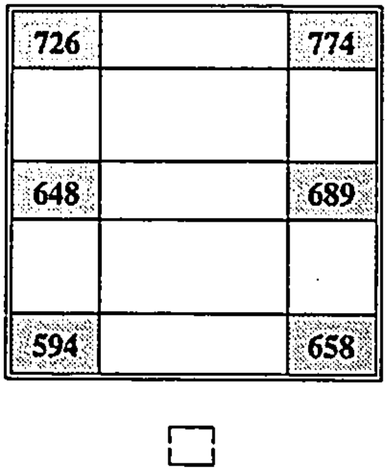
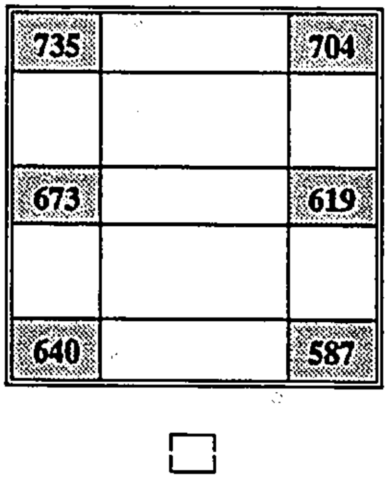


Figure 3



Left Hand



Right Hand

CHAPTER III

The results of Experiment 1 were clearly consistent with the response competition hypothesis. However, the location interference effects may have been due to visual-spatial biases to certain locations resulting from some aspect of the selective reaching procedure. Experiments 2 and 3 were designed so that the response competition hypothesis made different predictions than several alternative hypotheses which implicated such visual-spatial biases. Specifically, Experiments 2 and 3 utilized manipulations that influenced the efficiency with which reaches could be made to spatial locations. The findings supported our hypothesis that visuomotor efficiency, rather than visual-spatial biases, determined interference in selective reaching.

Based on the results of Experiment 1 and Tipper et al., (1992), there were several changes designed to simplify the subsequent experiments. First, the number of stimulus locations on the display was reduced from six (see Figure 2 in Chapter II) to four (see Figure 4). Reducing the number of locations from nine in Tipper et al. to six in Experiment 1 did not influence the spatial interference effects. Second, because the ipsilateral effect was found consistently with both hands in Tipper et al. and Experiment 1, only the right hand was used by subjects in the remaining experiments. The third change was that only TT was measured in the remaining experiments. This change was justified by the results of Experiment 1, in which TT was divided into RT and MT components. It is clear that neither RT nor MT can be considered "process-pure" measures in the selective reaching task (similar conclusions have been drawn about RT and MT in reference to other motor tasks - see Abrams, Meyer, & Kornblum, 1990; Kerr, 1978; Rosenbaum, 1980; Zimmer & Fuchs, 1995). Because the spatial effects that were of interest in the thesis occurred in both RT and MT, these measures were examined in combination.

EXPERIMENTS 2A and 2B

Tipper et al. (1992) found substantial changes in spatial interference when the starting position was moved from the front to the back of the display. Specifically they showed that back row distractors interfered more than front row distractors on reaches from the back starting position to middle row targets. The response competition hypothesis would suggest that such interference changes occurred because shifting the starting position produced corresponding changes in the speed of reaching to the front and back locations. Because they did not report response times for reaches to front row and back row targets from the front and back starting positions, our hypothesis could not be evaluated. In order to test our hypothesis, Experiment 2 also manipulated the starting position of the hand.

Manipulation of the starting position also allowed a comparison between our hypothesis and other hypotheses which have been used to explain selective reaching findings. For example the "action attentional field" hypothesis, a popular alternative to our account, states that a certain region of space (or field), which is defined by action parameters, receives enhanced attentional processing relative to other regions of space. Distractors located in that field receive enhanced processing relative to distractors outside of the field, and thus cause more interference. An example of the attentional field hypothesis has been used to explain the "response path effect" of Tipper et al. (1992). Rizzolatti, Riggio, and Sheliga (1994) suggested that "arm location produces an attentional field extending from the hand to the target location" (p. 256). In other words, distractors between the hand and the target interfered more than distractors beyond the target because there was an attentional field from the hand to the target. Evidence against such an explanation was reported in Experiment 1 (see below).

Another example of the attentional field hypothesis, which I will refer to as the "ipsilateral attentional field" hypothesis, has been used to explain the ipsilateral effect. Rizzolatti et al. (1994), in reference to the findings of Tipper et al. (1992), suggested that an "arm-related attentional field changed location according to which hand was used" (p. 256). In other words, ipsilateral distractors interfered more than contralateral distractors because the use of a given hand produced an attentional field in the ipsilateral hemispace. Recall that our hypothesis explained the ipsilateral effect by reference to visuomotor processing advantages for ipsilateral relative to contralateral locations.

Evidence against attentional field hypotheses comes from the fact that there are differences in interference among distractors within attentional fields. For example, Experiment 1 showed differences in interference between front and middle row distractors on reaches to back row targets - both types of distractor were within the "hand-to-target attentional field". Furthermore, Tipper et al. (1992) reported differences between the front-right and front-left distractors, both of which were within the "hand-to-target attentional field". Such an argument can also be made against an "ipsilateral attentional field". For example, there are differences in interference between front and back distractors within the ipsilateral hemispace.

How do attentional field hypotheses explain such lack of uniformity within attentional fields? One might suggest that the ipsilateral attentional field overlaps with a proximity-based attentional field, creating an even greater attentional bias to stimuli that are both ipsilateral and proximate to the hand. However, an explanation that requires adding "attentional fields" for every spatial asymmetry that arises is not very parsimonious. Our hypothesis, on the other hand, handles all such spatial asymmetries with a single explanation.

In addition to this evidence, the manipulation of hand starting position allowed a further discrimination between our hypothesis and the ipsilateral attentional field hypothesis. The ipsilateral attentional field hypothesis held that there was an attentional advantage to the ipsilateral field regardless of hand position. In other words, the ipsilateral effect should have been immune to a change in the starting position from the front to the back of the display. Our hypothesis, on the other hand, held that the ipsilateral effect should only have been found when there was a movement advantage to ipsilateral locations. In other words, if the change in starting position altered the speed with which reaches could be made to ipsilateral relative to contralateral locations, than there should have been corresponding changes in ipsilateral relative to contralateral interference.

There was some preliminary evidence to suggest that the change in starting position could produce such a change in ipsilateral-contralateral reaching performance. For example, Schmidtke and Stier (1960, cited in Sanders & McCormick, 1993) examined reaches to locations along the circumference of a circle (in the horizontal and depth planes) from a starting position at the centre of the circle. Reaches away from the body, similar to reaches from the front starting position in the selective reaching task, showed an ipsilateral advantage. Conversely, reaches towards the body, similar to reaches from the back starting position in the selective reaching task, showed a contralateral advantage.

Tipper et al. (1992) reported results that were consistent with a lack of an ipsilateral effect when reaches were made from the back starting position. They reported interference from distractors at locations 7 and 9 on reaches with the right hand to location 5 from the back starting position located behind location 8 (see Figure 1). There was significant interference from location 7, which was in the contralateral (left) hemispace, but not from location 9, which was in the ipsilateral (right) hemispace. Tipper et al. suggested that this finding (i.e., no ipsilateral effect) was due to the fact stimuli on the right side were sometimes blocked from view by the arm of the subject for the back starting position. To ensure that a lack of an ipsilateral effect in Experiment 2B could not be attributed to reduced visibility of ipsilateral locations, we eliminated the back row locations used by Tipper et al. (1992). This change allowed subjects to see all four locations without the arm blocking their view.

There is another alternative hypothesis for explaining the ipsilateral effect which, like the ipsilateral attentional field hypothesis, would have difficulty explaining the absence of an ipsilateral effect for the back starting position. Although the hand is at the midline, the arm is in the ipsilateral hemispace. It is thus possible that the proprioceptive or visual presence of the arm in the ipsilateral hemispace biased performance ipsilaterally. In Experiment 2B, when the right hand was at the back starting position (at midline), the right arm was located in the right hemispace just as when the hand was at the front starting position. In other words, any such ipsilateral bias should be the same for the back starting position.

In summary, the "ipsilateral attentional field" and "arm presence bias" hypotheses predicted that an ipsilateral effect would also be seen for reaches from the back starting position. Our hypothesis predicted that the ipsilateral effect would only be seen if there was an ipsilateral advantage for reaches from the back starting position. Concerning front-back interference, based on the results of Tipper et al. (1992) we expected back distractors to interfere more than front distractors. Our hypothesis could account for such a result if reaches to back targets were completed faster than reaches to front targets. The main prediction of our hypothesis was that any changes in interference due to hand position would correspond to changes in visuomotor efficiency.

Method

Subjects

40 undergraduate students (12 males and 28 females) from McMaster University participated in the experiment for course credit. All subjects were right handed, had normal colour vision, and had normal or corrected-to-normal acuity. All subjects used their right hand for the experiment. Experiments 2A and 2B were run coincidentally, and subjects were randomly assigned to use the front (2A) or back (2B) starting positions.

Reaching Apparatus

The stimulus board in Experiment 2A is displayed in Figure 4. It was identical to the apparatus used in Experiment 1, except that the two "back row" locations were not used. In this and in subsequent experiments, the two locations nearest the torso of the subject are referred to as the front row locations, and the farthest two locations as the back row locations. There were four locations: front-right, front-left, back-right, and back-left.

The stimulus board used in Experiment 2B is displayed in Figure 5. It was identical to the apparatus used in Experiment 2A, except that the starting position was at the back of the display. As in all of the experiments, the descriptions front, back, left, and right indicated stimulus locations relative to the torso of the subject, rather than relative to the hand.

(FIGURES 4 AND 5 ABOUT HERE)

Design

There were 16 trial types: one no-distractor (target-only) control trial type and three distractor trial types for each of the four target locations. Twenty trials of each type appeared randomly for each subject for a total of 320 trials.

Response time for each correct trial was measured from the time the stimulus light(s) appeared until the target button was pressed. An error was recorded if the distractor button was pressed. Interference scores for each subject in each distractor condition were calculated in the following manner. First the median response time was determined for each trial type. The difference between response times for each distractor trial type and its respective control was then calculated. Multiple distractor trial types were combined into one distractor condition by calculating a mean of the multiple difference scores.

Procedure

The procedure for Experiment 2A was identical to that used in Experiment 1 except that there were 320 experimental trials which were completed in a single session without rest. In Experiment 2B, subjects were additionally instructed to hold the right arm toward the centre of the display, so that the right forearm or elbow did not block the view of the front-right stimulus location.

Results and Discussion

Experiment 2A

Experiment 2A was run coincidentally with Experiment 2B and the two experiments were compared to assess the influence of hand starting position. First, however, we wanted to ensure that the results of Experiment 2A were consistent with those of Experiment 1 despite the changes mentioned above. In other words, we expected to find both ipsilateral and proximity effects in the distractor interference and target response time data of Experiment 2A.

We expected more interference from front than back distractors (proximity), and more interference from right than left distractors (ipsilateral). Mean interference scores were submitted to a 2 x 2 ANOVA with distractor hemispace (right or left) and distractor row (front or back) as factors (see Figure 6A). There was a main effect of row; front row distractors (mean = 23.73 ms) interfered more than back row distractors (mean = 12.65 ms) [$F(1,19) = 7.914$, $p < .02$]. There was also a main effect of hemispace; right distractors (mean = 23.63 ms) interfered more than left distractors (mean = 12.75 ms) [$F(1,19) = 20.940$, $p < .001$]. The interaction of hemispace (ipsilaterality) and row (proximity) was not significant [$F(1,19) = 3.136$, $p < .10$]. These results replicated the interference results from Experiment 1.

We also expected that the response time data for the control (target-only) trials would conform to the response competition hypothesis. In other words, as in Experiment 1, we expected that response time would be less for reaches to front row and right hemispace targets, relative to back row and left hemispace targets, respectively. Mean response times for control trials were submitted to a 2 x 2 ANOVA with target hemispace (right or left) and target row (front or back) as factors (see Figure 6B). There was a main effect of row; response time to front row targets (mean = 632.38 ms) was less than to back row targets (mean = 690.03 ms) [$F(1,19) = 191.52$, $p < .0001$]. There was also a main effect of hemispace; response time to right targets (mean = 644.68 ms) was less than to left targets (mean = 677.73 ms) [$F(1,19) = 42.701$, $p < .0001$]. There was no row x hemispace interaction ($F < 1$). These results were consistent with the hypothesis that distractor interference from a distractor at a given location was determined by the speed with which a response could be generated to a stimulus at that location.

(FIGURE 6 ABOUT HERE)

Errors

As in Experiment 1, we expected that more errors would be made to locations associated with greater distractor interference. All 20 subjects combined made only 10 errors (.156% of trials). Such a small number of errors is difficult to analyze statistically. However, the greatest number of errors (4) were made to the front-right location, the fewest errors (1) were made to the back-left location, and intermediate numbers of errors were made to the front-left (2) and back-right (3) locations.

Summary

Despite the changes introduced in Experiment 2A, the results were very consistent with those of Experiment 1. The remaining experiments were variants of the task used in Experiment 2A.

Experiments 2A and 2B

Target Response Time as a Function of Hand Starting Position

To see how manipulating hand position influenced visuomotor processing efficiency of reaches to the four locations, mean response times for control trials were submitted to a 2 x 4 mixed ANOVA with hand position (front, back) and target location (front-left, back-left, front-right, back-right) as factors (see Figures 6B and 7B). There was a significant position x location interaction [$F(3,114) = 169.512$, $p < .0001$]. Simple effects analyses (Keppel, 1982) revealed that this interaction was due to the fact that reaching to the front-right location was slower from the back position ($p < .0001$) than from the front, and reaching to the back-left location was faster from the back position ($p < .01$) than from the front; reaches to the other two locations were not affected by hand position.

Distractor Interference as a Function of Hand Starting Position

According to our hypothesis, there should have been a similar hand position x location interaction for distractor interference. Mean interference scores were submitted to a 2 x 4 mixed ANOVA with hand position (front, back) and distractor location (front-left, back-left, front-right, back-right) as factors (see Figures 6A and 7A). There was a significant position x location interaction [$F(3,114) = 9.034$, $p < .001$]. As expected from the target response time results, simple effects analyses revealed that this interaction was due to the fact that interference from the front-right distractor was less for the back position ($p < .002$) than for the front, and interference from the back-left distractor was (marginally) greater for the back position ($p = .0509$) than for the front; interference from the other two distractor locations was not affected by hand position.

(FIGURE 7 ABOUT HERE)

Other Predictions

The preceding analyses were very consistent with the response competition hypothesis. For the back starting position, we also wanted to test front-back interference to see if our results were consistent with those of Tipper et al. (1992), and right-left interference to test the predictions of the "ipsilateral attentional field" and "arm presence bias" hypotheses. These alternatives predicted that an ipsilateral effect (i.e., right > left interference) would also be seen for reaches from the back starting position. Mean interference scores from the four distractor locations were submitted to a 2 x 2 ANOVA with distractor hemispace (right or left) and distractor row (front or back) as factors (see Figure 7A). The interaction of hemispace and row was not significant [$F(1,19) = 1.378$, $p > .25$]. There was a main effect of row; back row distractors (mean = 19.72 ms) interfered more than front row distractors (mean = 10.26 ms) [$F(1,19) = 7.701$, $p < .02$]. This was a replication of the findings of Tipper et al. (1992). There was not a main effect of hemispace; right distractors (mean =

14.96 ms) did not interfere more than left distractors (mean = 15.02 ms) [$F(1,19) < 1$]. This absence of an ipsilateral effect for the back starting position was not consistent with suggestions that the ipsilateral effect for the front starting position was due to the presence of the arm, or the existence of an attentional field, in the ipsilateral hemispace.

Errors

As in Experiment 2A, errors in Experiment 2B were minimal and thus difficult to analyze. All 20 subjects combined made only 7 errors (.109% of trials). Two errors were made to the front-left, back-left and back-right locations, and one error was made to the front-right location.

Summary

Hand position based changes in interference from distractors at certain locations corresponded to changes in the visuomotor processing efficiency of reaches to targets at those locations. As found in Tipper et al. (1992), back distractors produced greater interference than front distractors on reaches from the back starting position. There was no difference in interference from right and left distractors on reaches from the back starting position. This absence of an ipsilateral interference effect for the back starting position was not consistent with suggestions that the ipsilateral effect for the front starting position was due to the presence of the arm, or the existence of an attentional field, in the ipsilateral hemispace.

EXPERIMENTS 3A and 3B

Despite the consistency of the results of Experiments 1 and 2 with the response competition hypothesis, it remained possible that the spatial interference effects were due to visual-spatial biases. Experiment 3 was designed to specifically test our hypothesis, by ensuring that our hypothesis made a prediction that was unique from the predictions of alternative accounts implicating visual-spatial biases. We will first review seven alternative accounts for various selective reaching interference effects.

Tipper et al. (1992) found the proximity interference effect (for reaches from the front and back starting positions) when fixation was directed toward the centre of the display as stimuli were presented. This finding deflected the argument that the proximity effect could have been due to a fixation bias to the location of the hand. However, covert visual orienting mechanisms (i.e., attention) can be moved independently from overt visual orienting mechanisms such as eye and head movements (Posner, 1980). For this reason, in the Tipper et al. experiment, it was possible that covert attention was directed to the location of the hand despite the maintenance of fixation at the centre of the display. In other words, the finding that distractors closest to the hand caused the most interference could be explained by the fact that they were closer to the focus of covert attention.

An explanation for the ipsilateral effect which could not be ruled out by the findings of Experiment 2 was the possibility of eye movement biases. This hypothesis comes from studies which have measured eye movement latencies during reaching movements to visual targets. Eye movements, like reaches, were initiated faster to visual targets in the hemispace ipsilateral to the reaching hand (Fisk & Goodale, 1985; Prablanc, Echallier, Komilis, &

Jeannerod, 1979; but see Prablanc, Echallier, Jeannerod, & Komilis, 1979). Thus it is possible that the ipsilateral interference effect was due to the fact that eye movements were biased to ipsilateral locations when two stimuli were present during reaching. This explanation could not be ruled out by the hand starting position manipulation in Experiment 2, because there was no available data to suggest that such an ipsilateral bias also occurred during reaches towards the body.

A similar argument could be made for the possibility of an ipsilateral bias of covert attentional orienting. Although the eyes and attention can be moved independently, the two systems are likely related. Thus it is possible that during reaching there is also a covert attentional bias which favours stimuli in the hemispace ipsilateral to the reaching hand.

The attentional field hypothesis, which was discussed in Experiment 2, could not be conclusively ruled out based on the results of previous experiments. For example, in Experiment 2 the attentional field hypothesis was criticized for lacking parsimony. However, complex behaviours do not always have parsimonious explanations. The absence of an ipsilateral effect for the back starting position in Experiment 2 could thus be explained by suggesting that an arm-related attentional field moved with the hand position.

In Experiments 1 and 2, through instructions prior to the experiment and monitoring during the experiment, the experimenter attempted to ensure that the head and body midlines were positioned at the centre of the display, and that the head and torso did not turn to either side. Despite these efforts, it is possible that the head and body were biased to either side. This was of particular concern because, in an effort to mimic naturalistic reaching conditions, head position was not controlled with a chin rest in these experiments. Thus, the ipsilateral effect for reaches from the front starting position could have been due to the head or body being turned toward, or leaning into, the ipsilateral hemispace. Similarly, the change in right-left interference in Experiment 2B could have been due to corresponding changes in head or body posture due to the movement of the hand starting position to the back of the display.

The results of Experiment 2B appeared to be inconsistent with the possibility that the visual or proprioceptive presence of the arm in the ipsilateral hemispace could explain the ipsilateral effect. However, subjects were instructed to hold their arm toward the centre of the display, so that the right forearm or elbow did not block the view of the front-right, stimulus location. It is possible that this difference lessened the ipsilateral arm presence bias thereby reducing the ipsilateral effect.

A similar hypothesis could be used to explain the proximity effect. Visual or proprioceptive information from the arm or hand could bias processing to the front or back of the display depending on the starting position of the hand. The arm (and obviously the hand) was positioned closer to the back of the display when the hand was at the back starting position, relative to when the hand was at the front starting position.

There is one primary commonality among all of these alternative accounts - they all suggest that the spatial properties of the interference effects were products of visual processing biases to certain regions of space. Our account is similar in that it also explains the spatial properties of the interference effects as products of processing biases to certain regions of space. What makes our hypothesis unique is that the processing biases implicated are visual-*motor* rather than visual-*spatial* in nature. The reason that our account has not yet been able to uniquely explain differences in interference produced by different stimuli is because those stimuli have been defined by their spatial locations (e.g., right vs left, front vs back, etc.). However, visuomotor processing differences between different visual stimuli need not be based on differences in spatial location. In other words, it is possible that two stimuli at the same location could differ in terms of the nature of the visuomotor processing required to generate a reaching movement to that location. If interference differed between two stimuli which differed in visuomotor but not visuospatial aspects, then our hypothesis would be distinguished from the alternative hypotheses. Experiment 3 was designed to create such an experimental situation.

How can one manipulate the relative visuomotor processing efficiency of two different reaches to the same visual location? We manipulated the complexity of reaches to a location.[2] With increases in movement complexity come decreases in motor processing efficiency. For example, reaction time is increased when movement complexity is increased (e.g., Henry & Rogers, 1960; Sternberg, Monsell, Knoll, & Wright, 1978; see reviews in Keele, 1981; Kerr, 1978; Klapp, 1977). Movement time is also obviously influenced by movement complexity (Fitts, 1954; Keele, 1981). We increased the complexity of a reach to a location by placing a transparent plastic obstacle in front of the target button. In order to press the target button, subjects had to reach over the top of the obstacle once the hand was in the vicinity of the target. The obstacle thus increased movement complexity by adding a second component to the target movement.

The critical comparison was between a condition in which the obstacle was present at the critical location and a condition in which the obstacle was not present at the location. We expected that the complexity manipulation would increase response time for reaches to the obstacle location, relative to reaches to the same location when no obstacle was present. Except for the difference in movement complexity, everything about the obstacle and no-obstacle conditions should have been same: use of the right hand, the starting position of the hand, the position of the right arm, the location of the stimuli, the location of the response, the position of the head and body, the focus of covert attention, the position of the stimulus relative to the eyes, etc.

What did the different accounts predict for interference from a distractor at the obstacle location compared to a distractor at the same location when no obstacle was present? Our account predicted that the obstacle distractor would interfere less than the no-obstacle distractor because the motor processing efficiency of a reach to the obstacle location was reduced (due to its increased movement complexity). All of the other accounts, which implicated differences in visual-spatial processing efficiency, predicted no difference in interference from obstacle and no-obstacle distractors, because both distractors were visually and spatially identical.[3]

A confirmation of our prediction would constitute strong support for the suggestion that irrelevant visual distractors were represented as actions, because the only parameter that differed between the obstacle and no-obstacle distractors was the nature of the action afforded by each.

Method

Subjects

36 undergraduate students (11 males and 25 females) from McMaster University participated

in the experiment for course credit. All subjects were right handed, had normal colour vision, and had normal or corrected-to-normal acuity. All subjects used their right hand for the experiment. Experiments 3A and 3B were run coincidentally, and subjects were randomly assigned to perform in either the no-obstacle (3A) or obstacle (3B) conditions.

Reaching Apparatus

The stimulus board used in the no-obstacle condition (3A) was identical to the apparatus used in Experiment 2A (Figure 4). The stimulus board used in the obstacle condition (3B) is displayed in Figure 8. It was identical to the apparatus used in the no-obstacle condition, except that a transparent plastic half-dome was fastened to the board in front of the front-right button. This obstacle was placed in a position such that it was in front of the button but not the target and distractor lights below it. It was completely transparent and vision of the button and lights was not occluded.

(FIGURE 8 ABOUT HERE)

Design

Half of the subjects performed the experiment with the obstacle at the front-right location (obstacle condition). The design was otherwise identical to the design of Experiment 2A.

Procedure

The only special instruction given to subjects in the obstacle condition was that they were to avoid touching the obstacle by reaching over the top of it. The procedure was otherwise identical to that used in Experiment 2A.

Results and Discussion

Experiment 3A

The no-obstacle condition was identical to Experiment 2A and we first wanted to be sure that the results were consistent across experiments.

Distractor Interference

We expected that there were proximity and ipsilateral effects in the interference data. In other words, we expected more interference from front than back distractors (proximity), and more interference from right than left distractors (ipsilateral). Mean interference scores were submitted to a 2 x 2 ANOVA with distractor hemispace (right or left) and distractor row (front or back) as factors (see Figure 9A). There was a main effect of row; front row distractors (mean = 25.50 ms) interfered more than back row distractors (mean = 14.92 ms) [$F(1,17) = 6.888$, $p < .02$]. There was also a main effect of hemispace; right distractors (mean = 25.26 ms) interfered more than left distractors (mean = 15.16 ms) [$F(1,17) = 22.040$, $p < .001$]. The interaction of hemispace (ipsilaterality) and row (proximity) was not significant [$F(1,17) = 2.214$, $p < .16$]. These results replicated the distractor interference results from Experiment 2A (compare Figures 6A and 9A).

Target Response Time

We also expected that the response time data for the control (target-only) trials would conform to the response competition hypothesis. In other words, as in Experiment 2A, we expected that response time would be less for reaches to front row and right hemispace targets, relative to back row and left hemispace targets, respectively. Mean response times for control trials were submitted to a 2 x 2 ANOVA with target hemispace (right or left) and target row (front or back) as factors (see Figure 9B). There was a main effect of row; response time to front row targets (mean = 610.19 ms) was less than to back row targets (mean = 665.08 ms) [$F(1,17) = 212.87$, $p < .0001$]. There was also a main effect of hemispace; response time to right targets (mean = 623.75 ms) was less than to left targets (mean = 651.53 ms) [$F(1,17) = 32.709$, $p < .0002$]. There was no row x hemispace interaction ($F < 1$). These results replicated the target response time results from Experiment 2A (compare Figures 6B and 9B).

(FIGURE 9 ABOUT HERE)

Errors

All 18 subjects combined made only 19 errors (.33% of trials). As in Experiment 2A, the greatest number of errors (9) were made to the front-right location, the fewest errors (2) were made to the back-left location, and intermediate numbers of errors were made to the front-left (5) and back-right (3) locations.

Summary

As expected, the results were very consistent with the results of the Experiment 2A.

Experiments 3A and 3B

Target Response Time as a Function of Obstacle Condition

The complexity manipulation was designed to increase response time of reaches to only the front-right location in the obstacle condition. To test whether this manipulation was successful, mean response times for control trials were submitted to a 2 x 4 mixed ANOVA with condition (obstacle, no-obstacle) and target location (front-left, back-left, front-right, back-right) as factors (see Figures 9B and 10B). As expected, there was a significant condition x location interaction [$F(3,102) = 77.883$, $p < .0001$]. Simple effects analyses (Keppel, 1982) revealed that this interaction was due to the fact that response time to the front-right location in the obstacle condition (mean = 751.78) was slower ($p < .0001$) than in the no-obstacle condition (mean = 595.83 ms); response times to the other three locations did not differ between conditions.

Distractor Interference as a Function of Obstacle Condition

According to our hypothesis, there should have been a similar condition x location interaction for distractor interference. Mean interference scores were submitted to a 2 x 4 mixed ANOVA with condition (obstacle, no-obstacle) and target location (front-left, back-left, front-right, back-right) as factors (see Figures 9A and 10A). There was a significant condition x location interaction [$F(3,102) = 4.748$, $p < .005$]. As expected from the target response time results, simple effects analysis revealed that interference from a distractor at the front-right location was reduced ($p < .05$) in the obstacle condition compared to the no-obstacle condition.[4]

(FIGURE 10 ABOUT HERE)

The condition x location interaction also seemed to be partly due to an *increase* in interference from the other three distractor locations in the obstacle condition (see Figures 9A and 10A), although the simple effects analyses showed that this increase was only significant for the back-right location ($p < .05$). A closer examination of the data revealed that this increase was due to heightened interference from the front-left, back-left, and back-right distractors specifically for reaches to the front-right target in the obstacle condition (see Figure 11). This finding was consistent with the response competition hypothesis because, due to the motor processing disadvantage caused by the obstacle, the front-right target was less competitive and thus more susceptible to interference from distractors at the other locations.[3] When reaches to the front-right target were excluded, there were no longer any differences in interference between obstacle and no-obstacle conditions for the front-left, back-left, and back-right distractors (see Figure 12).

(FIGURES 11 AND 12 ABOUT HERE)

Errors

The error data for the no-obstacle condition were presented above. In the obstacle condition, all 18 subjects combined made only 6 errors (.104% of trials). 0 errors were made to the front-right location in the obstacle condition, compared to the 9 errors made to the front-right distractor in the no-obstacle condition. Such a decrease in errors corresponded to the increase in target response time and the decrease in distractor interference when the obstacle was at the front-right location. Two, three and one error(s) were made to the front-left, back-left and back-right locations, respectively, in the obstacle condition.

Summary

The complexity manipulation successfully decreased motor processing efficiency (i.e., increased response time) of reaches to the front-right target in the obstacle condition. As predicted by the response competition hypothesis, this decreased motor processing efficiency also produced a decrease in interference from a distractor at the front-right location in the obstacle condition. Because the front-right distractors in the obstacle and no-obstacle conditions were visually and spatially identical, this finding is very difficult to explain using alternative hypotheses which claim that selective reaching interference effects are products of visual-spatial biases. These findings provided strong support for our suggestion that distractors achieve action representations, because the only difference between the front-right distractors in the obstacle and no-obstacle conditions was the nature of the action afforded by each.

CHAPTER IV

There was an assumption underlying interpretations of selective reaching interference effects that required validation. Experiment 4 was a critical control experiment designed to test this assumption.

EXPERIMENT 4

Studies of visual-spatial selective processes, which traditionally have not used reaching responses to localize targets, provide little explanation for the spatial interference effects found in selective reaching tasks. In other words, non-reaching examples from the selective attention literature have difficulty explaining the right-left and front-back interference asymmetries that have been found in selective reaching tasks. For this reason, there has been an underlying assumption in this thesis (and in Tipper et al., 1992) that the spatial properties of the interference effects were a product of the use of spatially-directed reaching responses. Even the aforementioned alternatives to the response competition hypothesis have contained this assumption in suggesting that visual-spatial processes were biased due to reaching-related aspects of the experiments. Experiment 4 tested the validity of this assumption. Such a test was necessary because it was possible that there was something unique to the visual display or task, but not related to reaching responses, that produced the spatial interference effects.

Visually, the task used in Experiment 4 was almost identical to that used in Experiments 2A and 3A, but the responses were not reaching responses. Instead, subjects had to localize targets by making verbal responses associated with the target locations; the locations were numbered and the response time to name the target number was measured.

In addition to the visual display, it was important that the verbal task was the same as the reaching task in all other respects except for the type of response. In the reaching task, the right hand not only reached for and localized the target, it also began each trial from a starting position at the body midline. It is possible that the placement of the right hand at the starting position could have unwanted influences on the results. For example, relative to when the right hand is not at the starting position, the torso or head could be turned slightly, despite our attempts to eliminate such spatial biases in Experiments 1, 2, and 3 through instructions and monitoring by the experimenter. To ensure that such possible influences were the same in the verbal and reaching tasks, the right hand was maintained at the same starting position used in Experiments 2A and 3A.

If it is true, as we have assumed, that selective reaching interference effects are due to the use of reaching responses, then the interference effects in the verbal task should not show the same spatial properties as those in reaching tasks. Thus, in contrast to the results of Experiment 2A and 3A, we expected that right distractors would not interfere more than left distractors and that front distractors would not interfere more than back distractors.

Method

Subjects

24 undergraduate students (5 males and 19 females) from McMaster University participated in the experiment for course credit. All subjects were right handed, had normal colour vision, and had normal or corrected-to-normal acuity. All subjects used their right hand for the experiment.

Equipment

The stimulus board in the experiment was the same as in Experiment 2A and 3A (see Figure 4). The numbers "1", "2", "3", and "4" appeared at the four stimulus locations. The numbers were printed in black, centred on a white paper background (1.7 cm x 1.7 cm), and fastened to the buttons at the locations. The vertical extent of each number was 1.4 cm and the horizontal extent varied from 0.8 cm ("1") to approximately 1.0 cm ("2", "3", "4"). Because a chin rest was not used (see Experiment 1), the visual angle subtended by the numbers varied between subjects.

A clip-on microphone was interfaced to the Apple IIe computer via a voice-key interface which detected the onset of an utterance into the microphone.

Design

For each of the 24 subjects, the locations of the numbers were chosen randomly (without replacement) from the 24 possible combinations of the 4 numbers at the 4 locations, so that each of the 24 combinations was used once in the experiment. This was done for two reasons. First, there may have been differences in how quickly subjects could say, for example, "2" relative to "3". If "2" and "3" appeared at the same locations for all subjects, then the spatial nature of response time differences to the locations would be confounded. Second, subjects may have more quickly learned the association between a particular number (e.g., "1") and its location, and thus would have been faster to say that number when a target appeared at the location. If "1" appeared at the same location for all subjects, then response time results would be similarly confounded.

In the reaching task, it was possible that subjects could have initiated reaching responses on some trials without foveating the target location. However, in the verbal task, if subjects did not learn the numbers associated with the locations, then it was not likely that they could have initiated accurate responses without foveating the target locations and reading the numbers. Thus, to satisfy the requirement that the verbal task be as similar as possible to the reaching task, it was hoped that subjects learned the number-location associations. To this end, the number of practice trials was increased from 20 to 50. During the break following the first half of the experimental trials, subjects were asked if they were responding without reading the number at the target location, and all subjects responded affirmatively.

As in Experiments 2 and 3, there were 16 trial types: one no-distractor (target-only) control trial type and three distractor trial types for each of the four target locations. Twenty-four trials of each type appeared randomly for each subject for a total of 384 trials. Pilot work indicated that procedural differences in the verbal task decreased the likelihood that trials would produce usable response times; more trials per condition were used in the verbal task to ensure that the number of usable trials in the verbal task was comparable to the reaching task.

One procedural difference was that the experimenter had to listen to the verbal response of the subject and enter that response into the computer keyboard. On some trials, the experimenter could not clearly hear which of the four numbers was spoken, and such trials could not be used. Also, on rare occasions (three in total) the experimenter mistakenly entered a number other than that spoken by the subject. The computer program coded these trials as subject errors, and did not record the response times for the trials.

A second procedural difference was related to the sensitivity of the microphone and the voice-key for detecting sounds. A small light on the voice-key device indicated to the experimenter when a sound had been detected. If it was clear to the experimenter that the voice-key detected a sound prior to the subject making a vocal response (i.e., an extraneous sound was detected), or if the voice-key did not detect the initial vocal response, then the trial was not used.

Voice Onset Time (VOT) for each usable trial was measured from the time the stimulus light(s) appeared until the voice-key detected an utterance into the microphone. Interference scores for each subject in each distractor condition were calculated as in the previous experiments, using VOT rather than TT.

Errors in the verbal task were not easily comparable to errors in the reaching task, because of the manner in which they were coded by the computer program running the experiment. In the reaching tasks, an error indicated a trial on which the distractor button was pressed. In the verbal task, a trial was coded as an error when a number, other than the target number, was entered into the computer keyboard by the experimenter. There were two problems. First, on three occasions the experimenter erroneously entered a number other than that spoken by the subject. Second, the computer did not code what was entered into the computer, it only coded that something other than the target number was entered. In other words it cannot be assumed that the response on an error trial was the distractor number; evidence against such an assumption comes from the fact that 17.8% of errors in the verbal task occurred on trials on which no distractor was present. Because of these two problems, an error may have been something other than a response to the stimulus at the distractor location. Errors in the verbal task could thus not be compared to errors in the reaching task. They will be presented, but not discussed, in the *Results*.

Procedure

The microphone was clipped to the subject's shirt. The subjects were instructed to begin each trial by pressing and releasing the start key with the tip(s) of the index and/or middle finger of the right hand, and to keep the hand at this position throughout each trial. They were also instructed to respond as quickly as possible by clearly saying the number corresponding to the target location. Following stimulus presentation and response, the experimenter pressed the character on the keyboard which corresponded to the verbal response. Unusable trials, which were defined above, were coded by pressing another key on the computer keyboard. Subjects rested for several minutes after 192 of the experimental trials had been completed, and then completed the remaining 192 trials. In all other respects, the procedure was the same as that used in Experiment 2A and 3A.

Results and Discussion

An average of 1.45% of trials were coded as unusable. No subject had more than five combined errors and unusable trials for any one trial type. A total of three errors were experimenter errors.

Distractor Interference

In contrast to the results of Experiments 2A and 3A, we expected that right distractors would not interfere more than left distractors and that front distractors would not interfere more than back distractors. As in Experiments 2A and 3A, mean interference scores were submitted to a 2 x 2 ANOVA with distractor hemispace (right or left) and distractor row (front or back) as factors (see Figure 13A). There was no interaction of hemispace and row [$F(1,23) < 1$]. There was also no main effect of hemispace [$F(1,23) < 1$]; in other words there was no difference in interference from right (mean = 67.68 ms) and left (mean = 71.13 ms) distractors. This finding was consistent with our prediction that right distractors would not interfere more than left distractors. There was a main effect of row; back row distractors (mean = 79.58 ms) interfered more than front row distractors (mean = 59.22 ms) [$F(1,23) = 15.604$, $p < .001$]. The latter finding was consistent with our prediction that front distractors would not interfere more than back distractors.

(FIGURE 13 ABOUT HERE)

Although consistent with our expectations, the finding that back row distractors interfered more than front row distractors begged an explanation. A consideration of the relative positions of back and front distractors in three-dimensional space may help to explain this finding. Back row distractors were located farther in the depth plane and higher in the vertical plane than front row distractors. Recent studies of spatial attention in the depth plane would seem to predict the opposite result for far and near distractors (Andersen & Kramer, 1993; Downing & Pinker, 1985; Gawryszewski, Riggio, Rizzolatti, & Umiltà, 1987). For example, Andersen and Kramer (1993) measured interference from flanking distractors which were nearer or farther than the target in the depth plane, and found larger interference from near than far distractors. When compared with such a result, the finding from Experiment 4 seems not best explained by differences in the depth plane between back and front distractors. Back row distractors were also higher than front row distractors in the vertical plane, but there is no evidence of attentional biases to different locations along the vertical axis (e.g., Gawryszewski et al., 1987). Based on these findings, it is difficult to explain why back row distractors interfered more than front row distractors.

Most importantly though, the front-back interference results of the verbal task differed from the reaching task. This gives more weight to the claim that the front-back interference results in the reaching tasks were a product of the fact that reaching responses were used. If front distractors had also caused larger interference than back distractors in the verbal task, then one could argue that the proximity effect in the reaching task could have been due to a spatial attentional bias to near space which was unrelated to the use of reaching responses.

Target Response Time

Although we were primarily concerned with how distractor interference results from the verbal task compared to distractor interference from the reaching task, we will also present the target response time data from the verbal task. Perhaps, as in the reaching task, interference in the verbal task could have been response-related. Indeed, response processing of irrelevant information is implicated in many cognitive tasks that show interference (e.g., Stroop, 1935; Eriksen & Eriksen, 1974). If this hypothesis is true then response time to back targets should have been faster than to front targets, and response time to right and left targets should have been the same. Mean response times were submitted to a 2 x 2 ANOVA with target hemispace (right or left) and target row (front or back) as factors (see Figure 13B). There was no interaction of hemispace and row [$F(1,23) = 1.031$]. There was also no main effect of hemispace [$F(1,23) = 1.095$]; in other words there was no difference in response time to right (mean = 650.06 ms) and left (mean = 660.92 ms) targets. There was a main effect of row; back row targets (mean = 633.81 ms) were responded to faster than front row targets (mean = 677.17 ms) [$F(1,23) = 16.574, p < .001$]. These results were consistent with the interference being response-related.

Errors

Three of the errors presented here were experimenter errors. For trials on which a distractor was present, the following number of errors (for the 24 subjects combined) occurred when a distractor appeared at the front-left, back-left, front-right, and back-right locations, respectively: 24, 35, 28, and 19. For trials on which only a target was present, the following number of errors occurred when a target appeared at the front-left, back-left, front-right, and back-right locations, respectively: 7, 5, 5, and 6.

Summary

As expected, the spatial interference results of the verbal task used in Experiment 4 differed from those of the reaching task used in Experiments 2A and 3A. Given that the verbal task was almost identical to the reaching task in every respect other than the nature of the response, it is safe to assume that the differences in interference between the two experiments were a result of the response differences. In other words, the spatial properties of the interference effects found in selective reaching tasks are likely a product of the use of reaching responses.

CHAPTER V

GENERAL DISCUSSION

The combined results of Experiments 1, 2 and 3 confirmed that spatial aspects of distractor interference in a reaching task were not determined by visuospatial biases to the locations of distractors. Experiment 4 confirmed that these spatial aspects of interference were unique to a reaching task, by showing that the same spatial interference effects were not seen when verbal responses were used to localize targets on the same visual display. The response competition hypothesis suggested that spatial aspects of interference were due to visuomotor processing biases to the locations of distractors. This hypothesis was confirmed in Experiment 3 when two distractors at the same location produced different degrees of interference because of differences in their visuomotor properties. This finding provided strong support for our suggestion that distractors achieved action representations, because the only difference between the two distractors was the nature of the action afforded by each.

Implications for Search Theory

In Chapter I, serial search explanations for distractor interference effects were discussed. Castiello (1996) suggested that selective reaching interference could be explained by the fact that "attention", which operates serially (although see Castiello & Umiltà, 1992), is focused on the distractor initially on approximately half of target-distractor trials. This account cannot explain why distractors at certain locations caused more interference than distractors at other locations, unless "attention" was biased to the former locations. The results of the present experiments, particularly Experiment 3, ruled out the possibility of an attentional bias to the locations at which distractors produced more interference.

It is commonly presumed that when distractors and targets are discriminated by colour in visual search, there is no increase in response time to targets when distractors are present. This finding is commonly referred to as "pop out", "parallel search", "pre-attentive search", or "feature search" (e.g., Treisman & Gelade, 1980), although other theories would describe such a finding as an efficient search due to target-distractor dissimilarity (e.g., Duncan & Humphreys, 1989). However, when the colours are not easily discriminated, there is ample evidence for increases in response time to targets when distractors are present (e.g., Carter, 1982; Duncan, 1989; Treisman & Gormican, 1988). This finding is commonly referred to as "serial search", or "attentive search" (e.g., Treisman & Gelade, 1980), although other theories would describe such a finding as an inefficient search due to target-distractor similarity (e.g., Duncan & Humphreys, 1989). Because we found increases in response time to red targets in the presence of yellow distractors, one might conclude that the colours were not easily discriminable, and thus the search was serial (Treisman & Gelade, 1980), or inefficient (Duncan & Humphreys, 1989).

Our account is immune to the possibility that serial "attention" was required to resolve the colour discrimination in the task, because a serial colour search account cannot explain the visuomotor aspects of distractor interference. In Chapter I, we suggested that visuomotor and colour processing of stimuli occurs independently and in parallel in the visual system. Considering each parallel stream separately, targets and distractors are processed in parallel in the dorsal stream, but colour processing in the ventral stream is not necessarily parallel, according to our account.

Colour discriminability between a target and distractor can vary on a continuum from high to low (Duncan, 1989), and this can influence a continuum of search efficiency from high to low, respectively (Duncan & Humphreys, 1989). For the present findings, although interference in general could be partially produced by an inefficient search due to low colour discriminability, interference differences among distractors at different locations could only be attributed to their visuomotor properties.

Action Representations of Visual Objects

How do action representations rapidly form for visual objects? This thesis is specifically concerned with the formation of the representations of arm movements which bring the hand to the location of visual objects.

There is much evidence suggesting that information received and processed by visual areas is inevitably passed to related motor areas (see Allport, 1993; Goodale, 1988). The visual processes that code the locations of objects in the dorsal stream are linked in this manner to motor processes that enable visually-directed actions to those locations. For example, premotor cortex (Brodmann's area 6) is a particularly important frontal motor area for visually-guided arm movements (Gentilluci & Rizzolatti, 1990; Kurata, 1994; Wise, 1985). The dorsal stream is linked to premotor cortex via projections from posterior parietal cortex (Andersen, 1987; Cavada & Goldman-Rakic, 1989; Petrides & Pandya, 1984). Tanné, Boussaoud, Boyer-Zeller, and Rouiller (1995) also recently documented a direct projection to premotor cortex from area PO, a visual area in the dorsal stream (see also Pandya & Kuypers, 1969; Shipp & Zeki, 1995).

It is likely that such visuomotor pathways are "primed" to operate quickly in a visually-guided reaching task. The goal of the subject is to rapidly reach to the target location. When stimuli appear, such internal goals will certainly act to facilitate the transmission of visual information to those motor areas that will complete the goals. It is also possible that action representations can be prepared to some degree before a trial begins. In the present experiments subjects knew in advance they would be making one of four (Experiments 2 and 3) or six (Experiment 1) movements. The choice RT literature has provided evidence that multiple response choices can be preprogrammed in advance (see Rosenbaum, 1980 for a review).

Consider the example of a control (target-only) trial in the present experiments. A subject, before a trial begins, is prepared to make a reach to one of four (or six) potential locations in response to a red light that appears at the target location. When a red light appears at one of the locations, visual processes in the dorsal stream code the location of the object in a topographic map of visual space. Because of direct and primed links between these visual processes and related motor processes, the formation of a representation of a reaching action directed to the location would proceed automatically when the visual stimulus appears.

Action Representations of Non-Target Objects

Can such automatic, stimulus-driven activation of action processes occur for two objects in parallel, even when one is an irrelevant distractor object? Evidence in the affirmative is provided by behavioural and physiological studies on the processing of irrelevant information.

Delays in responding to the stimulus of interest have been attributed to response competition from irrelevant information for several behavioural tasks, including the Stroop (1935) colour-naming task (e.g., Morton & Chambers, 1973; Posner & Snyder, 1975), the flanker task (see Eriksen, 1995), and the Simon task (Simon, 1969). In each of these cases the irrelevant stimulus information is thought to automatically elicit competing response processes.

There is also physiological evidence for the response-based processing of irrelevant information. For example, Coles, Gratton, Bashore, Eriksen, and Donchin (1985) reported evidence of electromyographic activity and "subthreshold" overt responses associated with responses to distractor stimuli in a flanker task. Also, Duncan-Johnson and Koppell (1981) showed that event-related brain potentials associated with perceptual processing (P300) were the same for trials which varied in the amount of Stroop interference, suggesting that interference from distracting information was at the level of response processing.

Oculomotor Representations of Non-Target Objects

Convincing behavioural and physiological evidence for action representations of irrelevant visual objects comes from the study of eye movements to targets in the presence of non-targets. Compared to the reaching system, the oculomotor system has been examined more extensively under multiple stimulus conditions. For example, spatial inaccuracies of saccades to targets in the presence of non-targets (or other potential targets) are consistently biased towards the location of the non-targets (e.g., Findlay, 1982; Ottes, Van Gisbergen, & Eggermont, 1985). Also, eye movement latencies to a visual target are longer when a visual non-target object is presented simultaneously (e.g., Walker, Kentridge, & Findlay, 1995).

This latter finding is analogous to selective reaching interference.

As in the visually-guided reaching system reviewed above, frontal motor areas in the visually-guided saccade system receive visual information from the dorsal stream via posterior parietal cortex (Milner & Goodale, 1993; Schall, 1995). Perhaps neurophysiological investigations of non-target representations in the oculomotor system (Goldberg & Segraves, 1987; Schall, 1995) can shed some light on analogous representations in the reaching system.

Schall and colleagues (Schall & Hanes, 1993; Schall, Hanes, Thompson, & King, 1995) examined the properties of neurons in the frontal eye field (FEF) of monkeys during a visual search task in which directed eye movements were made to a single target which was presented among several distractors of a different colour. FEF is a motor area in frontal cortex involved in the production of voluntary eye movements which receives visual information from the dorsal stream. The visuomotor neurons they examined fired preceding a saccade destined for the location of their response fields. They examined how such neurons responded to either a target or distractor in their response fields. The initial response of these neurons was the same whether a target or distractor was in their response fields. Following this initial indiscriminant response, selective processes quickly acted to discriminate between targets and distractors before target saccades were generated. This finding shows that distractors achieved action representations before selective processes were able to operate. Schall (1995) also reviewed similar findings in superior colliculus, which is another important oculomotor area.

Another very interesting aspect of their findings was that target eye movements took no longer to complete on search trials than on trials without distractors (J.D. Schall, personal communication; see also Schall & Hanes, 1993; Schall et al., 1995). Had the only behavioural measure in this task been movement response time, experimental psychologists would have concluded that this lack of interference signified a very efficient selective act. Most would go further to suggest that such efficient selection could only have been accomplished had selective processes filtered out distractor information early in the visual system (if selective processes were necessary at all).

That a motor signal associated with the distractor was present in frontal cortex has implications for such theoretical conclusions. A lack of interference obviously cannot be taken as evidence that information about the distractor was filtered out "early", if "early" is used to signify a stage in the processing hierarchy. "Early" can also be used as a chronological term to signify how long it takes for selective processes to filter out distractor information following stimulus onset. Note that for serial discrete stage models (e.g., Sternberg, 1969), both uses of "early" are indistinguishable because a "late" stage would not be active until "late" chronologically. Such models would have difficulty explaining how, for example, visually responsive neurons in FEF respond on average within 80 ms (range from 40 ms to over 100 ms) following visual stimulus onset (Schall, 1995).

Parallel models and continuous flow models, on the other hand, allow that "late" stages could be active "early" chronologically. Parallel models, like the one we have hypothesized here for colour and visuomotor processing, could explain such a result because processing leading to motor activation is working in parallel with processing leading to colour discrimination. Similarly, continuous flow models (e.g., Eriksen & Schultz, 1979; McClelland, 1979), hold that partial information from perceptual processes may flow continuously into motor processes before perceptual processing is complete. The findings of Schall and colleagues provide evidence for such models because there was "late" stage processing despite selective processes acting "early" enough chronologically to allow an undelayed eye movement to the target. In summary, the impressive efficiency of selective processes cannot be used as evidence for the hierarchical stage at which they disallow further processing of non-target information (for related ideas see Allport, 1987; Driver & Tipper, 1989).

Walker et al. (1995) concluded that their findings of distractor interference in an eye movement task were due to response competition from potential targets. Schall and colleagues showed that eye movements to targets were not delayed despite distractor processing in FEF. In selective reaching, reaches to targets were delayed by distractors. Our suggestion that distractors achieved action representations in selective reaching seems very plausible when compared with such findings, especially considering the similarity of the visuomotor pathways involved in reaching and eye movements (Milner & Goodale, 1993).

Consider the example of a target-distractor trial in the present experiments. A subject, before a trial begins, is prepared to make a reach to one of four (or six) potential locations in response to a red light that appears at the target location. When a red light appears at one of the locations and a yellow light appears at another, visual processes in the dorsal stream code the locations of the objects in a topographic map of visual space. Because of direct and primed links between these visual processes and related motor processes, the formation of representations of reaching actions directed to those locations would proceed automatically when the visual stimuli appear.

The following two sections review the factors underlying why reaching representations of certain visual distractors cause more interference than others. The first section considers why reaching representations of certain visual objects form more rapidly than others. The second section suggests that the coordinate systems in which reaches are represented may be biased to certain spatial locations.

Factors Underlying Visuomotor Processing Efficiency

The efficiency with which movements can be made to different visual objects, and thus the amount of interference caused by those objects as distractors, is likely the product of a combination of several factors which will be reviewed here.

The relationship between target response time and distractor interference has interesting implications for the central (i.e., brain) representation and control of movement. On their own, differences in response time to targets at different locations cannot be solely attributed to visuomotor processing factors. In other words, such findings can also be attributed to peripheral (i.e., musculoskeletal) factors. For example, on reaches from the front starting position in Experiments 1, 2A, and 3A, reaches to the front-right location could be completed by rotating the forearm around the elbow joint with minimal shoulder involvement, but reaches to the back-left location additionally required rotating the upper arm at the shoulder. Thus the quickness with which reaches were made to the front-right relative to the back-left location could be attributed to such biomechanical factors. However, because no movement is actually made to distractors, distractor interference is clearly a measure of central processing. That front-right distractors interfered more than back-left distractors is evidence for the central representation of movements to the front-right and back-left locations.

This evidence for the central representation of movement implies that (1) visuomotor factors should not be abandoned in favour of biomechanical explanations for spatial movement efficiency, and/or (2) biomechanical constraints may have central representations. Consider the latter implication from a learning perspective. How would you respond manually to an object that is far in the periphery of the right hemispace? Ninety-nine times out of one hundred, you are going to reach for that object with your right hand, even if you are left-handed. This seems obvious given the relative biomechanical difficulty of reaching with the left hand. However, years and years of such a one-way relationship between a region of visual space and an effector is going to affect central visuomotor wiring. Under this scenario, the above implications could be combined: perhaps visuomotor and biomechanical factors together explain spatial movement efficiency because plastic visuomotor networks have been influenced by biomechanical constraints.

This learning scenario cannot be the only explanation for the motoric aspects of distractor interference, however. For certain space-effector relationships, central wiring could be the product of phylogenetic, in addition to ontogenetic, development. In other words, space-effector relationships could be "hard-wired". For instance, ipsilateral movements have an advantage because, e.g., vision of the right hemispace and control of the right hand are both processed in the left hemisphere, so visual information does not have to cross the cerebral commissures (see references in Chapter II). However, such hard-wiring cannot explain findings such as the lack of an ipsilateral advantage for movements toward the body from the back starting position.

Neither ontogenetic or phylogenetic development could explain the effect of the complexity manipulation on distractor interference in Experiment 3, because subjects were presumably receiving their first exposure to the that particular two-component movement. Thus it is likely that an on-line increase in programming time for a more complex movement was responsible for the reduced distractor interference (e.g., Henry & Rogers, 1960; Sternberg et al., 1978; see reviews in Keele, 1981; Kerr, 1978; Klapp, 1977). Interestingly, the amount of interference caused by the obstacle distractor was likely a product of such programming factors in combination with other visuomotor factors.[4]

In summary, the efficiency with which movements can be made to different visual objects, and thus the amount of interference caused by those objects as distractors, is the product of a combination of several factors: learning, hard-wiring, and on-line programming efficiency.

Spatial Coordinates in which Actions are Represented

As mentioned above, visual processes in the dorsal stream code the location of stimuli in a topographic map of visual space. This information is then passed on to motor processes that enable visually-directed reaches to those locations. The coordinate system of space in which the stimuli are represented undergoes transformations along this visuomotor continuum (Andersen, Snyder, Li, & Stricanne, 1993). Initially, all visual information is mapped in retinotopic coordinates. When this visual information is used for reaching, it likely undergoes a transformation into a coordinate system centred on some relevant component of the effector system, such as the hand (e.g., Gordon, Ghilardi, & Ghez, 1992), or the shoulder (e.g., Flanders, Helms Tillery, & Soechting, 1992). We have suggested that both targets and distractors achieve action representations, and these representations may be mapped in such effector-centred coordinates (see Tipper et al., 1992).

Just like retina-centred maps are biased to the fovea (i.e., the fovea is more prominently represented), an effector-centred map may be biased to the space surrounding the effector. When selective processes operate on distractor representations in coordinate maps, selection time is going to be affected by the prominence of the distractor representation in those maps. Thus the amount of interference caused by a distractor could be influenced by its position relative to the centre of the effector-centred map in which it is represented.

The preceding section considered visuomotor processing efficiency factors affecting interference, and this section has considered representational coordinate factors affecting interference. How do these factors coexist? Perhaps each of these factors influences the maps in which actions are represented. A map consists of a number of receptive field units. If a stimulus appears in the receptive field of a unit, then the unit becomes active. In spatiomotor maps, the degree of activation of the units associated with a stimulus is determined by the visuomotor efficiency factors discussed in the preceding section. If such a map is effector-centred, then the number of units devoted to a particular area of space is greater for the space surrounding the effector. A stimulus which is located closer to the effector would thus activate more units. Selection efficiency is reduced (i.e., interference is increased) when (1) the number of units activated by a distractor is greater, or (2) the degree of activation of those distractor units is greater.

Although the manipulations used in the present experiments were designed primarily to influence visuomotor processing efficiency, certain interference findings were consistent with a hand-centred coordinate bias. For example, the proximity effect in Experiment 1 was consistent with hand-centred coordinates, because there was a gradient of interference that reduced as distractors were further from the hand. Similarly, the fact that front-back interference reversed when the hand was at the back of the display was very consistent with hand-centred coordinates (Experiment 2B; Tipper et al., 1992). This evidence suggests that action representations of visual stimuli in selective reaching may be mapped in spatial coordinates centred on the reaching hand.

Conclusions

It may sound strange to some who study cognitive processing to say that visual objects are represented as actions, because researchers often are not concerned with how visual information is used by motor systems (Eriksen, 1995; Neisser, 1976; Stelmach, 1982). As Eriksen (1995) states: "Today many cognitive models...pay too little attention to how cognitive processing is translated or eventuates into behaviour. Perhaps this represents an unconscious over-reaction against the extreme behaviourism of the 1930s and the 1940s. All too often clever and elaborate models of cognitive processing end in a decision stage where a command is given and the appropriate response is emitted. But when the choice reaction-time procedures are used in the study of cognitive processing, there is a serious risk that conclusions concerning this processing can be confounded with characteristics of the response or motor system" (p.114). The results of this research provide clear evidence of such a confound for models of selective attention that purportedly apply to real-world situations such as picking a ripe among unripe apples, but that do not take into account the act of picking itself.

ENDNOTES

2. Another potential method for a non-spatial manipulation of motor processing efficiency that has been used by motor behaviour researchers has been to vary the size of the target (Fitts, 1954; Fitts & Peterson, 1964). When the size of the target was increased, accuracy requirements were reduced, and movements were faster. Based on such results, we considered manipulating the size of the button at a particular location. However, the interpretation could have been confounded by the fact that the spatial accuracy required at the endpoint of each movement would have differed for big and small stimuli at the same location. The manipulation we used varied motor processing efficiency without varying endpoint accuracy.

3. In addition to movement complexity, there may have been other unwanted differences between obstacle and no-obstacle conditions. For example, despite the obstacle's transparency, its presence may have made the obstacle distractor more visually salient. However, if that was the case, then one would have predicted that the obstacle distractor would have caused more interference (rather than less interference as predicted by our account).

Conversely, one might suggest that the obstacle distractor's distinctiveness would make it less likely to cause interference because of its dissimilarity to the other stimuli. For example, distractors may achieve action representations (as the response competition hypothesis has suggested), but their competitiveness may be based on the similarity of their action representations to the target representation. In other words, distractors which are motorically-similar to the target are more likely to cause interference. Such an account would also have predicted less interference from the obstacle distractor, because it was less simiiar to the target than the no-obstacle distractor.

However, Experiment 3 provided evidence against such an account. When the target appeared at the obstacle location, the "similarity" hypothesis would have predicted less interference from distractors at the other locations because they were motorically dissimilar to the obstacle target. Our account, on the other hand, would have predicted more interference from those distractors because, due to the motor processing disadvantage caused by the obstacle, the target would have been less competitive and thus more susceptible to interference. The results of Experiment 3 supported the latter account (see *Results and Discussion*).

4. The reduction in front-right distractor interference from 33.20 ms in the no-obstacle condition to 20.85 ms in the obstacle condition was not as dramatic as might have been expected given the dramatic increase in front-right target response time from 595.83 ms to 751.78 ms. By comparison, look at the changes at the front-right location when hand position was manipulated in Experiment 2: front-right distractor interference decreased from 32.10 ms for the front starting position to 12.43 ms for the back starting position, and front-right target response time increased from 617.00 ms to 757.85 ms.

The reason there was not a comparable reduction in interference in Experiment 3 could be related to how the obstacle changed the movement to the front-right location. Effectively, the obstacle added a second component to the movement. The first component of the movement was likely very similar to the movement to the front-right location in the no-obstacle condition. If so, and the two components of the obstacle movement had quasi-independent representations, then the representation of the first component of the movement was sufficiently established to produce interference. But because the component representations were only partially independent, the establishment of the first component representation was limited by the establishment of the second. Thus, the representation of the first component was not as well established as the representation of the similar no-obstacle movement, and did not cause as much interference.

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Figure Captions

Figure 4: Reaching display used in Experiments 2A and 3A. The same display was used in a verbal localization task in Experiment 4.

Figure 5: Reaching display used in Experiment 2B. Hand starting position was at the back of the display.

Figure 6: Mean dependent measures (in msec) as a function of stimulus location from Experiment 2A.

A: Distractor Interference

B: Target Response Time on Control Trials

Figure 7: Mean dependent measures (in msec) as a function of stimulus location from Experiment 2B. Hand starting position was at the back of the display.

A: Distractor Interference

B: Target Response Time on Control Trials

Figure 8: Reaching display used in Experiment 3B. A transparent plastic half-dome was fastened to the display in front of the front-right button.

Figure 9: Mean dependent measures (in msec) as a function of stimulus location from Experiment 3A (no-obstacle condition).

A: Distractor Interference

B: Target Response Time on Control Trials

Figure 10: Mean dependent measures (in msec) as a function of stimulus location from Experiment 3B (obstacle condition).

A: Distractor Interference

B: Target Response Time on Control Trials

Figure 11: Mean interference (in msec) from distractors at the front-left, back-left, and back-right locations in Experiment 3B (obstacle condition).

A: Reaches to target at front-right location

B: Reaches to other three target locations

Figure 12: Mean interference (in msec) as a function of distractor location, excluding reaches to the front-right target.

A: Experiment 3A (no-obstacle condition)

B: Experiment 3B (obstacle condition)

Figure 13: Mean dependent measures (in msec) as a function of stimulus location from Experiment 4. Targets were localized using verbal, rather than reaching responses.

A: Distractor Interference

B: Target Response Time on Control Trials

Figure 4

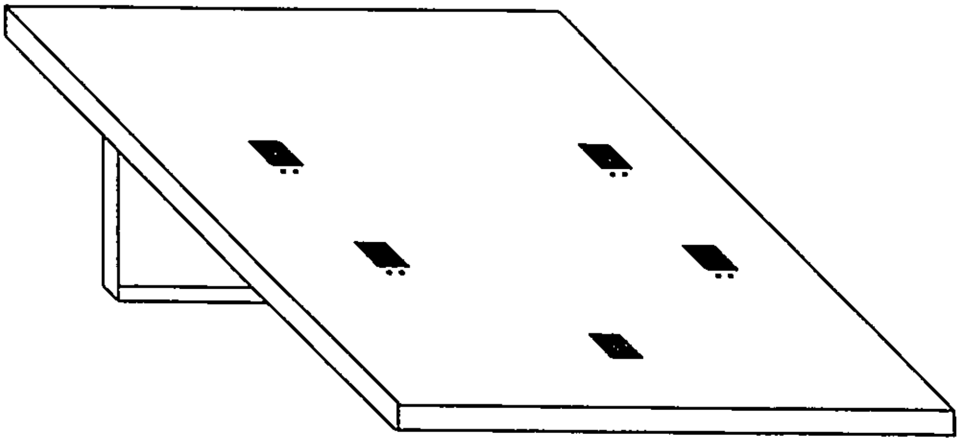
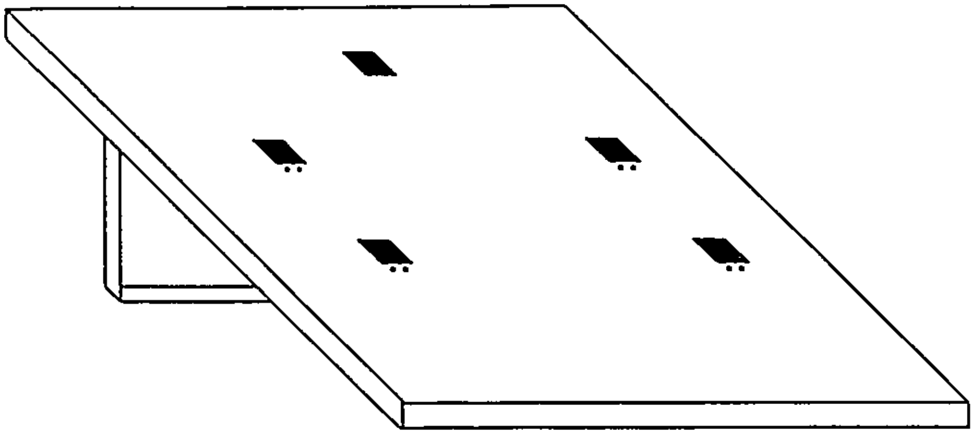


Figure 5



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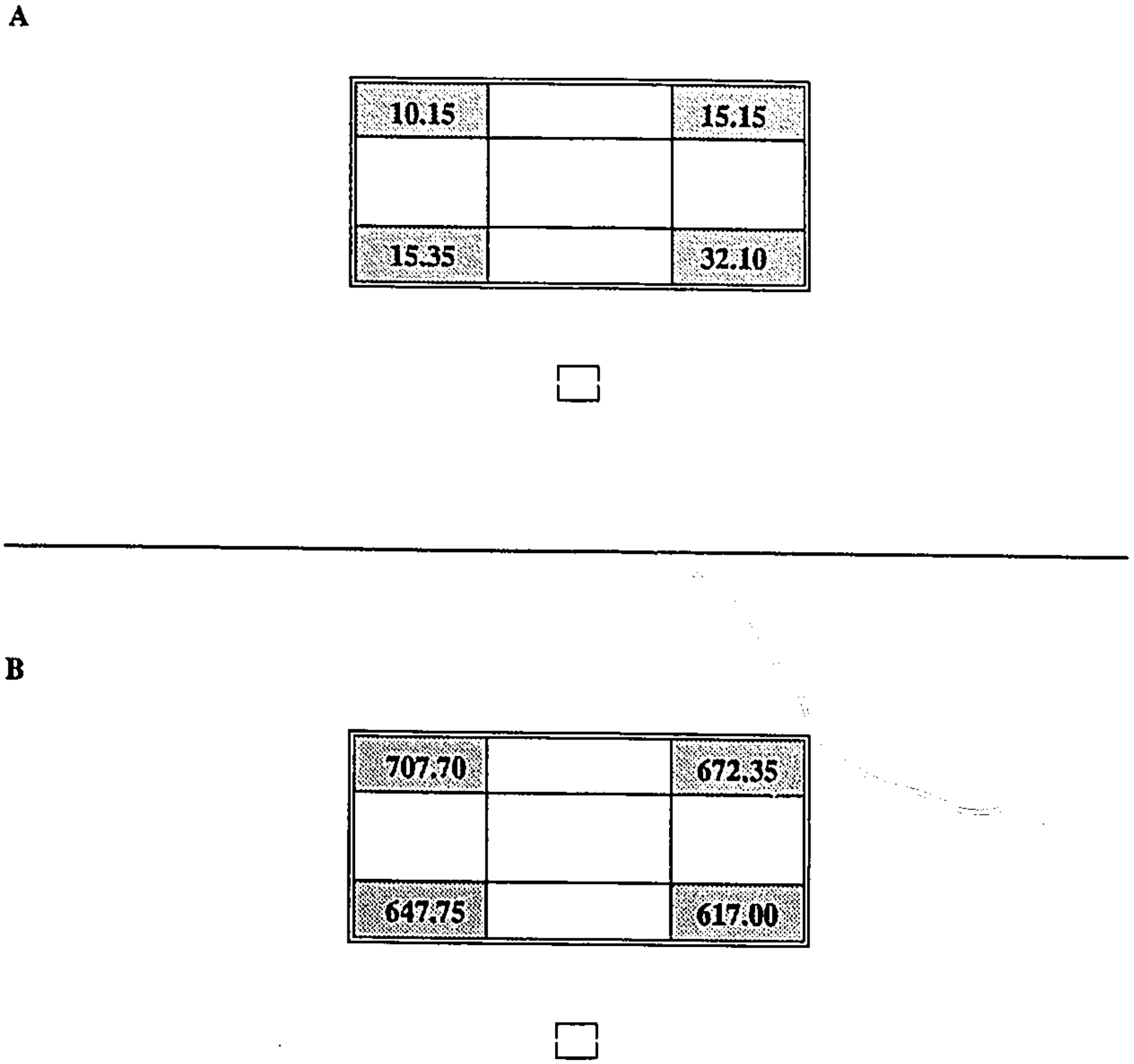


A

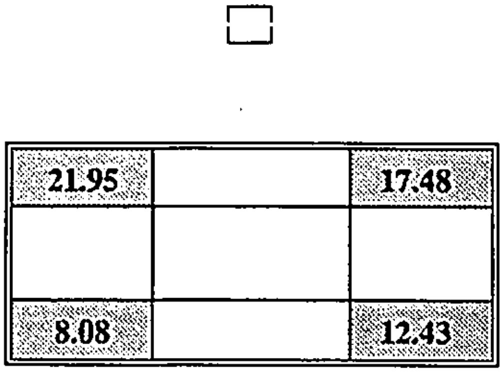
10.15		15.15
15.35		32.10

B

707.70		672.35
647.75		617.00

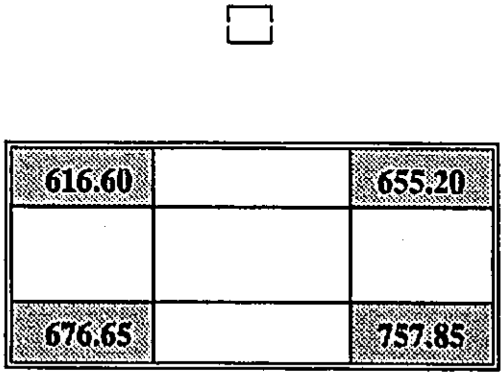
Figure 7

A



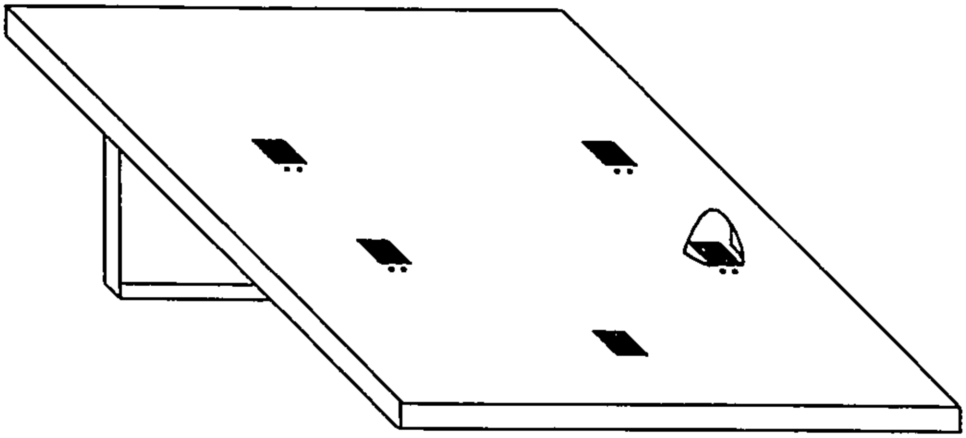
21.95		17.48
8.08		12.43

B

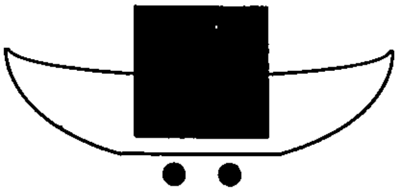


616.60		655.20
676.65		757.85

Figure 8



top view



side view

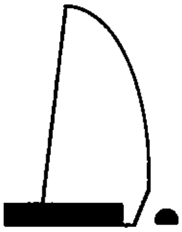


Figure 9

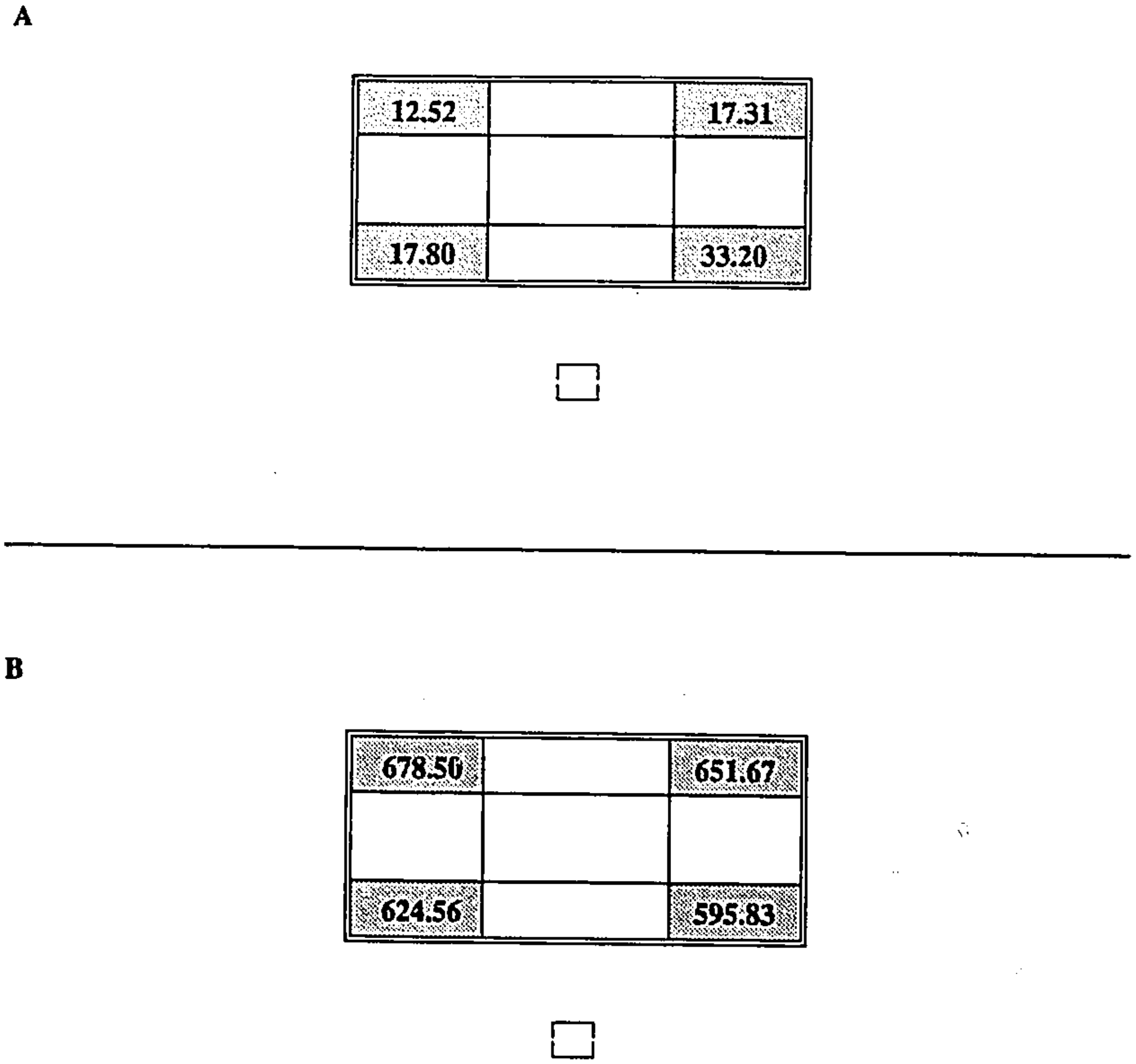


Figure 10

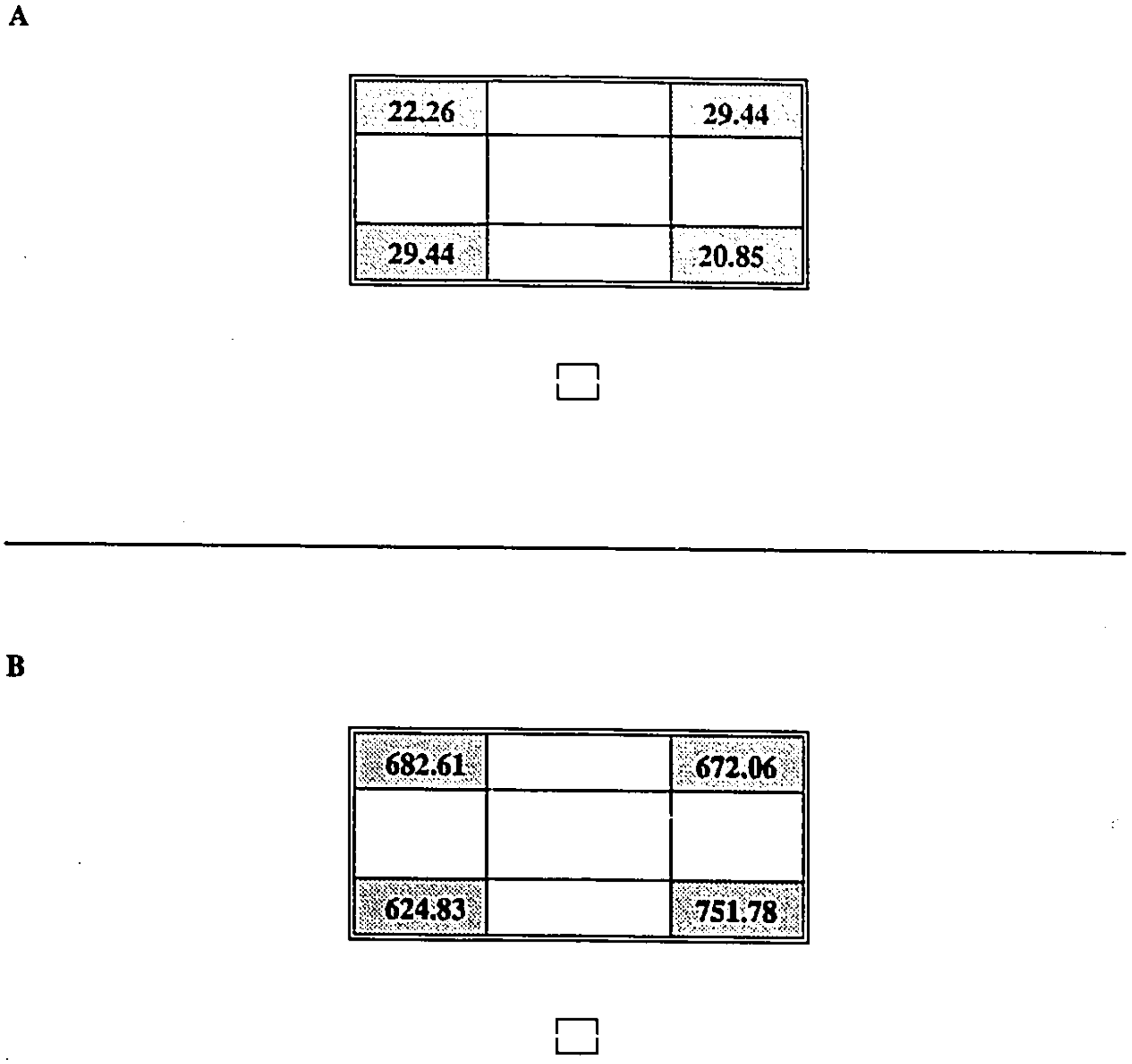


Figure 11

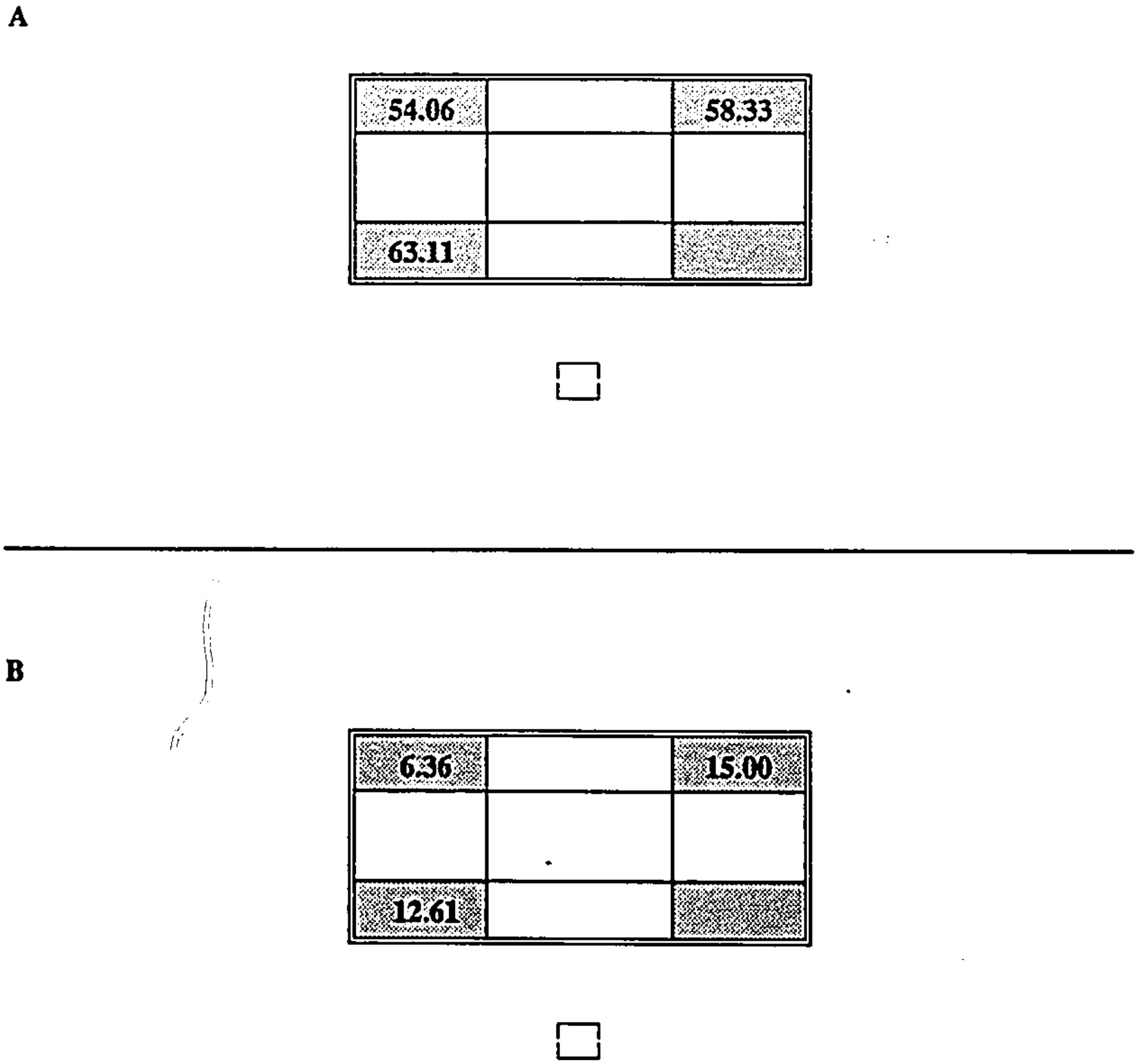


Figure 12

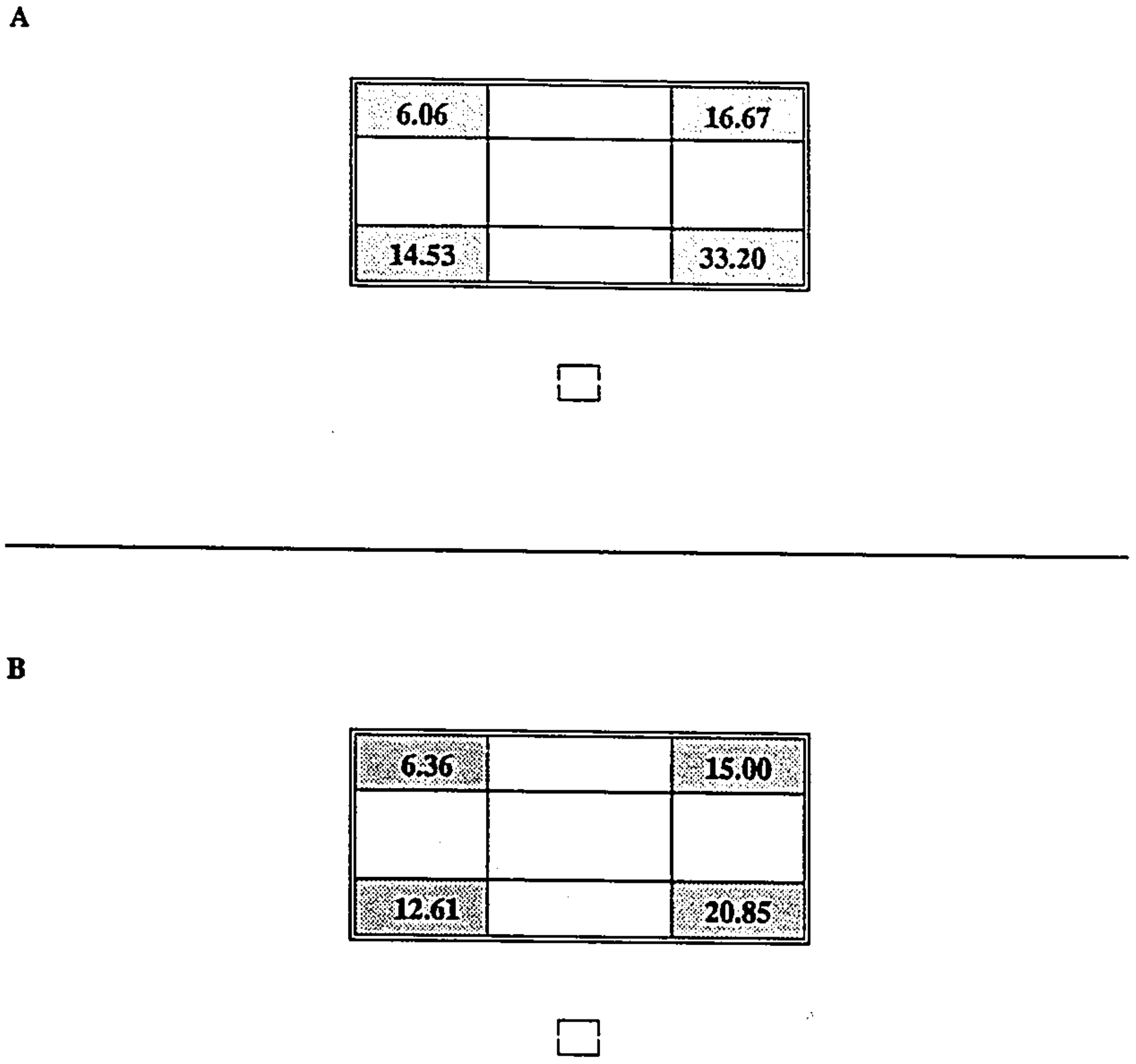


Figure 13