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# SEQUENTIAL EFFECTS IN REACHING AROUND OBSTACLES

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by

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# ABSTRACT

Many models of human reaching propose that movements are planned by minimizing movement costs. A common assumption of these models is that movements are planned anew each time one is desired. In this thesis I will suggest that movement planning instead relies on the reuse and modification of previous movement plans. One prediction that follows from this proposal is that the ability to minimize movement costs may be limited by the perceptual-motor system's ability to modify the reused plan. The results from five experiments in which participants performed reaching movements in the presence of or in the absence of an intervening obstacle support this prediction. When both movement types were required within a block, direct movements were more curved when preceded by obstacle–avoiding movements than by other direct movements. Thus, the cost of performing a direct movement was not fully minimized when its path differed significantly from the previous trial's path. In addition, obstacle-avoiding movements were *less* curved when preceded by direct movements than by other obstacle-avoiding movements. This second finding provides additional evidence for the reuse of previous movement plans. In general, the sequential effects suggested that the perceptual–motor system reused a relatively high–level hand path representation that could be translated to other regions of space. Further experiments showed that the observed sequential effects were not anticipatory in nature, that they persisted for many trials, and that they were reduced when the time between movements was increased or when participants were instructed to move as straight as possible when no obstacle appeared. Collectively, the results show that physical movement costs may not always be minimized if computational

demands favor the reuse of movement plans. This outcome contradicts current models of motor control which assume physical cost minimization.

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# CHAPTER 1

## INTRODUCTION

### *Overview*

Many models of human reaching propose that movements are planned by minimizing movement costs. A common assumption of these models is that movements are planned anew each time one is desired. In this thesis I will suggest that movement planning instead relies on the reuse and modification of previous movement plans. One prediction that follows from this proposal is that the ability to minimize movement costs may be limited by the perceptual-motor system's ability to modify the reused plan. The results from five experiments in which participants performed reaching movements in the presence of or in the absence of an intervening obstacle support this prediction. When both movement types were required within a block, direct movements were more curved when preceded by obstacle–avoiding movements than by other direct movements. Thus, the cost of performing a direct movement was not fully minimized when its path differed significantly from the previous trial's path. In addition, obstacle-avoiding movements were *less* curved when preceded by direct movements than by other obstacle-avoiding movements. This second finding provides additional evidence for the reuse of previous movement plans. In general, the sequential effects suggested that the perceptual–motor system reused a relatively high–level hand path representation that could be translated to other regions of space. Further experiments showed that the observed sequential effects were not anticipatory in nature, that they persisted for many trials, and that they were reduced when the time between movements was increased or when participants were instructed to move as straight as possible when no obstacle appeared. Collectively, the results show that physical movement costs may not always be minimized if computational demands favor the reuse of movement plans. This outcome contradicts current models of motor control which assume physical cost minimization.

Before turning to the experiments, I will review the reaching models that rely on cost minimization. This review will include models for planning both direct and obstacle-avoiding movements. Next, I will discuss criticisms of the cost minimization approach and present a previously-published model that addresses these criticisms. Finally, I will give an overview of the thesis' experiments and present hypotheses that extend previous models of reaching to include the reuse of previous movement paths.

*Movement Planning Based on Cost Minimization*

One of the core problems in the study of movement planning is understanding the process by which intentions are translated into overt actions. Understanding this process is made difficult by the one–to–many relationship that often exists between behavioral goals and possible movements to achieve them. Over the last 20 years, a prominent approach to this so-called degrees-of-freedom problem (Bernstein, 1967) has been to propose that movement selection entails minimizing costs defined with respect to one or more criteria. A brief review of the major models of cost minimization is presented below. The purpose of this review is to emphasize the importance of cost minimization to the field of motor control and to inform a critique of the general approach presented later in the introduction. Therefore, rather than providing an in–depth description of each model, I will simply illustrate the variety of costs that have been proposed and follow this summary with a discussion of potential problems with the cost minimization approach as a whole.

One of the earliest models of cost minimization was the minimum jerk model of Flash and Hogan (1985). This model proposed that the perceptual–motor system selects a movement trajectory by minimizing the mean squared jerk (third time derivative of position) of the hand’s trajectory over the duration of the movement. Such a constraint leads to straight hand paths in external space and symmetric, bell–shaped tangential velocity profiles of the hand. These qualities have been shown, to a first approximation, to describe manual pointing movements (Abend, Bizzi, & Morasso, 1982; Atkeson & Hollerbach, 1985; Flash & Hogan, 1985; Georgopoulos, Kalaska, & Massey, 1981; Hogan, 1984; Morasso, 1981).

Another example of cost minimization is the minimum torque change model of Uno, Kawato, and Suzuki (1989). This model changes the focus of where in the motor system constraints are satisfied, from extrinsic coordinates (e.g., minimizing the jerk of the hand path in space) to intrinsic coordinates – in this case, minimizing the change in muscle torque. By doing so, the model of Uno et al. could account for more qualities of movements than the minimum jerk model, such as non–symmetric tangential velocity profiles (Elliot, Helsen, & Chua, 2001) and systematic deviations from straight hand paths (Van Thiel, Meulenbroek, & Hulstijn, 1998).

Other cost minimization models focus on the energy required to complete a movement. Examples of these models include the minimum work model of Soechting, Buneo, Herrmann, and Flanders (1995) and the minimum metabolic energy expenditure model of Kashima and Isurugi (1997). The value of minimizing a movement's metabolic energy expenditure has intuitive appeal from an evolutionary standpoint, and has been proposed in other models of non–reaching movements such as walking (e.g. Hatze, 1976).

Not all cost minimization concerns the cost of *completing* a movement. For example, Harris and Wolpert (1998) claimed that the perceptual–motor system attempts to minimize the behavioral consequences of noise in the efferent signal sent to the limbs. Harris and Wolpert proposed that the perceptual–motor system can take this noise into account during planning by selecting a time course of motor commands that minimizes the variability of the trajectory's endpoint.

A common property of the models described above is that they have mainly been applied to direct point-to-point movements. Studying these relatively simple movements is understandable in view of the fact that scientists generally start with simple systems before tackling more complex ones. Nevertheless, a complete understanding of movement planning should include how more complex movements are planned. One type of complex movement is the circuitous trajectory needed to avoid an obstacle. Owing to their increased path lengths, obstacle–avoiding movements are almost always more biomechanically costly than direct movements. Although obstacle avoiding movements are common in everyday life, they have received surprisingly little attention in the study of movement planning. I will summarize the limited research pertaining to reaching around obstacles, including two cost minimization models that can produce movements around obstacles.

At a broad, descriptive level, one can characterize the problem of obstacle avoidance as the need to avoid making a movement through a part of the environment where an unwanted collision would occur. Such a description is congenial to a dynamical systems approach to motor control. For example, Fajen and Warren (2003) showed that walking around an obstacle can be modeled as a movement between a current position and an attractor (the desired end position) while avoiding a repellor (the obstacle), each specified in extrinsic coordinates. Early behavioral work on reaching around obstacles supported this dynamical systems approach by showing that obstacles are commonly given a consistent clearance in extrinsic space across a variety of movement tasks (Dean & Bruwer, 1994, 1997).

Later work by Sabes and Jordan (1997, 1998) showed that planning obstacle–avoiding movements in extrinsic space is not sufficient to account for some properties of reaching behavior. In these studies, participants made reaching movements between two targets in the presence of an obstacle. Across blocks, the orientation of the targets and the obstacle varied, although the spatial relationship between the targets and the obstacle remained fixed. If the obstacle was only represented as a repellor in extrinsic space, similar movement paths for all orientations would be predicted because the same obstacle would be represented by the same repellor for all movements. Reliable effects of movement orientation were found, however. Using a simulation of the arm's inertial properties, Sabes and Jordan showed that the observed hand paths minimized the effect of possible perturbations when the arm came closest to the obstacle.

The results of Sabes and Jordan (1997, 1998) showed that reaching around obstacles requires consideration of the inertial properties of the arm. Another dynamical systems model of obstacle avoidance (Haugsjaa, Souccar, Connolly, & Grupen, 1998) could potentially consider these properties because the model represents the body's position in intrinsic coordinates (e.g., a coordinate frame whose axes are joint angles) rather than in extrinsic coordinates (as used by Fajen and Warren, 2003, albeit in connection with whole-body locomotion rather than movement of a single limb). There are two limitations of the Haugsjaa et al. (1998) model, however. The first is that, before moving, all possible body positions that could result in an obstacle collision need to be calculated. This process is computationally very complex for a system with many joints. A second limitation is that although the model *could* provide an account of the Sabes and Jordan findings, its predictions have not been compared to any human reaching performance. Thus, one may question its usefulness in understanding human reaching.

A second cost minimization model of obstacle avoidance whose predictions have been compared to human reaching performance comes from Hamilton and Wolpert (2002). Hamilton and Wolpert criticized Sabes and Jordan's minimum perturbation model because it, in its reported format, could not predict movement paths. The Hamilton and Wolpert model, an extension of Harris and Wolpert's (1998) model mentioned above, took up this challenge. In the Hamilton and Wolpert model, movement paths around obstacles are planned subject to three constraints: (1) the hand passes smoothly through three via points while (2) keeping the probability of a collision below a fixed limit (3) such that end point variance is minimized. The idea that the hand must pass through spatially defined via points has also been suggested by Abend, Bizzi, and Morasso (1982), Bullock, Bongers, Lankhorst, and Beek (1999), and Wada and Kawato (2004). Invoking these planning criteria, Hamilton and Wolpert (2002) could account for the orientation–

dependent variations in hand paths that were observed by Sabes and Jordan (1997). The model's second constraint could also be used to account for one property of real life obstacle avoidance that the Sabes and Jordan model could not account for, namely, the consequence of an obstacle collision is not the same for all obstacles. Obstacle avoiding movements are sometimes imperative (e.g., avoiding a collision with a rotating saw blade) whereas sometimes they are merely preferred (e.g., avoiding a collision with a branch on a walking trail). By being able to vary the probability of obstacle collisions, the Hamilton and Wolpert model can account for this consideration.

*Limitations of the Cost Minimization Approach*

The preceding review shows that cost minimization has been a common approach to solving the degrees-of-freedom problem. The ability of these models to account for a wide variety of reaching behaviors attests to their usefulness. As valuable as this approach has been, however, at least three criticisms can be raised against it. First, studies comparing models have reported little consensus on which cost is the one that is minimized (Hermens & Gielen, 2004; Kashima & Isurugi, 1997; Klein Breteler, Meulenbroek, & Gielen, 2002; Miyamoto, Nakano, Wolpert, & Kawato, 2004; Uno et al., 1989; Vetter, Flash, & Wolpert, 2002). This lack of consensus has led some to suggest that movement planning may instead entail minimizing *multiple* costs (Desmurget, Pelisson, Rossetti, & Prablanc, 1998; Kawato, 1996; Klein Breteler et al., 2002; Vetter et al., 2002; Rosenbaum, Meulenbroek, Vaughan, & Jansen, 2001). The multiple cost approach has intuitive appeal given the variety of possible movement tasks that can be accomplished. A remaining challenge for future research is the development of a model that can predict, *a priori*, which particular costs are contained in what situations, as well as how these costs are simultaneously considered (Desmurget et al., 1998).

A second criticism of the cost minimization approach is that it can be so computationally complex as to stretch credulity. For example, the planning of a single obstacle-avoiding movement took the Hamilton and Wolpert (2002) model, on average, 1,070 cycles of simulated annealing. Similarly, minimization of torque change (Uno, Kawato, & Suzuki, 1989) has no known solution for large numbers of muscles. Computational complexity is problematic because the perceptual-motor system can initiate movements quickly (within a few hundred milliseconds) in most circumstances. It is therefore questionable whether planning based on overly complex computations could be performed in such a short amount of time.

A third criticism of the cost minimization approach is that these models assume that movements are planned anew each time one is desired. This proposal ignores the increased planning efficiency that could come from reuse and modification of a previous plan. I will return to evidence for the reuse of previous plans later in the introduction, after reviewing one model that addresses the three criticisms of the cost minimization approach.

*Posture–Based Motion Planning Model*

The posture–based (PB) motion planning model was designed as a possible alternative to the cost minimization approach. For a complete discussion of the most recent version of the model, see Rosenbaum et al. (2001) or Jax, Rosenbaum, Vaughan, and Meulenbroek (2003). According to the model, movements are planned by selecting a desired end posture (the set of joint angles at the end of a movement) using a two–step process of recall of stored arm postures and generation of novel postures around those stored postures. Once the final posture is determined, a movement trajectory to it is computed using interpolation in joint space.

Movements to possible end postures are evaluated for their suitability with reference to what Rosenbaum et al. (2001) called a *constraint hierarchy*. A constraint hierarchy is a prioritized list of requirements that the actor wishes to satisfy. The most important constraint occupies the highest level, the second most important constraint occupies the second highest level, and so on. Movements to end postures that do not satisfy the most important constraint are ruled out first, movements that do not satisfy the second most important constraint are ruled out second, and so on. The process continues until only one possible end posture is left or until the lowest level is accessed. This procedure amounts to a "weeding out" process, or what Tversky (1972) called *elimination by aspects*. Unlike the cost minimization models described above, the constraint hierarchy does not ensure that an optimal solution is found. Instead, it looks for a solution that is merely acceptable. This approach, which Simon (1955) called *satisficing*, is computationally less expensive than optimizing (Simon, 1989).

The PB model can also produce movements around obstacles. If a movement to a desired end posture would result in a collision, the model plans a second, back–and–forth, movement to an intermediate "bounce" posture. When this second movement is executed at the same time as the movement to the end posture, a curved path is produced around the obstacle. The process of selecting a bounce posture also relies on recall of stored arm postures and generation of novel postures around those stored postures. The evaluation of potential bounce postures is also completed using the same constraint hierarchy as used to evaluate possible end postures.

Using the planning mechanisms described above, the PB model can address the three criticisms of the cost minimization approach. The model addresses the first criticism (that there is little consensus for one cost over the others) by using a flexible constraint hierarchy. Therefore, any of the previously-proposed costs could potentially be used within the constraint hierarchy. Admittedly, this flexibility leaves the question of which costs are considered for a given task unanswered. However, by proposing that constraints are satisfied in a given order, the constraint hierarchy provides an approach to the previously described problem of how multiple costs can be simultaneously considered.

The model addresses the second criticism (that minimization is computationally complex) in two ways. First, computational complexity is reduced by satisficing rather than by optimizing. Second, planning requirements are reduced because planning begins with a search through recently adopted stored postures rather than starting anew. Such reliance on recently planned movements is intuitively appealing and has been supported in studies of brain activity. Movement-related cortical potentials (EEG potentials that precede voluntary movements) recorded during a sequence of joystick and button press movements are lower for sequences of repeated movements than for sequences of randomly changing movements (Dirnberger, Fickel, Lindinger, Lang, & Jahanshahi, 1998; Praamstra, Stegeman, Horstink, Brunia, & Cools, 1995; Touge, Werbahn, Rothwell, Marsden, 1995). Later work has suggested that this decrease in potentials cannot be attributed to memory or attentional differences between the two sequence types (Dirnberger et al., 2000). Further evidence using neuro-imaging has verified that this decrease in cortical activity can be localized to brain regions associated with motor planning in particular (Dassonville et al., 1998; Deiber et al., 1991; Playford et al., 1992).

In addition to reducing computational complexity, by beginning planning with a search through recently adopted stored postures rather than starting anew, the PB model can addresses the third criticism of the cost minimization approach (that movements are always planned from scratch). Relevant results from several studies that suggest movements are not planned anew will be summarized below, but it is useful to mention first that the concept of successive changes to a single plan occupying working memory has an obvious computational attraction: Changing just those features that distinguish the plan that is needed next from the plan that has just been used may be more efficient than generating a new plan *de novo*. An analogy to computer programs is irresistible: Computer programs owe their power to the fact that small changes can be made to them to allow for comparable, but wide-ranging computations. Plans for action may have the same characteristic.

*Evidence for the Reuse of Previous Movement Plans*

What previous studies have supported the plan–reuse view? One of the first was a study by Rosenbaum (1980), which used precuing of the amplitude, direction, and hand of to-be-performed aiming movements. Such precues led to reductions in movement initiation times. By analyzing the precue effects, Rosenbaum found that different types of information could be specified in advance of movement–plan completion, regardless of which type of information was precued. Rosenbaum suggested that this outcome argued against the view that plans must be specified in a fixed order (e.g., arm before direction before extent). Instead, he suggested that individual features of motor plans can be swapped in and out depending on which ones need to be changed – a plan-reuse method of motor programming.

A second source of evidence that movement plans are modified as needed rather than being generated anew concerns sequential effects in manual prehension. Cohen and Rosenbaum (2004) studied where participants took hold of a vertical cylinder to move it to a new position at a different height. As predicted by the end–state comfort effect (Rosenbaum et al. 1990, 1992, 1993, 1996), grasp heights along the cylinder were inversely related to the height of the target position. Analysis of grasp heights for movements back to the original position showed a weakening of the end-state comfort effect such that participants took hold of the cylinder close to where they had just held it, apparently recalling the last grasp position.

The preceding two examples show how reuse of a previous plan can be advantageous. In other situations, such reuse may be detrimental. For example, slowing of performance when the same motor act must be performed in different ways on successive occasions has been shown for speech, finger tapping, and violin bowing movements (Rosenbaum, Weber, Hazelett, & Hindorff, 1986). In one example of this *parameter remapping effect*, participants repeated the first $n$ letters of the alphabet as quickly as possible, alternating between stressed and unstressed syllables. The number of letters participants could recite in 10 seconds was larger when $n$ was even (e.g., AbCdAbCd... for $n = 4$, where capital letters denote stressed letters and lower–case letters denote unstressed letters) than when $n$ was odd (e.g., AbCaBc... for $n = 3$). Rosenbaum et al. explained this finding by proposing that participants produced each letter by accessing a memory trace from its last production. If the stress level from the last production was appropriate for the next production, the trace would be executed. However, if the stress of previous use was not appropriate for the next production, adjusting the letter's stress level required extra processing time, thereby reducing the number of letters that could be recited. Thus, by reusing the previous utterance's trace in the odd–*n* condition, performance suffered.

The three studies cited above show that the reuse and modification of a previous plan can be either advantageous or detrimental to performance. The effect of plan reuse on performance likely depends on what parts of the previous plan are reused and how effective these parts are for completing the required task. For example, past research has shown that movement initiation times are reduced with repeated movements to the same spatial location (Requin, Brener, & Ring, 1991; Fischer, Rosenbaum, & Vaughan, 1997; Sparrow & Newell, 1998). By beginning the planning process with a search through recently adopted stored postures, the PB model can account for this finding. Repeated movements to the same, or similar, end posture is one of two instances where the PB model's reuse of end postures would predict an improvement in performance. The second instance occurs for repeated reaches around an obstacles in which the same bounce posture could be used. One commonality between these two predicted improvements in performance is that they can not be generalized to other regions of the workspace.[1]

For other movement tasks, such as making repeated movements around obstacles to different target locations, the reuse of a previous end posture would be less useful in improving performance. In this task, reusing the previous movement's hand path would be more useful, especially if this hand path could be translated to other regions of the workspace. In its strongest form, the PB model does not predict this type of reuse, which is not to say that the authors of the PB model deny the possibility of this occurring. For example, in the final two sentence of Rosenbaum et al. (2001), the authors state that "...identifying different ways of moving to a goal posture might rely on retrieval of stored movements or on generating movements d*e novo* using joint interpolation. The model we have developed does not resolve this issue but may help stimulate future research on it" (p. 731). In fact, the PB model has previously used stored spatial forms as the primary means of planning handwriting movements (Meulenbroek, Rosenbaum, Thomassen, Loukopoulos, & Vaughan, 1996).

To my knowledge, no research exists on the reuse and modification of complex hand paths to simplify planning. The aim of the five experiments reported here was to test whether planning of a desired movement relies on the reuse and modification of a previous hand path (herewith referred to as the *hand-path reuse hypothesis*). To anticipate the main result, such reuse is pronounced and indicates that computational efficiency may dominate over biomechanical efficiency.

*Overview of The Experimental Approach and Predictions*

All experiments used a procedure in which the hand moved from a central starting circle to each of a number of peripheral target circles equidistant from the center circle and then, following a brief delay, back to the center circle (see Figure 1). Between trials I varied whether or not an obstacle sat midway between the center circle and the peripheral target. To test the hand-path reuse hypothesis, I examined hand paths on trials in which trial-type switches occurred and compared these paths to those in which no trial-type switch had occurred. I focused on trial-type switches because hand paths in the two trial types were predicted to be observably different. These differences were predicted to result in more evident after-effects of the previous hand path[2].

The hand-path reuse hypothesis makes two predictions about performance on the outward movements of trial-type switches. If the hand-path reuse hypothesis is correct, direct movements preceded by obstacle-avoiding movements would be predicted to be *more* curved than if preceded by direct movements. Similarly, obstacle–avoiding movements preceded by direct movements would be predicated to be *less* curved than if preceded by obstacle-avoiding movements. Neither of these claims are predicted by current models of direct or obstacle avoiding movements (including the PB model) because all assume that the cost of making a direct movement, or the obstacle clearance on an obstacle-avoiding movement, should depend only on the immediate task demands.

The hand-path reuse hypothesis also predicts that movement properties of outward and return movements should be correlated. If the planning of a trial's return movement is based on the path used for the trial's outward movement, the after-effects of the previous trial on the outward movement would be predicted to affect, to a lesser degree, the return movement as well. For example, an outward movement with no intervening obstacle preceded by an obstacle-present trial would be predicted to be more curved than if preceded by an obstacle-absent trial. If the return movement is planned by reusing and modifying the curved outward movement path, the hand-path reuse hypothesis predicts that the return movement path should also be slightly curved.

If the previous movement's hand path is reused and modified, a second question concerns how much previous experience could influence a to-be-completed movement.

One possibility is that only the previously planned movement is reused. This model predicts that curvature on obstacle–absent trials should only be affected by the presence or absence of an obstacle on the immediately preceding trial. Previous research in other domains has shown, however, that performance can often be influenced by more than just the previous trial (Kirby, 1976; Remington, 1968; Soetens et al., 1985; Thoroughman & Shadmehr, 2000; Witney, Vetter, & Wolpert, 2001). Thus, it is also conceivable here that repeated movements with the same general path (e.g., many repeated obstacle-avoiding movements) may strengthen the path's representation in memory and therefore be more difficult to modify later. A prediction that follows from this hypothesis is that direct movements preceded by multiple obstacle-present trials would be more curved than if preceded by a single obstacle-present trial.

Finally, if previous hand paths are reused and modified, a third question concerns if and by how much a previously planned hand path might generalize to other areas of the workspace. To answer this question, I varied the sequence of peripheral targets quasi–randomly so that the angular separations between targets in successive trials ranged from 30 to 180 degrees in 30 degree steps. The zero-degree case (i.e., exact repetition of a target) was not used so participants would always have to do some planning. Different models of generalization predict different effects of angular separation on hand path curvature. The most limited model predicts no generalization. This model predicts that evidence for hand path reuse should be limited to repeated movements in the same area of workspace (i.e., only low angular separations). By contrast, the most general model predicts unlimited generalization across the workspace. This model predicts that evidence for hand path reuse should be equal for all angular separation values. Intermediate models predict graded generalization patterns. The most obvious model of this sort predicts diminishing generalization as the angular separation increases.

To conclude, the five experiments presented in this thesis were designed to answer three questions about the possible reuse and modification of previous movement paths: (1) Is there evidence that previous movement paths are reused in movement planning? (2) If reuse does occur, does repeated execution of a similar hand path (e.g., many repeated obstacle-avoiding movements) strengthen the reused path's representation in memory? (3) In addition, if reuse does occur, to what extent does the previous movement path generalize to other parts of the workspace?

# CHAPTER 2

## EXPERIMENT 1

### Method

*Participants*

Fifty–one right handed Penn State undergraduates participated in exchange for course credit. All participants were treated in accordance with the Institutional Review Board's approval of this and the other studies described here.

*Materials, Design, and Procedure*

The participant sat at a table in front of a TV set and made arm movements that caused a stick–figure corresponding to the arm to move on the TV screen (see Figure 1). There was no perceptible delay between the participant's movements and the visual feedback, which was comparable to the cursor feedback from a computer mouse. The stick–figure moved as the subject did, to and from targets and around obstacles that were also displayed on the TV screen. The reason for using virtual targets and obstacles was to control the timing of the appearance of the targets and obstacles more precisely, inconspicuously, and safely than would have been possible with physical objects. Finally, a stick-figure representation of the whole arm, and not just the hand, was used so that the obstacle would need to be avoided with the entire arm, as is needed in real-life obstacle avoidance.

Before the experiment began, infrared light–emitting diodes (IREDs) were attached to the participant's left and right shoulders, right elbow, right wrist, and the top of a vertically oriented wooden dowel (3 cm in diameter, 9 cm high) which was mounted on a round base (15 cm in diameter, 0.75 cm thick) whose underside was covered with felt to allow the manipulandum to slide with very little friction over the smooth table top on which the participant rested his or her right forearm. Participants wore a spandex–lycra "surfer" shirt to which the IREDs were attached. This shirt allowed the IRED positions to faithfully reflect the anatomical landmarks beneath them while also permitting free movement. The IRED locations were recorded by an OPTOTRAK 3020 motion tracking system (Northern Digital, Inc.) sampling at 100 Hz. The x–y IRED positions from the OPTOTRAK were input to a program used to display the instantaneous position of the arm, along with relevant targets and obstacles, on the TV monitor viewed by the subject.

At the beginning of each block of trials, a circle (2.4 cm diameter) appeared at the center of the TV monitor. The participant moved his or her "hand" (i.e., the stick figure's end–effector dot) into this circle, whereupon its color changed from blue to green. After the end–effector dot stayed within the start circle for 250 ms, one of 12 peripheral target circles appeared, at which time the participant was supposed to move the hand as quickly and accurately as possible into the target circle. When the end–effector dot entered the target circle, the target turned from blue (its original color) to green. After the end–effector dot stayed in the target for 250 ms, the target circle disappeared, signaling the participant to move as quickly and accurately as possible back to the start circle. The participant kept the end–effector dot in the start circle for another 250 ms, at which time the next target circle was presented, and so on.

The peripheral target circles were all 2.4 cm in diameter, their centers were all 16 cm from the center of the start circle, and they were spaced around the center circle at 30º intervals. The angular positions of the targets were rotated 15º counterclockwise from the cardinal directions (zero degrees being the straight–ahead angle) to allow all targets to be reached in the obstacle condition.

Within each block of trials, each target position was presented equally often in an order that was random except for the constraint that the same target location not appear in successive trials. Exact target replications were not used so participants would always have to do some planning. Each participant performed 10 blocks of 48 trials each. The first 2 blocks were considered practice and were not analyzed.

There were three groups of 17 participants, distinguished by the frequency with which obstacles appeared between the start and target circles. For the participants in one group the obstacle *always* appeared, for a second group the obstacle *sometimes* appeared (with probability .5), and for a third group the obstacle *never* appeared. Four trial types were possible: (1) Trials in which an obstacle appeared in the context of obstacles always appearing (herewith A trials); (2) Trials in which an obstacle appeared when obstacles would only sometimes randomly appear (herewith + trials); (3) Trials in which an obstacle did not appear though obstacles would sometimes randomly appear (herewith – trials); and (4) Trials in which an obstacle did not appear in the context of obstacles *never* appearing (herewith N trials). The symboled trials (+ and -) were the trials of primary interest and the lettered trials (A and N) were the comparison, or control, trials.

Whenever an obstacle appeared, it sat midway between the start and target circles. Each obstacle was a filled red circle whose size was the same as the start and target circles. The obstacle was presented at the same time as the target circle and remained on the screen during outward movements from the start to the target circles as well as during the subsequent return movements from the target circles to the start circle. Participants were instructed to avoid hitting the obstacle with any portion of the stick-figure arm, which turned red when an obstacle collision occurred.

To encourage participants to move quickly and also to discourage obstacle collisions, I showed participants a score, $S = T(1 + C)$, at the end of each block, where $T$ was the total time (in ms) to complete the block and $C$ was the number of collisions. Participants were urged to strive for ever-lower end-of-block scores.

## Results and Discussion

Onsets and offsets of individual movements were identified using a 30 mm/s hand velocity criterion. Trials in which any of the IREDs was not in view of the OPTOTRAK (approximately 3% of trials) were removed from analysis, as were trials in which an obstacle collision occurred (approximately 1.5% of trials). The frequency of collisions was approximately the same across conditions.

The primary movement property examined in this thesis will be hand path curvature. To quantify hand path curvature, I calculated two measures for each path: the initial angular offset and the curvature index (CI). Initial angular offset measured how indirectly the initial portion of the hand path was relative to the direct path to the target. Initial angular offset was defined as the absolute value of the angle between the line connecting the hand location at the start and end of the movement and the line connecting the hand location at the start of the movement and 150 ms after movement initiation. The motivation for analyzing initial angular offset 150 ms after movement initiation was that the portion of the movement before this point represented the perceptual-motor system's preplanned movement before online movement correction was possible (Elliot et al., 2001). The second measure, CI, was defined as the maximum perpendicular distance of the path from a straight line connecting the start and end positions, divided by the distance between the start and end positions, multiplied by 100.[3] These two measures were moderately correlated ($r = .467$ for all movements in Experiment 1, $p < .001$). The reason for these two measures being only moderately correlated may have been due to online movement corrections, as discussed below.

Figures for all analyses of Experiment 1 have been combined with the analyses of Experiment 3 to reduce the total number of figures and to allow for easier comparison between experiments. For all figures referenced in the following sections, data from Experiment 1 are labeled as A, N, and the .5 values of the + and – conditions.

Due to the number of analyses discussed below, I will provide an overview of the to-be-presented results. First, I will examine the effect of previous trial type on outward (start to target) movements. This presentation will include example hand paths and analyses of both initial angular offset and CI. Second, I will compare similarities in hand paths between the outward and return movements. Third, I will examine the effects of movements that preceded those in the previous trial. Fourth, I will examine how the effects of previous trial type depended on the angular separation between targets in successive trials. Finally, I will examine the time it took to initiate movements.

The ordering of analyses map onto the three questions at the end of the introduction. The first question will be answered using the first and second sets of analyses, the second question will be answered using the third set of analyses, and the third question will be answered with the fourth set of analyses. The analysis of initiation times will suggest an alternative explanation for the findings and provide motivation for the second experiment.

*Example Hand Paths*

Examples of hand paths for outward movements are shown in Figure 2. All the movements shown here are to the same target. The upper row of panels shows, from left to right, hand paths in A trials and + trials preceded by an obstacle-present (+ + trials) or an obstacle-absent (– + trials) trial. All of these movements were curved, as needed to avoid obstacle collisions. Although movements in these conditions appear similar, close examination shows that movements in the two + conditions were initially directed more towards the target than movements in the A condition. Analyses presented below will confirm this difference. The lower row of panels shows hand paths for obstacle–absent trials. The right panel shows hand paths for the N condition. As expected from previous research (Morasso, 1981), the hand paths were relatively straight. The middle and right panels show hand paths for – trials preceded by an obstacle–present (+ – condition) and an obstacle–absent (– – condition) trial, respectively. Here the unnecessarily curved hand paths were clearly influenced by being intermixed with obstacle-present trials. Hand paths in both conditions were more curved than those in the N condition, and paths from trials preceded by obstacle-present trials showed greater curvature than paths from trials preceded by other obstacle-absent trials.

*Hand Path Curvature for Outward Movements*

The mean values of initial angular offset for outward movements appear in Figure 3. Overall, obstacle-present trials (A and + conditions) had higher initial angular offsets than obstacle-absent trials (N and – conditions). Both trial types showed after-effects from the previous trial. That is, both movement types had higher initial angular offsets when preceded by a + trial than when preceded by a – trial. Finally, previous movements appeared to influence hand path curvature beyond the previous trial. For example, – trials preceded by another – trial were still *more* curved than the N condition. Similarly, + trials preceded by another + trial were still *less* curved than the A condition. Thus, paths did not return to control-like performance after two repetitions of the same trial type. I will return to the effects of more than just the previous trial later. Overall, these results support the hand-path reuse hypothesis because the initial angular offsets of movements were clearly affected by the previous trial types in the direction predicted by the hypothesis.

The mean CI values for outward movements appear in Figure 4. The results for both measures were similar in the – conditions but not the + conditions. In the – conditions, movements preceded by a + trial had higher CIs than movements preceded by a – trial, both of which had higher CIs than the N condition. This result, as described in the previous section, is predicted by the hand-path reuse hypothesis.

A different pattern of CI values was observed in the + conditions. First, previous trial type did not affect CI values in the + conditions. Second, no differences were observed between CIs in the A and + conditions. That no effect of previous trial type was observed for + trials using the CI measure is surprising given that a reliable effect of previous trial type *was* observed for the initial angular offset measure. The different results observed for the two measures may have been caused by the + movements requiring a minimum total curvature to allow participants sufficient clearance of the obstacle. For example, movements on + trials may have been planned to be initially less curved when preceded by a – trial than when preceded by a + trial. (The lower initial angular offsets in the – + trials relative to the + + trials support this claim.) The curvature of – + movements might have been increased during movement execution to allow for sufficient obstacle clearance. If this adjustment occurred, it would mask the effect of reusing the previous trial's hand path. Quick and smooth online adjustments of hand paths are commonly observed, such as when a target location is shifted at movement onset (Goodale, Pelisson, & Prablanc, 1986). Therefore, if one assumes that a minimum clearance is given to obstacles, the results of the CI analyses need not be inconsistent with the hand-path reuse hypothesis.

The initial angular offset measure was evaluated with a 2 (trial type: + or -) × 2 (previous trial type: + or -) ANOVA, which showed a main effect of trial type, $F(1, 16) = 116.62$, $p < .001$, a main effect of previous trial type, $F(1, 16) = 75.89$, $p < .001$, and no interaction between these two factors, $F(1, 16) < 1$, *ns*. The final statistical tests compared trials in the mixed-trial blocks with their respective blocked-trial control conditions. Both + conditions had lower initial angular offsets than the A condition. Likewise, both – conditions had higher initial angular offsets than the N condition ($p < .05$ for all four comparisons using an independent sample t-tests with Bonferroni correction for multiple comparison with an overall a of .05; this same method of comparing mixed and blocked trials will be used throughout the thesis).

The CI measure was evaluated with the same ANOVA, which showed a main effect of trial type, $F(1, 16) = 464.32$, $p < .001$, a main effect of previous trial type, $F(1, 16) = 46.18$, $p < .001$, and a significant interaction between the two factors, $F(1, 16) = 40.29$, $p < .001$. In the interaction, there was a significant effect of previous trial type on – trials but not + trials. That is, – – trials had lower CI values than + – trials, but CI values on – + and + + trials did not differ. The final statistical tests compared trials in the mixed-trial blocks with their respective blocked-trial control conditions. Both + conditions had CI values that were not reliably different from CI values in the A condition ($p > .5$). However, both – conditions had higher CI values than those in the N condition ($p < .05$, Bonferroni corrected).

*Practice Effects*

If reuse and modification of a previous plan is customarily part of the movement planning process, the evidence for reuse should not be subject to significant effects of practice. Overall, this prediction was supported. The correlations between the curvature measures and block number were mostly unreliable in the two trial-type switch conditions (the conditions that showed the strongest evidence of reuse in the previous analyses). In the + – condition, the correlation between initial angular offset and block number was .04 ($p = .10$) and the correlation between CI and block number was -.004 ($p = .86$). In the – + condition, the correlation between initial angular offset and block number was .008 ($p = .76$) and the correlation between CI and block number was -.17 ($p$

< .001). This final weak correlation was the only reliable evidence for practice effects. One may speculate that the latter result may have been caused by participants learning to give less clearance to the obstacle with practice. Support for this explanation comes from the correlation between CI and block number for the A condition, which was -.11 ($p < .001$). Overall, though, the evidence for plan reuse was robust over the levels of practice sampled in this experiment.

*Hand Path Curvature for Return Movements*

As discussed in the introduction, the hand-path reuse hypothesis predicts that hand path curvature on outward and return movements should be positively correlated. As reported above, hand paths for outward movements of + – trials were more curved (as measured by both initial angular offset and CI) than hand paths on – – trials, both of which were more curved than hand paths on N trials. Similarly, hand paths for outward movements on – + trials were less curved (as measured by only initial angular offset) than hand paths on + + trials, which were both less curved than hand paths on A trials. If the return movements were planned by reusing and modifying the previous trial's hand path, a similar pattern of curvature should be observed for the return movements. The following analyses will show that the pattern of curvature results were similar for the outward and return movements, thereby supporting the hand-path reuse hypothesis.

I will begin the discussion of return movements by presenting the same analyses as were presented for the outward movements. These analyses will examine how similar the pattern of results between outward and return movements were *on average*. I will follow these analyses with a more fine-grained, movement-by-movement, analysis of the correlations between outward and return movements.

Initial angular offsets of the return movements are shown in Figure 5. The pattern of results for the outward and return movements were well correlated, as would be expected if the return movements were planned by reusing and modifying the previous trial's hand path. The effect of previous trial type was similar for both outward and return movements of – trials, with both being more initially curved if the previous trial had been a + trial than a – trial. No effect of previous trial type was found for + trials, however. As previously discussed, this null effect may have resulted from the need to maintain a minimum obstacle clearance on these trials. This explanation had previously been used for the CI measure, but may have applied to the initial angular offset measure when participants knew in advance whether an obstacle-avoiding movement would be required (as was the case for the return movements). Similar results were observed for CIs of the return movements, as shown in Figure 6. The one difference between the two measures is that CIs in both + conditions were not different from the A condition, a difference that was reliable for the initial angular offset measure. Overall, though, the similarities between the outward and return movements were consistent with the hand-path reuse hypothesis.

As a further test of the hand-path reuse hypothesis, I performed an analysis of the movement-by-movement correlations between curvature on outward and return movements. This analysis was needed to verify that the observed similarities between the outward and return movements at an average level held up at a more fine grained level. Again, this comparison tested the hypothesis that if the hand-path reuse hypothesis is correct, hand path curvature on outward and return movements should be positively correlated. Correlations were performed separately for the – and + conditions because of the sizable differences in the mean curvature of the two conditions. That is, outward and return movements of the – conditions in general had low curvature (because no obstacle was present) and outward and return movements of the + conditions in general had higher curvature (to avoid the obstacle). Correlations between the outward and return movements combining both trials types would lead to a spurious positive correlation, which was the prediction of the hand-path reuse hypothesis. To provide a stronger test of the hypothesis, I analyzed both trial types separately. For the – conditions, the correlations between outward and return movements were .42 for the initial angular offset measure and .55 for the CI measure ($p < .001$ for both). For the + conditions, the correlations between outward and return movement were .37 for the initial angular offset measure and .54 for the CI measure ($p < .001$ for both). These positive correlations support the hand-path reuse hypothesis because properties of successive movements were correlated with one another.

The mean initial angular offsets were evaluated with a 2 (trial type: + or -) × 2 (previous trial type: + or -) ANOVA, which showed a main effect of trial type, $F(1, 16) = 1222.20$, $p < .001$, a main effect of previous trial type, $F(1, 16) = 17.40$, $p < .001$, and an interaction between the two factors, $F(1, 16) = 6.86$, $p = .012$. In the interaction, there was a significant effect of previous trial type on – trials but not on + trials. The final statistical tests compared trials in the mixed-trial blocks with their respective blocked-trial control conditions. Both + conditions had lower initial angular offsets than the A condition ($p < .05$, Bonferroni corrected). Likewise, both – conditions had higher initial angular offsets than the N condition ($p < .05$, Bonferroni corrected).

The mean CI measures were evaluated with the same ANOVA used for the initial angular offset measure. This ANOVA showed a main effect of trial type, $F(1, 16) = 863.03$, $p < .001$, a main effect of previous trial type, $F(1, 16) = 24.01$, $p < .001$, and an interaction between the two factors, $F(1, 16) = 5.43$, $p = .023$. This interaction pattern was the same as observed for the initial angular offset measure. The final statistical tests compared trials in the mixed-trial blocks with their respective blocked-trial control conditions. Both – conditions had higher CIs than the N condition ($p < .05$, Bonferroni corrected). However, CIs in the + and A conditions did not differ ($p > .4$).

*Effect of Obstacle Recency for Outward Movements*

In the following analyses I examined whether repeated execution of a similar hand path (e.g., many repeated obstacle-avoiding movements) strengthened the reused path's representation in memory. I did so by analyzing the effects of trial-type repetitions on hand path curvature. The independent variable in these analyses was obstacle recency, or the number of preceding trials since an obstacle-present trial had occurred. Obstacle recency in Experiment 1 varied from -3 (trials preceded by 3 obstacle-absent trials) to 3 (trials preceded by 3 obstacle-present trials).

The effects of obstacle recency on initial angular offsets are shown in Figure 7. For both trial types, movements became less curved with fewer preceding + trials or a greater number of preceding – trials. With more trial-type repetitions, initial angular offsets for both trial types became more similar to, but still statistically different from, their corresponding blocked-trial control conditions. For example, initial angular offsets on – trials were never as low as those in the N condition, even when preceded by three other – trials. Similarly, initial angular offsets on + trials were never as high as those in A trials, even when preceded by three other + trials. Thus, initial angular offsets were influenced by at least three previous trials.

A similar, but slightly different, pattern of results was observed for the effects of obstacle recency on CI, as shown in Figure 8. Hand paths in the – condition, but not in the + condition, became less curved with fewer preceding obstacle-present trials or a greater number of preceding obstacle-absent trials. As previously discussed, the null effect of previous trials on + trials using the CI measure may have been due to a minimum clearance given to obstacles. The reliable effects of obstacle recency observed for the initial angular offsets but not CIs are consistent with this explanation. Overall, findings using both measures support the claim that repeated execution of a similar hand path strengthened the reused path's representation in memory, and that this strengthening could be influenced by at least three previous trials.

The effects of obstacle recency on initial angular offset were evaluated with two 2 (previous trial type: + or -) × 3 (obstacle recency) ANOVAs, performed separately for the – and + conditions. The second factor, obstacle recency, had three levels: most prior obstacle exposure (recency of 3 and –1), medium prior obstacle exposure (recency of 2 and –2), or least prior obstacle exposure (recency of 1 and –3). For movements in the + condition, there was a main effect of previous trial type, $F(1, 16) = 63.75$, $p < .001$, a main effect of obstacle recency, $F(2, 32) = 5.67$, $p = .008$, but no significant interaction between the two variables, $F(2, 32) < 1$, *ns*. The same pattern of results was observed for movements in the – condition: a main effect the previous trial type, $F(1, 16) = 76.72$, $p < .001$, a main effect prior obstacle recency, $F(2, 32) = 3.32$, $p = .049$, but no interaction between the two factors, $F(2, 32) < 1$, *ns*. The final statistical tests compared trials in the mixed-trial blocks with their respective blocked-trial control conditions. All + conditions had initial angular offset values that were lower than initial angular offset values in the A condition ($p < .05$, Bonferroni corrected). Likewise, all – conditions had higher initial angular offset values than those in the N condition ($p < .05$, Bonferroni corrected).

The effects of obstacle recency on CI were evaluated with the same ANOVAs as used for the initial angular offset measure. For movements in the – condition, there was a main effect of previous trial type, $F(1, 16) = 62.77$, $p < .001$, a main effect of obstacle recency, $F(2, 32) = 6.20$, $p = .005$, but no significant interaction between the two variables, $F(2, 32) = 2.40$, $p = .10$. Unlike the CI values on – trials, CI values on + trials were not affected by the previous trial type, $F(1, 16) = 3.02$, $p = .09$, nor by prior obstacle recency, $F(2, 32) < 1$, *ns*. The interaction between the two factors was not significant, $F(2, 32) < 1$, *ns*. The final statistical tests compared trials in the mixed-trial blocks with their respective blocked-trial control conditions. All + conditions had CI values that were not reliably different from CI values in the A condition ($p > .3$). However, all – conditions had higher CI values than those in the N condition ($p < .05$, Bonferroni corrected).

*Angular Separation Between Targets In Successive Trials*

To analyze how previously planned hand paths might generalize to other areas of the workspace, I studied how hand path curvature on trial-type switches varied as a function of angular separation between targets in successive trials. As discussed in the introduction, different models of generalization predict different effects of angular separation. The most limited model predicts no generalization across the workspace, the most general model predicts unlimited generalization, and intermediate models predict graded generalization.

The effect of angular separation on initial angular offsets is shown in Figure 9. I will focus on the conditions in which trial-type switches occurred (the – + and + – conditions). Overall, the previously planned hand paths did generalize to other areas of the workspace, but the generalization was greater for the – + condition than the + – condition. One reason for this difference may be that direct hand paths may have more readily generalized to other areas of the workspace than obstacle-avoiding hand paths because of the greater complexity of the obstacle-avoiding hand paths. Because of the differences in generalization, I will discuss the two conditions separately.

When obstacle-present trials were preceded by obstacle-absent trials (the – + condition), the effect of the previous – trial generalized equally to all regions of the workspace. Evidence for this conclusion came from the absence of an effect of angular separation on initial angular offset within the – + condition.

When obstacle-absent trials were preceded by obstacle-present trials (the + – condition), the effect of the previous + trial also generalized. However, the generalization did not apply equally to all regions of the workspace. Within the + – condition, initial angular offsets were greatest near 30º and 180º of angular separation and decreased for intermediate values of angular separation. This outcome probably was related to the fact that an 180º angular separation is just a direction reversal. When the angular separation between targets in successive trials was 180º, the return movement in the previous trial was in the same direction as the current movement. Because the obstacle remained present for the return movement, the most recent movement the participant made was an obstacle–avoiding movement in the same direction as the current trial. Therefore, the generalization of the reused obstacle-avoiding hand paths was greater when the subsequent direct movement's path neared the location of the previous trial's target location and when a movement's path was in the same direction as the preceding movement.

The effect of angular separation on CI was similar to the effect of angular separation on initial angular offset, as shown in Figure 10. The one exception was that, as previously described, no differences were observed in CI between the A and – + conditions. However, CIs within the + – condition were again greatest near 30º and 180º of angular separation and decreased for intermediate values of angular separation.

The effects of angular separation on initial angular offset were evaluated with a single factor ANOVA, which showed no reliable effect of angular separation on the – + condition, $F(5, 80) = .78$, *ns*. The same ANOVA for the + – condition showed a reliable effect of angular separation, which was best fit with a quadratic contrast, $F(1, 16) = 23.78$, $p < .001$.

The effects of angular separation on CI were evaluated using the same ANOVA. There was a reliable effect of angular separation for the – + condition, $F(5, 80) = 5.43$, $p = .02$. However, because this condition showed no generalization of previous trial type (i.e., it was not different from the A condition), this effect was not of interest. There was a reliable effect of angular separation for the + – condition, which was best fit with a quadratic contrast, $F(1, 16) = 29.42$, $p < .001$.

*Reaction Time*

If the hand-path reuse hypothesis is correct, the previous hand path should require greater modification on trial-type switches than on trial-type repetitions. Therefore, reaction times (RTs), defined as the time between target presentation and movement onset, should be longer on trial-type switches than on trial-type repetitions. A similar pattern of results has often been observed for the switching of mental tasks (Allport, Styles, & Hsieh, 1994; Rogers & Monsell, 1995). This predicted pattern was not observed, however, as shown in Figure 11. Instead, RTs seemed to be determined by the previous trial type, regardless of the current trial type. RTs were shorter (and not different from the A and N conditions) on trials preceded by + trial than on trials preceded by a – trial (which were slower than the A and N conditions). This interpretation of the reaction time findings will be discussed in more detail below in the Summary of Experiment 1 section.

The RT data were evaluated with a 2 (trial type: + or –) × 2 (previous trial type: + or –) ANOVA. The ANOVA yielded no main effect of trial type, $F(1, 16) < 1$, *ns*, a main effect of previous trial type, $F(1, 16) = 38.32$, $p < .001$, and no significant interaction between the two factors, $F(1, 16) < 1$, *ns*. Comparisons of the + and – trials with their respective blocked-trial control conditions showed no difference in RT for trials preceded by a + trial ($p > .6$), but reliably longer RTs for trials preceded by a – trial ($p < .05$, Bonferroni corrected).

*Correlations Between RT and Curvature*

The analyses of average RT showed that trial-type switches did not have higher RTs than trial-type repetitions. This finding was inconsistent with the hand-path reuse hypothesis. To further test the relationship between RT and influence of previous trial type, I performed a second set of analyses that looked at the correlation between RT and hand path curvature *within* each trial-type switch condition. The prediction for the within-trial-type analysis is that trials with longer RTs should show less effect of the previous trial than trials with shorter RTs because the perceptual-motor system had more time to adjust the previous movement path. As reported above, + – paths were more curved than N paths and – + paths were less curved than A paths. Therefore, the hand-path reuse hypothesis predicts that the relationship between RT and hand path curvature should be negative for + – trials (the more time taken, the straighter the path) and positive for – + trials (the more time taken, the more curved the path).

Overall, correlations between RT and hand path curvature supported the hand-path reuse hypothesis for the + – condition but not the – + condition[4]. In the + – condition, both correlations between RT and the two hand path curvature measures were negative, as predicted by the hand-path reuse hypothesis ($r = -.49$, $p < .001$, for the correlation between RT and initial angular offset; $r = -.44$, $p < .001$, for the correlation between RT and CI). In the – + condition, correlations were not positive, as would be predicted by the hand-path reuse hypothesis. Instead, the correlation between RT and initial angular offset was negative, $r = -.19$, $p < .001$, and the correlation between RT and CI was not reliably different from 0, $r = -.01$, $p = .66$. A possible reason for non-positive correlations is that additional planning time on obstacle-present trials would also allow participants to plan a less curved movement around the obstacle. Support for this proposal comes from a comparison between the correlations for the – + condition and the corresponding correlations for the A condition. Overall, correlations in the A condition were even more negative than those in the – + condition ($r$ = -.29, $p$ < .001, for correlation between RT and initial angular offset; $r$ = -.16, $p$ < .001, for the correlation between RT and CI). Thus, when a previous trial's hand path was different from the required hand path (as in the – + condition), the relationship between RT and curvature was less negative than when the two paths could be more similar (as in the A condition). This finding is in the direction of the prediction made by the hand-path reuse hypothesis.

## Summary of Experiment 1

Overall, the results of Experiment 1 supported the hand-path reuse hypothesis and provided answers to the three questions presented at the end of the introduction, as summarized below.

*Question 1: Is there evidence that previous movement paths are reused and modified?*

Yes. The clearest evidence came from hand paths for outward movements after a trial-type switch. These hand paths were often influenced by the previous trial type. For example, obstacle-absent trials had higher initial angular offsets and CIs when preceded by obstacle-present trials than when preceded by obstacle-absent trials. Similarly, obstacle-present trials had lower initial angular offsets, but not CIs, when preceded by obstacle-absent trials than when preceded by obstacle-present trials. Additional support for the hand-path reuse hypothesis came from the positive correlations in hand path curvatures for the outward and return movements.

*Question 2: If reuse did occur, did repeated execution of a similar hand path (e.g., many repeated obstacle-avoiding movements) strengthen the reused path's representation in memory?*

Yes. For both trial types, movements became less curved with fewer preceding + trials or a greater number of preceding – trials. With increasing numbers of trial-type repetitions, hand path curvature for both trial types became more similar to, but still statistically different from, their corresponding blocked-trial control conditions. For example, hand paths on – trials were more curved than hand paths on N trials, even when preceded by three other – trials. Similarly, hand paths on + trials were less curved than hand paths on A trials, even when preceded by three other + trials.

Question *3: If reuse did occur, to what extent did the previous movement path generalize to other parts of the workspace?*

Overall, the previously planned hand paths did generalize to other areas of the workspace, but the generalizability was greater for the – + conditions than the + – conditions. Hand paths for the – + conditions generalized across all angular separations, whereas generalization in the + – conditions was greatest when the subsequent direct movement's path neared the location of the previous trial's target location and when a movement's path was in the same direction as the preceding movement. Hand paths from preceding direct movements may have more readily generalized to other areas of the workspace than paths from obstacle-avoiding movements because of the greater complexity of the obstacle-avoiding hand paths.

None of these results is predicted by current models of direct or obstacle avoiding movements (including the PB model) because all assume that the cost of making a direct movement, or the obstacle clearance on an obstacle-avoiding movement, should depend only on the immediate task demands. The observed findings may not be uniquely predicted by the hand-path reuse hypothesis, though, as discussed in the following section.

*Trial-Type Expectations*

Participants initiated movements more quickly when preceded by an obstacle-present trial than when preceded by an obstacle-absent trial. One explanation for this finding is that participants may have expected trial-type switches. Thus, they may have anticipated an obstacle–present trial if the previous trial had been an obstacle-absent trial (and vice versa). The RT results may therefore be explained if one assumes that participants were more cautious about initiating movements, or possibly spent more time searching for an obstacle, when they anticipated an obstacle than when they did not. The hand path data did not support this trial-type switch hypothesis, though, and in fact were more supportive of the *opposite* expectation pattern. That is, the hand path data were more consistent with the idea that participants expected trial-type *repetitions*. Take, for example, the + – condition. Reaction times on + – trials were shorter than – – trials, which is consistent with a trial-type switch expectation (again, assuming that participants initiated movement more quickly when they did not anticipate an obstacle). However, hand paths on + – trials were *more* curved than – – trials, which is more consistent with a trial-type repetition expectation.

Further evidence against the switch expectation hypothesis comes from the effect of obstacle recency on hand path curvature. If participants had expected trial-type switches, one would predict that repeated trial types would enhance the expectation of a trial-type switch. For example, a participant would be more likely to expect an obstacle-present trial after *three* repeated obstacle-absent trials than after only *one* obstacle-absent trial. This pattern of expectation would predict, for example, that hand paths on – trials would become more curved when preceded by multiple – trials. The opposite pattern of hand path curvature was actually observed.

It is clear that expectation may have influenced performance, although the exact nature of the expectation is unclear given the inconsistencies between the RT and curvature data. The role of expectation is important for testing the hand-path reuse hypothesis because the repetition-expectation hypothesis makes many similar predictions to the hand-path reuse hypothesis (most critically, more curvature on trials preceded by obstacle-present trials than trials preceded by obstacle-absent trials). One observed result may lend more support to the hand-path reuse hypothesis. This result comes from the return movement analyses, in which return movements of the + – trials continued to be unnecessarily curved, even when participants knew no obstacle would be present. This result is not easily predicted by the repetition-expectation hypothesis. This single piece of evidence is not sufficient to reject the repetition-expectation hypothesis, however. Experiment 2 was designed to provide a stronger test of the repetition-expectation and hand-path reuse hypotheses.

# CHAPTER 3

## EXPERIMENT 2

To further investigate the influence of expectations, and to provide a stronger test of the repetition-expectation and hand path reuse hypotheses, I eliminated uncertainty about the upcoming trial type in Experiment 2 by using a predictable trial sequence. When trial type uncertainty is eliminated, the repetition-expectation hypothesis would predict that the effects of previous trial type should be reduced or eliminated. However, if the reuse of a previous trial's hand path is obligatory (as predicted by a strong form of the hand-path reuse hypothesis), the effect of previous trial type should be the same for predictable and unpredictable trial sequences. To anticipate the main result, the effect of previous trial type was the same in Experiment 2 as it was in Experiment 1. This result therefore supports the hand-path reuse hypothesis.

### Method

The method in Experiment 2 was the same as in Experiment 1, except that the order of obstacle-present and obstacle-absent trials followed a predictable AABBAA… pattern. The trial type at the beginning of each block was chosen randomly. I used the predictable trial sequence of AABBAA and not another pattern (e.g. ABABAB or AAABBB) because it maintained Experiment 1's overall probability of trial-type repetitions and switches, which was also .5.

Two groups of 17 participants completed Experiment 2. The first group was given no specific instructions about the predictable trial sequence (the *no-instruction condition*).

For the second group of participants, the experimenter told each participant during the first block of practice trials that the trial-type sequence would be fully predictable (the *instruction condition*). The second group of participants was required because, as I will show, participants in the first group did not appear to recognize the predictable trial sequence. This result was surprising given the ability of humans to detect patterns in their environments (e.g., Geisler & Diehl, 2003). Even though the manipulation of trial sequence predictability did not succeed for the first group of participants, their data are informative for two reasons. First, the results will show the importance of explicit knowledge about, rather than implicit learning of, the predictable trial sequence. Second, because they behaved as if the trial-sequence was random, data from the first group of participants provide an additional replication of the sequential effects observed in Experiment 1. Such a replication for a newly reported phenomenon is clearly important. For these two reasons, data from the first groups of participants were included in the analyses presented below.

## Results and Discussion

Trials in which any of the IREDs was out of view of the OPTOTRAK (approximately 2.8% of trials) were removed from analysis, as were trials in which an obstacle collision occurred (approximately 0.7% of trials). Data from Experiment 1 are included in all the analyses and figures pertaining to Experiment 2 because of the importance of comparing the two experiments.

As mentioned above, it was important to verify that participants recognized and made use of the predictable pattern of trials. If they did so when planning, their reaction times should be lower in Experiment 2 than in Experiment 1. Therefore, I will reverse the order in which the results are presented and begin by discussing the reaction time data and then move to the hand path curvature data.

*Reaction Time*

Reaction times for Experiment 2 are shown in Figure 12. Reaction times were shorter for the instruction condition than the no-instruction and random conditions, which did not differ from one another. This pattern of RTs suggests that participants were aware of the predictable sequence only when explicit instructions about it were provided. The decrease in RT for the instruction condition showed that participants made use of trial-type foreknowledge when planning movements. It was surprising, then, that reaction times were again shorter on trials preceded by a + trial than a – trial. The explanation for this finding in Experiment 1 was that participants may have expected trial-type switches. It is unlikely that participants had the same expectations in the instruction condition of the current experiment. This pattern of RT results was inconsistent across all experiments, however, as will be discussed in the General Discussion section.

The RT results were confirmed with a 3 (trial sequence: random, predictable without instructions, predictable with instructions) x 2 (trial type: + or -) x 2 (previous trial type: + or -) mixed factor ANOVA, with all factors manipulated within participants except trial sequence. The significant findings were a main effect of trial sequence, $F(2, 48) = 4.41$, $p = .017$, a main effect of trial type, $F(1, 48) = 8.52$, $p = .005$, and a main effect of previous trial type, $F(1, 48) = 98.82$, $p < .001$. None of the interactions was reliable, $F < 1$ for each test. For the main effect of trial sequence, a Bonferroni-corrected post-hoc analysis showed that reaction times were shorter for the instruction condition than the no-instruction ($p$ = .04) and random conditions ($p$ = .02), which did not differ from one another ($p$ = .78).

*Hand Path Curvature of Outward Movements*

The reaction time data showed that when instructed about the predictable trial sequence, participants made use of trial-type foreknowledge to initiate movements more quickly than when the trial-type sequence was random. Having shown evidence that the manipulation of the trial sequence succeeded, I next compared hand path curvature between the two experiments to test the repetition-expectation and hand-path reuse hypotheses. The repetition-expectation hypothesis predicts that the effects of previous trial type should be reduced or eliminated in the instruction condition of Experiment 2 because participants had foreknowledge of the upcoming trial type. If the reuse of a previous trial's hand path is obligatory (as predicted by a strong form of the hand-path reuse hypothesis), the results of Experiment 1 and the instruction condition of Experiment 2 should not differ.

Mean initial angular offsets of outward movements of Experiment 2 are shown in Figure 13. All three conditions (instructions, no-instructions, and random) showed similar patterns of mean initial angular offsets. As observed in Experiment 1, trials of both types had higher initial angular offsets when preceded by obstacle-present trials than obstacle-absent trials. The same results were observed for the CI measure of outward movements, as shown in Figure 14. This similarity across experiments supports the hand-path reuse hypothesis.

The initial angular offset measure was evaluated with a 3 (trial sequence: random, predictable without instructions, predictable with instructions) x 2 (trial type: + or -) x 2 (previous trial type: + or -) mixed factor ANOVA, with all factors manipulated within participants except trial sequence. Most importantly, there was no main effect of trial sequence, $F(2, 48) = .11$, $p = .88$, and none of the interactions between trial sequence and the other factors was reliable, $F < 1$ for all. The only significant effects, which replicated the results of Experiment 1, were a main effect of trial type, $F(1, 48) = 248.97$, $p < .001$, and a main effect of previous trial type, $F(1, 48) = 168.57$, $p < .001$.

The CI measure was evaluated with same ANOVA. As in the initial angular offset measure, there was no main effect of trial sequence, $F(2, 48) = .20$, $p = .81$, and none of the interactions between trial sequence and the other factors was reliable, $F < 1$ for all. The only significant effects, which replicated the results of Experiment 1, were a main effect of trial type, $F(1, 48) = 917.24$, $p < .001$, and a main effect of previous trial type, $F(1, 48) = 110.43$, $p < .001$.

*Practice Effects*

As in the previous experiment, the evidence for plan reuse was robust over the levels of practice sampled. The only reliable effects of practice came from the CI measures of – + trials. As discussed in Experiment 1, this may have been caused by participants learning to give less clearance to the obstacle with practice.

For the + – trials of the no-instruction condition, the correlation between initial angular offset and block number was .03 ($p = .12$) and the correlation between CI and block number was -.01 ($p = .57$). For – + trials, the correlation between initial angular offset and block number was -.01 ($p = .58$) and the correlation between CI and block number was -.13 ($p < .001$).

For the + – trials of the instruction condition, the correlation between initial angular offset and block number was -.03 ($p = .31$) and the correlation between CI and block number was .02 ($p = .43$). For – + trials, the correlation between initial angular offset and block number was .004 ($p = .88$) and the correlation between CI and block number was -.05 ($p = .11$).

For the remaining results, no figures will be presented because of the similar results in Experiment 1 and Experiment 2. However, statistical tests showing the null effect of trial sequence, and replicating the findings of Experiment 1, are reported below.

*Return Movements*

The pattern of results for the curvature of return movements in Experiment 2 was similar to that of Experiment 1. As in the forward movements, no differences were observed between the three trial sequences for both the initial angular offset and CI measure.

On a movement-by-movement analysis, positive correlations were observed between the hand path curvature measures for outward and return movements, as in Experiment 1. In the no-instruction condition, the correlations between outward and return movement curvature were .30 and .46 for – trials (as measured by initial angular offset and CI, respectively) and .44 and .61 for + trials ($p < .001$ for all). In the instruction condition, the correlations between outward and return movement curvature were .37 and .52 for –

trials and .56 and .51 for + trials (as measured by initial angular offset and CI, respectively; $p < .001$ for all). These positive correlations are predicted by the hand-path reuse hypothesis.

The effects reported above for mean initial angular offsets were evaluated with a 3 (trial sequence: random, predictable without instructions, predictable with instructions) x 2 (trial type: + or -) x 2 (previous trial type: + or -) mixed factor ANOVA, with all factors manipulated within participants except trial sequence. Most importantly, there was no main effect of trial sequence, $F(2, 48) = .05$, $p = .95$, and none of the interactions between trial sequence and the other factors was reliable, $F < 1$ for all. The only significant effects, which replicated the results of Experiment 1, were a main effect of trial type, $F(1, 48) = 1302.35$, $p < .001$, and a main effect of previous trial type, $F(1, 48) = 46.32$, $p < .001$, and the interaction between trial type and previous trial type, $F(1, 48) = 24.55$, $p < .001$.

The effects for the mean CIs were evaluated with the same ANOVA. As in the initial angular offset measure, there was no main effect of trial sequence, $F(2, 48) = .23$, $p = .78$, and none of the interactions between trial sequence and the other factors was reliable, $F < 1.33$, $p > .27$, for all. The only significant effects, which replicated the results of Experiment 1, were a main effect of trial type, $F(1, 48) = 1045.92$, $p < .001$, a main effect of previous trial type, $F(1, 48) = 82.17$, $p < .001$, and the interaction between trial type and previous trial type, $F(1, 48) = 18.13$, $p < .001$.

*Effect of Obstacle Recency for Outward Movements*

The effects of obstacle recency for outward movements that were obtained in Experiment 1 were replicated in Experiment 2. As in the previous analyses, no differences were observed between the three trial sequences for either the initial angular offset or the CI measure.

The number of previously repeated trial types was limited in Experiment 2 because of the nature of the predictable obstacle sequence. Obstacle-absent trials could only be preceded by one obstacle-absent trial (recency of -1) or two obstacle-present trials (recency of 2). Similarly, obstacle-present trial could only be preceded by two obstacle-absent trials (recency of -2) or one obstacle-present trial (recency of 1). Analyses were therefore limited to the cases that could be compared across experiments. Also, analyses were performed separately for + and – trials because there was no overlap in recency values across + and – trials for the predictable trial sequence.

The initial angular offset measure was evaluated with two 3 (trial sequence: random, predictable without instructions, predictable with instructions) x 2 (obstacle recency: -1 and 2 for + trials; -2 and 1 for – trials) ANOVAs. For + trials, there was no main effect of trial sequence, $F(2, 48) < 1$, *ns,* a main effect of obstacle recency, $F(1, 48) = 119.91$, $p < .001$, and no interaction between trial sequence and obstacle recency, $F(2, 48) = 2.62$, $p = .10$. For – trials, there was no main effect of trial sequence, $F(2, 48) < 1$, *ns,* a main effect of obstacle recency, $F(1, 48) = 112.81$, $p < .001$, and no interaction between trial sequence and obstacle recency, $F(2, 48) < 1$, *ns*.

The same two ANOVAs were used to evaluate the CI measure. For + trials, there was no main effect of trial sequence, $F(2, 48) < 1$, *ns*, a main effect of obstacle recency, $F(1, 48) = 6.29$, $p = .016$, and no interaction between obstacle recency and trial sequence, $F(2, 48) < 1$, *ns*. For – trials, there was no main effect of trial sequence, $F(2, 48) < 1$, *ns*, a main effect of obstacle recency, $F(1, 48) = 118.81$, $p < .001$, and no interaction between trial sequence and obstacle recency, $F(2, 48) < 1$, *ns*.

*Angular Separation Between Targets In Successive Trials*

The effects of angular separation between targets in successive trials for outward movements obtained in Experiment 1 were replicated in Experiment 2. As in the previous analyses, no differences were observed between the three trial sequences for either the initial angular offset or the CI measure.

The effects of angular separation on initial angular offset were evaluated with two ANOVAs, one for – + trials and one for + – trials. Both ANOVAs had a 3 (trial sequence: random, predictable without instructions, predictable with instructions) x 6 (angular separation) design. For the – + trials, there was no main effect of trial sequence, $F(2, 48) = .21$, *ns*, no main effect of angular separation, $F(5, 240) = 2.07$, $p = .07$, and no interaction between trial sequence and angular separation, $F(10, 240) < 1$, *ns*. For + – trials, there was no main effect of trial sequence, $F(2, 48) < 1$, *ns*, a main effect of angular separation that was best fit with a quadratic contrast, $F(1,48) = 4.48$, $p = .04$, and no interaction between trial sequence and angular separation, $F(10, 240) < 1$, *ns*.

The effects of angular separation on CI were evaluated with the same ANOVAs. For the – + trials, there was no main effect of trial sequence, $F(2, 48) = .18$, *ns*, no main effect of angular separation, $F(5, 240) = 1.93$, $p = .14$, and no interaction between trial sequence and angular separation, $F(10, 240) = 1.30$, $p = .24$. For + – trials, there was no main effect of trial sequence, $F(2, 48) < 1$, *ns*, a main effect of angular separation that was best fit with a quadratic contrast, $F(1,48) = 4.48$, $p = .04$, and no interaction between trial sequence and angular separation, $F(10, 240) < 1$, *ns*.

*Correlations Between RT and Curvature*

The correlations between RT and hand path curvature in Experiment 2 were similar to those in Experiment 1. Again, this correlation relates to the hand-path reuse hypothesis' prediction that as participants take more time to initiate movements on trial-type switches, their performance should become more similar to performance on trials in which no trial-type switch occurred. The hand-path reuse hypothesis predicts that the relationship between RT and hand path curvature should be negative for + – trials (the more time taken, the straighter the path) and positive for – + trials (the more time taken, the more curved the path).

For the + – trials of the instruction condition, both correlations between RT and hand path curvature were negative, as predicted by the hand-path reuse hypothesis ($r = -.45$, $p < .001$, for the correlation between RT and initial angular offset; $r = -.40$, $p < .001$, for the correlation between RT and CI). For the – + trials of the instruction condition, both correlations between RT and hand path curvature were also negative ($r = -.28$, $p < .001$, for the correlation between RT and initial angular offset; $r = -.11$, $p < .001$, for the correlation between RT and CI). As discussed in Experiment 1, a possible reason for non-positive correlations on + trials is that additional planning time also allowed participants to plan a less curved movement around the obstacle. This reasoning was confirmed with the corresponding correlations in the A condition (*r* = -.29, *p* < .001, for correlation between RT and initial angular offset; *r* = -.16, *p* < .001, for the correlation between RT and CI).

For the + – trials of the no-instruction condition, *r* = -.29 (*p* < .001) for the correlation between RT and initial angular offset and *r* = -.36 (*p* < .001) for the correlation between RT and CI. For the – + trials of the no-instruction condition, *r* = -.002 (*p* = .943) for the correlation between RT and initial angular offset and *r* = -.03 (*p* = .31) for the correlation between RT and CI.

The overall negative correlations between RT and hand path curvature on the + – trials, and correlations on – + trials that were less negative than those in the A condition, support the proposal that as participants took more time to initiate movements on trial-type switches, their performance became more similar to performance on trials in which no trial-type switch occurred.

**Summary of Experiment 2**

The goal of Experiment 2 was to provide a stronger test of the repetition-expectation hypothesis and the hand-path reuse hypothesis. These tests were pursued by using a predictable trial sequence and by comparing the results to those of Experiment 1, where obstacle-present trials occurred randomly. The two hypotheses made diverging predictions about performance between the two experiments. When trial type uncertainty was eliminated, the repetition-expectation hypothesis predicted that the effects of previous trial type would be reduced or eliminated. However, if the reuse of a previous trial's hand path was obligatory (as predicted by a strong form of the hand-path reuse hypothesis), the effect of previous trial type would be predicted to be the same for predictable and unpredictable trial sequences. The effect of previous trial type was the same in both experiments, supporting the hand-path reuse hypothesis.

# CHAPTER 4

## EXPERIMENT 3

The primary unanswered question at the end of Experiment 1 was whether the results were best explained by expectations about the upcoming trial or the reuse and modification of previously planned hand paths. This question was taken up in Experiment 2, and the results supported the hand-path reuse hypothesis. A second unanswered question in Experiment 1 concerned the number of previous trials that could influence hand path curvature. The results of Experiment 1 showed that with an increasing number of trial-type repetitions, hand path curvature for both trial types became more similar to, but still statistically different from, their corresponding blocked-trial control conditions. Analyses were limited to three trial-type repetitions in Experiment 1 because the .50 probability of obstacle-present trials could not produce sufficient data to afford a greater number of trial-type repetitions. To test whether performance in the mixed blocks would eventually return to control-condition-like performance with more trial-type repetitions, I varied the probability of obstacle-present trials to allow for more data from a larger number of trial-type repetitions. For one group of participants the probability of obstacle-present trials was .25, whereas for another group the probability of obstacle-present trials was .75.

### Method

The method was the same as in the mixed-trial-type conditions of Experiment 1, except that I varied the probability of obstacle-present trials. For one group of 17 participants the probability of obstacle-present trials was .25. For the other group of 17 participants the probability of obstacle-present trials was .75. Otherwise, as in Experiment 1, obstacle-present trials occurred randomly within each block.

## Results and Discussion

Trials in which any of the IREDs was out of view of the OPTOTRAK (approximately 2.6% of trials) were removed from analysis, as were trials in which an obstacle collision occurred (approximately 1.7% of trials). The frequency of collisions was similar across the two probability conditions.

Data from Experiment 1 (obstacle probability = .50) are included in all analyses and figures presented below to facilitate the comparison of the overall effect of obstacle probability.

### *Hand Path Curvature for Outward Movements*

Similar patterns of initial angular offset data were observed across all three obstacle probabilities, as shown in Figure 3. For all three probabilities, trials preceded by a + trial had higher initial angular offsets than those preceded by a – trial. The effect of previous trial type again supports the hand-path reuse hypothesis. Beyond the effects of the previous trial type, initial angular offsets for most conditions decreased with decreases in obstacle probability, and mean initial angular offsets on – – trials in the .25 condition were not reliably different from the N condition. This outcome suggests that performance on – trials did return to control-condition-like performance in the .25 condition. However, initial angular offsets in the + + trials of the .75 probability condition were still lower than in the A condition. Thus, performance in this condition had not returned to control-condition-like performance with two repeated obstacle-present trials.

Similar patterns were also observed across all three obstacle probabilities for the CI measure, as shown in Figure 4. As described in Experiment 1, the previous trial type affected CI values on – trials but not on + trials. CIs on – trials were more curved when preceded by a – trial than by + trial. The reliable effect of previous trial type across all probabilities supports the hand-path reuse hypothesis. Like the findings using the initial angular offset measure, CIs on the – – trials of the .25 probability condition were not reliably different from those in the N condition. However, unlike the findings using the initial angular offset measure, CIs on all + trials were not reliably different from the A condition.

The initial angular offset measure was evaluated with a 3 (obstacle probability: .75, .50, or .25) x 2 (trial type: + or -) x 2 (previous trial type: + or -) mixed factor ANOVA, where all factors were manipulated within participants except for obstacle probability. The reliable findings were a main effect of obstacle probability, $F(1, 48) = 315.76$, $p < .001$, a main effect of trial type, $F(1, 48) = 315.76$, $p < .001$, a main effect of previous trial type, $F(1, 48) = 175.89$, $p < .001$, and a significant three way interaction, $F(2, 48) = 6.12$, $p = .004$. The three way interaction was caused by a reliable interaction between trial type and previous trial type for the .25 probability but not the .75 and .50 probabilities. The interaction in the .25 probability showed that previous trial type had a larger effect on + trials than – trials. The final statistical tests compared trials in the mixed-trial blocks with their respective blocked-trial control conditions. All + conditions had initial angular offset values that were lower than those in the A condition ($p < .05$, Bonferroni corrected). Initial angular offsets on all – trials were higher than those in the N condition (*p* < .05, Bonferroni corrected) except for – – trials of the .25 probability condition.

The CI measure was evaluated with the same ANOVA, in which all main effects and interactions were reliable, *p* < .05. When the three-way interaction was parsed by obstacle probability, the interaction between trial type and previous trial type was reliable for the .25 and .50 probabilities, but this interaction was not quite reliable for the .75 probability, *p* = .12. The final statistical tests compared trials in the mixed-trial blocks with their respective blocked-trial control conditions. All + conditions had CI values that were not reliably different from those in the A condition (*p* > .35). CI values on all – trials were higher than those in the N condition (*p* < .05, Bonferroni corrected) except for – – trials of the .25 probability condition.

*Practice Effects*

As in the previous experiments, the evidence for plan reuse was robust over the levels of practice sampled. The only reliable effects of practice came from the CI measures of – + trials. As discussed in Experiment 1, this may have been caused by participants learning to give less clearance to the obstacle with practice.

For the + – trials of the .75 condition, the correlation between initial angular offset and block number was .03 (*p* = .60) and the correlation between CI and block number was .006 (*p* = .91). For – + trials, the correlation between initial angular offset and block number was .003 (*p* = .88) and the correlation between CI and block number was -.08 (*p* < .001).

For the + – trials of the .25 condition, the correlation between initial angular offset and block number was .008 ($p$ = .80) and the correlation between CI and block number was .02 ($p$ = .47). For – + trials, the correlation between initial angular offset and block number was .06 ($p$ = .09) and the correlation between CI and block number was -.12 ($p$ < .001).

*Return Movements*

Similar patterns of initial angular offset data for return movements were observed across all three obstacle probabilities, as shown in Figure 5. On return movements, there were reliable effects of previous trial type for the – trials of the .50 and .25 conditions, but not for the – trials of the .75 condition or any of the + trials. However, performance on the mixed-trial conditions was still almost always reliably different from the blocked-trial control conditions, showing an overall effect of mixing the two trial types. For example, all + trials had reliably lower initial angular offsets than the A condition. Likewise, all – trials (except the – – trials of the .25 condition) had reliably higher initial angular offsets than the N condition. A similar pattern of results for return movements was observed for the CI measure, as shown in Figure 6.

Although the correlations between forward and return movements at the average level were not strongly supportive of the hand-path reuse hypothesis, correlations at the movement-to-movement level of analysis were more encouraging. In the .75 condition, the correlations between outward and return movement curvature were .31 and .53 for – trials (as measured by initial angular offset and CI, respectively) and .22 and .55 for + trials ($p$ < .001 for all). In the .25 condition, the correlations between outward and return movement curvature were .27 and .41 for – trials and .23 and .47 for + trials (as measured by initial angular offset and CI, respectively; $p < .001$ for all). These positive correlations are predicted by the hand-path reuse hypothesis.

The mean initial angular offsets were evaluated with a 3 (obstacle probability: .75, .50, or .25) x 2 (trial type: + or -) x 2 (previous trial type: + or -) mixed factor ANOVA, where all factors were manipulated within participants except for obstacle probability. All main effects and interactions were reliable at the $p < .05$ level except the main effect of probability, $p = .17$, and the three way interaction, $p = .09$. The final statistical tests compared trials in the mixed-trial blocks with their respective blocked-trial control conditions. All + conditions had initial angular offset values that were lower than those in the A condition ($p < .05$, Bonferroni corrected). Initial angular offsets on all – trials were higher than those in the N condition ($p < .05$, Bonferroni corrected) except for – – trials of the .25 probability condition.

The same ANOVA for the mean CIs resulted in all main effects and interactions being reliable at the $p < .05$ level except the main effect of probability, $p = .39$, and the three way interaction, $p = .10$. The final statistical tests compared trials in the mixed-trial blocks with their respective blocked-trial control conditions. All + conditions had CI values that were not reliably different from those in the A condition ($p > .35$) except for the two + trials of the .75 obstacle probability condition ($p < .05$, Bonferroni corrected). CI values on all – trials were higher than those in the N condition ($p < .05$, Bonferroni corrected) except for – – trials of the .25 probability condition.

*Effect of Obstacle Recency for Outward Movements*

The most important analyses for Experiment 3 concerned the effect of obstacle recency because these analyses examined the number of trial-type repetitions it took participants to return to control-like-condition performance (the goal of introducing the probability manipulation). The effects of obstacle recency on initial angular offset are shown in Figure 7. For both trial types of all probabilities, movements became less curved with fewer preceding + trials or a greater number of preceding – trials. With more trial-type repetitions, initial angular offsets for both trial types became more similar to their corresponding blocked-trial control conditions. On – trials of the .25 condition, initial angular offsets returned to control-condition-like performance when preceded by two or more obstacle-absent trials. On + trials of the .75 condition, initial angular offsets returned to control-condition-like performance when preceded by four or more other obstacle-present trials. Therefore, the effect of previously-encountered obstacle-absent trials on obstacle-present trials was longer lasting than the effect of previously-encountered obstacle-present trials on obstacle-absent trials.

One caveat about the above conclusions is that there was often an overall effect of probability for a given obstacle recency. For example, although initial angular offsets of – trials preceded by two other – trials in the .25 condition were not different from the N condition, the same was not true for – trials preceded by two other – trials in the .50 and .75 conditions. Thus, participants were sensitive to the overall probability of an obstacle occurring within a block and not just the few previously experienced trials.

The effect of obstacle recency on CI were similar to the effect of obstacle recency on initial angular offset, as shown in Figure 8. The one difference, as reported in Experiment 1, was that + trials were not reliably different from the A condition (except for + trials preceded by – trials in the .75 condition).

For both the initial angular offset and CI measures, two sets of ANOVAs were performed to confirm the conclusions described above. The first set examined the effect of obstacle recency *within* each probability, using a single factor ANOVA (including all values of recency for a given probability) performed separately for obstacle-present and obstacle-absent trials. These single factor ANOVAs were limited to the .25 and .75 conditions because the effect of obstacle recency for the .50 condition was reported in Experiment 1. The second set examined the effect of obstacle recency *across* probabilities. This was limited to values of obstacle recency that could be compared across probabilities (i.e., recency values of -2, -1, 1, and 2). The design of this ANOVA was 3 (obstacle probability: .75, .50, and .25) x 2 (trial type: + or -) x 4 (obstacle recency: -2, -1, 1, 2). Finally, Bonferroni-corrected t-tests (with overall alpha of .05) were again used to compare conditions to the A and N conditions. To reduce the number of total comparisons performed, only – trials with negative recency values were compared to the N condition and only + trials with positive recency values were compared to the A condition.

For the initial angular offset measure, there was a reliable effect of obstacle recency for both + and – trials in both the .25 and .75 conditions ($p < .001$ for each). In the three way ANOVA to test the effect of obstacle recency across obstacle probabilities, the only reliable effects were the three main effects, $p < .05$. Finally, only – trials with a recency of -2 or less in the .25 condition were not different from the N condition. Likewise, only + trials with a recency of 4 or more were not different from the A condition.

For the CI measure, there was a reliable effect of obstacle recency for both + and – trials in both the .25 and .75 conditions ($p < .001$ for each). In the three way ANOVA to test the effect of obstacle recency across obstacle probabilities, only the main effects of trial type and previous trial type were reliable, $p < .05$. Finally, only – trials with a recency of -3 or less in the .25 condition were not different from the N condition. All + trials with positive recency values were not different from the A condition.

*Angular Separation Between Targets in Successive Trials*

The effects of angular separation between targets in successive trials was replicated in Experiment 3, as seen in Figures 9 and 10 for the initial angular offset and CI measures, respectively. When obstacle-present trials were preceded by obstacle-absent trials (the – + condition), the effect of the previous – trial generalized equally to all regions of the workspace. Evidence for this conclusion came from the absence of an effect of angular separation on initial angular offset within the – + conditions of all three probabilities. When obstacle-absent trials were preceded by obstacle-present trials (the + – condition), the effect of the previous + trial also generalized. However, the generalization did not apply equally to all regions of the workspace. Within the + – condition, initial angular offsets were greatest near 30º and 180º of angular separation and decreased for intermediate values of angular separation. Although there was an overall effect of obstacle probability on hand path curvature, with lower obstacle probabilities associated with less curvature, the effect of angular separation on – + and + – trials was not different across probabilities.

The effect of angular separation was evaluated with four 3 (obstacle probability) × 6 (angular separation) ANOVAs, performed separately for initial angular offset and CI measures as well as separately for – + and + – trials. For the initial angular offset measure of – + trials, there was a main effect of obstacle probability, $F(2, 48) = 5.57$, $p = .007$, no main effect of angular separation, $F(5, 240) < 1$, *ns*, and no interaction between obstacle probability and angular separation, $F(10, 240) < 1$, *ns.* For the initial angular offset measure of + – trials, there was a main effect of obstacle probability, $F(2, 48) = 6.20$, $p = .004$, a main effect of angular separation, $F(5, 240) = 8.50$, $p < .001$, and no interaction between obstacle probability and angular separation, $F(10, 240) < 1$, *ns*.

For the CI measure of – + trials, there was no main effect of obstacle probability, $F(2, 48) = 1.40$, $p = .25$, no main effect of angular separation, $F(5, 240) = 1.97$, $p = .08$, and no interaction between obstacle probability and angular separation, $F(10, 240) = 1.17$, $p = .32$. For the CI measure of + – trials, there was main effect of obstacle probability, $F(2, 48) = 5.16$, $p = .009$, a main effect of angular separation, $F(5, 240) = 23.53$, $p < .001$, and no interaction between obstacle probability and angular separation, $F(10, 240) < 1$, *ns.*

*Reaction Time*

Mean reaction times for Experiment 3 are shown in Figure 11. RTs in the .25 and .50 obstacle probability conditions did not differ from one another but were greater than in the .75 probability conditions. One possible reason for shorter RTs in the .75 condition is that obstacle-present trials were so frequent in this condition that, by default, participants prepared to make an obstacle-avoiding movement. Similarly short RTs were observed in the instruction condition of Experiment 2 (Figure 12), where participant knew in advance whether an obstacle would be present on the upcoming trial. More will be said about the overall pattern of reaction times across experiments in the General Discussion section.

Reaction times were evaluated with a 3 (obstacle probability: .75, .50, or .25) x 2 (trial type: + or -) x 2 (previous trial type: + or -) mixed factor ANOVA, where all factors were manipulated within participants except for obstacle probability. All main effects and interactions were reliable except the interaction between obstacle probability and trial type, $p = .881$, and the three way interaction, $p = .615$. Bonferroni-corrected post-hoc comparison of the main effect of obstacle probability showed that RTs in the .75 probability were marginally lower than the .50 probability ($p = .10$) and .25 probability ($p = .07$) conditions, which did not differ ($p = .85$).

*Correlations Between RT and Curvature*

The correlations between RT and hand path curvature in Experiment 3 were similar to those in Experiment 1. Again, the correlation relates to the hand-path reuse hypothesis' prediction that as participants take more time to initiate movements on trial-type switches, their performance should become more similar to performance on trials in which no trial-type switch occurred. The hand-path reuse hypothesis predicts that the relationship between RT and hand path curvature should be negative for + – trials (the more time taken, the straighter the path) and positive for – + trials (the more time taken, the more curved the path).

For the + – trials of the .25 condition, both correlations between RT and hand path curvature were negative, as predicted by the hand-path reuse hypothesis ($r = -.44$, $p < .001$, for the correlation between RT and initial angular offset; $r = -.61$, $p < .001$, for the correlation between RT and CI). For the – + trials of the .25 condition, both correlations between RT and hand path curvature were near or above zero ($r = -.05$, $p = .11$, for the correlation between RT and initial angular offset; $r = .095$, $p = .002$, for the correlation between RT and CI). As discussed in Experiment 1, a possible reason for non-positive correlations is that additional planning time on obstacle-present trials allowed participants to plan a less curved movement around the obstacle. This reasoning was confirmed with the corresponding correlations in the A condition ($r = -.29$, $p < .001$, for correlation between RT and initial angular offset; $r = -.16$, $p < .001$, for the correlation between RT and CI).

For the + – trials of the .75 condition, $r = -.39$ ($p < .001$) for the correlation between RT and initial angular offset and $r = -.20$ ($p < .001$) for the correlation between RT and CI. For the – + trials of the .75 condition, $r = -.12$ ($p = .020$) for the correlation between RT and initial angular offset and $r = -.14$ ($p = .011$) for the correlation between RT and CI.

The overall negative correlations between RT and hand path curvature on the + – trials, and correlations on – + trials that were less negative than those in the A condition, support the proposal that as participants took more time to initiate movements on trial-type switches, their performance became more similar to performance on trials in which no trial-type switch occurred.

## Summary of Experiment 3

By increasing the number of trial-type repetitions in Experiment 3, I found that mixed block performance did eventually return to control-condition-like performance. For obstacle-absent trials, this occurred after approximately two repeated obstacle-absent trials in the .25 obstacle probability condition. For obstacle-present trials, this occurred after approximately four repeated obstacle-present trials in the .75 obstacle probability condition. One caveat about the above conclusions is that there was often an overall effect of probability for a given obstacle recency. For example, although hand path curvature on – trials preceded by two other – trials in the .25 obstacle probability condition were not different from the N condition, the same was not true for – trials preceded by two other – trials in the .50 and .75 obstacle probability conditions. Thus, participants were sensitive to the overall probability of an obstacle occurring within a block and not just the few previously experienced trials. Nonetheless, the main conclusion of Experiment 3 is that the effects of trial-type switches did eventually disappear, but only after multiple trial-type repetitions.

# CHAPTER 5

## EXPERIMENT 4

Experiments 1, 2, and 3 all demonstrated consistent effects of previous trial type on hand path curvature. These data were taken as evidence for the hand-path reuse hypothesis. If the previously planned hand path was stored, its activation would be predicted to decay with time. In the previous three experiments the response-stimulus interval (RSI; the time between the completion of a movement to a target circle and the presentation of the next target circle) was constant and relatively short (250 ms). This brief time between movements may have made it more likely that the perceptual-motor system could reuse the previous hand path. If this activation did decay with time, the effects of the previous trial should be reduced or even eliminated when the RSI is increased. Similar logic has been tested, and verified, in studies of mental task switching (Rogers & Monsell, 1995). I tested this hypothesis in Experiment 4 by extending the RSI to 600 and 1000 ms.

### Method

The method in Experiment 4 was the same as in Experiment 1, except where noted below. The RSI for one group of 17 participants was 600 ms, and the RSI for a second group of 17 participants was 1000 ms. Two separate groups of 17 participants also completed A and N control conditions with either a 600 or 1000 ms RSI. Participants in the control conditions completed five blocks of A trials and five blocks of N trials. Data from Experiment 1 (RSI = 250 ms) are included in all analyses and figures presented below to facilitate evaluation of RSI effects.

## Results and Discussion

Trials in which any of the IREDs was out of view of the OPTOTRAK (approximately 2.6% of trials) were removed from analysis, as were trials in which an obstacle collision occurred (approximately 0.9% of trials).

*Hand Path Curvature for Outward Movements*

The effect of the previous trial on initial angular offset decreased as RSI increased, as shown in Figure 15. This pattern of results is consistent with a time-decaying memory trace of the previous hand path. The previous trial's memory trace remained active for at least 1000 ms, however, as evidenced by the reliable effect of previous trial type for both the + and – trials of the 1000 ms RSI condition. Finally, initial angular offsets for most movement conditions decreased as RSI increased, especially for – trials. Moreover, – – trials of the 1000 ms RSI condition were not reliably different from the 1000 ms N condition.

A similar pattern of results was observed for the CI measure, as shown in Figure 16. The one difference between the two measure being that, as reported in previous experiments, there was no effect of previous trial type for + trials, even though there was an effect of previous trial type on – trials.

The initial angular offset measure was evaluated with a 3 (RSI: 250 ms, 600 ms, or 1000 ms) x 2 (trial type: + or -) x 2 (previous trial type: + or -) mixed factor ANOVA, where all factors were manipulated within participants except for RSI. All main effects and interactions were reliable, $p < .01$, except for the interaction between trial type and previous trial type, $p = .84$, and the three way interaction, $p = .46$. The most important result was the interaction between RSI and previous trial type, which verified that the effect of previous trial type decreased with an increase in RSI. The final statistical tests compared trials in the mixed-trial blocks with their respective blocked-trial control conditions. All + conditions had initial angular offset values that were lower than those in their corresponding A conditions ($p < .05$, Bonferroni corrected) expect of the + + trials of the 600 ms RSI condition. Initial angular offsets on all – trials were higher than those in their corresponding N conditions ($p < .05$, Bonferroni corrected) except for – – trials of the 1000 ms RSI condition.

The CI measure was evaluated with the same ANOVA. All main effects and interactions were reliable, $p < .03$. In the three way interaction, the effect of previous trial type decreased with an increase in RSI, but only for the – trials. The final statistical tests compared trials in the mixed-trial blocks with their respective blocked-trial control conditions. All + conditions had CI values that were not reliably different from those in their corresponding A conditions ($p > .20$). CI values on all – trials were higher than those in their corresponding N conditions ($p < .05$, Bonferroni corrected).

*Practice Effects*

As in the previous experiments, the evidence for plan reuse was robust over the levels of practice sampled. The only reliable effects of practice came from the CI measures of – + trials. As discussed in Experiment 1, this may have been caused by participants learning to give less clearance to the obstacle with practice. For the + – trials of the 600 ms RSI condition, the correlation between initial angular offset and block number was .022 ($p$ = .47) and the correlation between CI and block number was -.023 ($p$ = .437). For – + trials, the correlation between initial angular offset and block number was -.01 ($p$ = .64) and the correlation between CI and block number was -.08 ($p$ = .009).

For the + – trials of the 1000 ms RSI condition, the correlation between initial angular offset and block number was -.03 ($p$ = .31) and the correlation between CI and block number was .02 ($p$ = .43). For – + trials, the correlation between initial angular offset and block number was .053 ($p$ = .10) and the correlation between CI and block number was -.10 ($p$ = .001).

*Hand Path Curvature for Return Movements*

The pattern of results for return movements was similar to that of the outward movements, as seen in Figures 17 and 18 for the initial angular offset and CI measures, respectively. This similarity between outward and return movements is predicted by the hand-path reuse hypothesis. As in the outward movements, the effect of previous trial type on the return movements of – trials decreased and was eventually eliminated as RSI increased. Return movements on – – trials of the 600 and 1000 ms RSI conditions, and + – trials of the 1000 ms RSI condition, were not reliably more curved than the corresponding return movements in the N conditions. Thus, as the time between trials increased, performance became more similar to the corresponding blocked-trial control conditions. This finding is consistent with a time-decaying trace of the previous movement path.

On a movement-by-movement analysis, positive correlations were again observed between the hand path curvature measures for outward and return movements. In the 600 ms RSI condition, the correlations between outward and return movement curvature were .16 and .38 for – trials (as measured by initial angular offset and CI, respectively) and .18 and .37 for + trials. In the 1000 ms RSI condition, the correlations between outward and return movement curvature were .19 and .41 for – trials and .24 and .46 for + trials (as measured by initial angular offset and CI, respectively; $p < .001$ for all). These positive correlations are predicted by the hand-path reuse hypothesis.

The mean initial angular offsets were evaluated with a 3 (RSI: 250 ms, 600 ms, or 1000 ms) x 2 (trial type: + or -) x 2 (previous trial type: + or -) mixed factor ANOVA, where all factors were manipulated within participants except RSI. All main effects and interactions were reliable, $p < .05$. In the three way interaction, the effect of previous trial type decreased with an increase in RSI, but only for the – trials. The final statistical tests compared trials in the mixed-trial blocks with their respective blocked-trial control conditions. All + conditions had initial angular offset values that were not different from those in the A condition ($p > .35$) except, as previously reported, the + trials of the 250 ms RSI condition ($p < .05$, Bonferroni corrected). Initial angular offsets on all – trials were higher than those in the N condition ($p < .05$, Bonferroni corrected) except for – – trials of the 600 and 1000 ms RSI conditions and the + – trials of the 1000 ms RSI condition.

The mean CI measures were evaluated with the same ANOVA. All main effects and interactions were reliable, $p < .05$, except the interaction between RSI and previous trial type, $p = .78$. In the three way interaction, the effect of previous trial type decreased with an increase in RSI, but only for the – trials. The final statistical tests compared trials in the mixed-trial blocks with their respective blocked-trial control conditions. All +

conditions had CI values that were not reliably different from those in the A condition ($p > .35$). CI values on all – trials were higher than those in the N condition ($p < .05$, Bonferroni corrected) except for – – trials of the 600 and 1000 ms RSI conditions and the + – trials of the 1000 ms RSI condition.

*Effect of Obstacle Recency for Outward Movements*

The effects of obstacle recency for outward movements are shown in Figures 19 and 20 for the initial angular offset and CI measure, respectively. Like the effect of previous trial type, the effect of obstacle recency decreased as RSI increased. The effects of obstacle recency were observed even in the 1000 ms RSI condition for both + and – trials (except for + trials using the CI measure), suggesting that the memory trace built up over multiple preceding trials remained active for at least 1000 ms.

These conclusion were supported with a 3 (RSI: 250 ms, 600 ms, or 1000ms) × 2 (previous trial type: obstacle-present or obstacle-absent) × 3 (obstacle recency: most, medium, and least) mixed factor ANOVA, where all factors were manipulated within participants except for RSI. Separate analyses were run for + and – trials. For the initial angular offset measure, the only reliable effects for + trials were a main effect of previous trial type, $F(2, 96) = 135.43$, $p < .001$, and a main effect of obstacle recency, $F(2, 96) = 17.81$, $p < .001$. For – trials using the initial angular offset measure, all main effects and interactions were reliable, $p < .01$, except the interaction between RSI and obstacle recency, $p = .57$, and the three way interaction, $p = .28$.

For the CI measure, there was no reliable effect of RSI for + trials. The only reliable result of the ANOVA was the interaction between previous trial type and obstacle recency, $F(2, 96) = 5.86$, $p = .003$. For this interaction, there was a small effect of obstacle recency for trials preceded by obstacle-absent trials, but no effect of obstacle recency for trials preceded by obstacle-present trials. In the – trials, all main effects and interactions were reliable, $p < .05$, except the interaction between RSI and obstacle recency, $p = .43$, and the three way interaction, $p = .33$.

*Angular Separation Between Targets in Successive Trials*

The pattern of hand path generalizability changed slightly as RSI increased, as shown in Figures 21 and 22 for the initial angular offset and CI measures, respectively. The overall pattern of generalizability for – + trials remained consistent across RSI values, with hand paths generalizing equally across all values of angular separation. However, the pattern of generalizability changed for the + – trials as RSI increased. The pattern of generalizability was similar across RSIs for low values of angular separation. For example, curvature in all RSI conditions was higher for angular separations of 30° than angular separations of 90°. The amount of generalization was different for the three RSI conditions for higher values of angular separation, however. For the 250 ms RSI condition (Experiment 1), curvature was higher for angular separations of 180° than angular separations of 90°. This difference was not observed in the 600 and 1000 ms RSI conditions. Thus, there was less generalization from a preceding movement made in the same direction for the 600 ms and 1000 ms RSI conditions than the 250 ms RSI condition. This finding is consistent with the earlier conclusion that longer RSIs reduced but did not eliminate the influences of preceding movements.

The effect of angular separation was evaluated with four 3 (RSI) × 6 (angular separation) ANOVAs, performed separately for initial angular offset and CI measures as well as separately for – + and + – trials.

For the initial angular offset measure of – + trials, there was no main effect of RSI, $F(2, 48) < 1$, *ns*, no main effect of angular separation, $F(5, 240) < 1$, *ns* , and no interaction between RSI and angular separation, $F(10, 240) < 1$, *ns*. On + – trials, there was a main effect of RSI, $F(2, 48) = 18.36$, $p < .001$, a main effect of angular separation, $F(5, 240) = 18.92$, $p < .001$, and an interaction between RSI and angular separation, $F(10, 240) = 1.95$, $p = .039$. In the interaction, the effect of angular separation did not interact with RSI when only the 600 and 1000 ms were compared, $F(5, 160) < 1$, *ns*, although both main effect were reliable, $p < .001$ for each.

For the CI measure, on – + trials there was a main effect of RSI, $F(2, 48) = 67.47$, $p < .001$, a main effect of angular separation, $F(5, 240) = 6.46$, $p < .001$, and an interaction between RSI and angular separation, $F(10, 240) = 5.05$, $p < .001$. These main effects and interactions were not of interest in the present analysis because – + trials did not show evidence of hand path reuse (their mean was not reliably different from that of the A condition). On + – trials, there was a main effect of RSI, $F(2, 48) = 70.26$, $p < .001$, a main effect of angular separation, $F(5, 240) = 11.79$, $p < .001$, and an interaction between RSI and angular separation, $F(10, 240) = 4.37$, $p < .01$. In the interaction, the effect of angular separation did not interact with RSI when only the 600 and 1000 ms conditions were compared, $F(5, 160) = 1.69$, $p = .14$, although both main effect were reliable, $p < .001$ for each.

*Reaction time*

The hand path analyses showed that the effect of previous trial-type decreased, but was not eliminated, at longer RSIs. This result was consistent with the hypothesis that the previous movement path's memory trace decayed with time. However, reaction times for all conditions increased with RSI, as shown in Figure 23. This effect was likely caused by participants being better able to predict the start of the next trial at short RSIs than at long RSIs, a conjecture supported by the well known finding that timing variability increases with the length of the interval to be timed (Getty, 1975). The positive correlation between RT and RSI makes it difficult to confirm the decaying memory trace hypothesis. An alternative explanation is that the effects of the previous trial on hand path curvature decreased because participants had more time to adjust the previously planned hand path before movement initiation. Correlations between RT and hand path curvature described in previous experiments support the possibility of this alternative explanation. Although the exact explanation for the effect is unclear, the results of Experiment 4 showed that the effect of preceding movements decreased with increased time between movements.

The effect of previous trial type on RT decreased as RSI increased, and was not present in the 600 ms and 1000 ms RSI conditions. The reason for this difference in the results for the 250 ms RSI condition and for the 600 ms and 1000 ms RSI conditions is unclear. The reaction time data across experiments will be discussed in more detail in the General Discussion section.

The conclusions about RT were supported with a 3 (RSI: 250 ms, 600 ms, or 1000ms) × 2 (previous trial type: obstacle-present or obstacle-absent) × 3 (obstacle recency: most, medium, and least) mixed factor ANOVA, where all factors were manipulated within participants except for RSI. All main effect and interactions were reliable, $p < .03$. Bonferroni-corrected post-hoc comparison of the main effect of RSI showed that RTs in the 250 ms RSI condition were lower than the 600 ms ($p = .003$) and 1000 ms ($p < .001$) RSI conditions, which did not differ ($p = .76$).

*Correlations Between RT and Curvature*

The correlations between RT and hand path curvature in Experiment 4 were similar to those in Experiment 1. Again, the correlation relates to the hand-path reuse hypothesis' prediction that as participants take more time to initiate movements on trial-type switches, their performance should become more similar to performance on trials in which no trial-type switch occurred. The hand-path reuse hypothesis predicts that the relationship between RT and hand path curvature should be negative for + – trials (the more time taken, the straighter the path) and positive for – + trials (the more time taken, the more curved the path).

For the + – trials of the 600 ms RSI condition, both correlations between RT and hand path curvature were negative, as predicted by the hand-path reuse hypothesis ($r = -.31$, $p < .001$, for the correlation between RT and initial angular offset; $r = -.23$, $p < .001$, for the correlation between RT and CI). For the – + trials of the 600 ms RSI condition, both correlations between RT and hand path curvature were positive, as predicted by the hand-path reuse hypothesis ($r = .15$, $p < .001$, for the correlation between RT and initial angular offset; $r = .25$, $p < .001$, for the correlation between RT and CI).

For the + – trials of the 1000 ms RSI condition, $r = -.33$ ($p < .001$) for the correlation between RT and initial angular offset and $r = -.18$ ($p < .001$) for the correlation between RT and CI. For the – + trials of the 1000 ms RSI condition, $r = .35$ ($p < .001$) for the correlation between RT and initial angular offset and $r = .10$ ($p = .003$) for the correlation between RT and CI.

The overall negative correlations between RT and hand path curvature on the + – trials and positive correlations on – + trials support the proposal that as participants took more time to initiate movements on trial-type switches, their performance became more similar to performance on trials in which no trial-type switch occurred.

**Summary of Experiment 4**

When the time between trials was increased in Experiment 4 relative to Experiment 1, the effect of previous trial type on hand path curvature decreased but was not eliminated, even when the time between trials was 1000 ms. However, as RSI increased, so did RTs. This finding makes it difficult to confirm that the decreased influence of the previous trial type at longer RSIs was caused by a decay in the previous movement path's memory trace. An alternative explanation is that the effect of the previous trial on hand path curvature decreased because participants had more time to adjust the previously planned hand path before movement initiation. Although the exact explanation for the finding is unclear, the results of Experiment 4 showed that the effect of preceding movements decreased with increased time between movements. The relationship between inter-movement interval and the effect of previous trial on hand path curvature was further explored in Experiment 5.

# CHAPTER 6

## EXPERIMENT 5

The previous experiments have all demonstrated consistent effects of previous trial type on hand path curvature. The after-effects of previous trials have been robust, occurring even when predictable trial sequences were used (Experiment 2) and when the time between trials was 1000 ms (Experiment 4). In fact, the after-effects were only eliminated on outward movements after multiple trial-type repetitions (Experiment 3). An unanswered question from the previous experiments is whether these after-effects are unavoidable or if they represent a functional property of movement planning. For example, the observed sequential effects may be a tradeoff in the perceptual-motor system between the ability to completely modify a previously used hand path and quickly initiate movements in an environment where significant changes in hand paths are required (such as in the task used in this thesis). The observed effects of preceding movements may therefore represent the perceptual-motor system's solution to this tradeoff. By not completely modifying the previous hand path, the perceptual-motor system may have been able to initiate movements more quickly than if complete modification of the previous hand path had occurred.

In Experiment 5 I tested whether the consistent effects of previous trial type on hand path curvature are avoidable. To do this, I simply instructed participants to move as directly as possible to a target when no obstacle was present (i.e., to move in a straight line to it). In addition to testing whether the effects are avoidable, I also tested the tradeoff hypothesis described in the previous paragraph. If the tradeoff hypothesis is correct, reaction times on obstacle-absent trials preceded by obstacle-present trials should be greater when participants were instructed to avoid unnecessarily curved movements than when no instructions about movement curvature were given. The basis for this prediction was that greater modification of the previous hand path is required in the move straight instruction condition than in the no-instruction condition.

## Method

The method for Experiment 5 was the same as Experiment 1, except that participants were given the following instructions at the beginning of the practice trials:

> *In an earlier experiment that was exactly the same as the one you'll be doing, we found that when participants had to switch from making an obstacle-avoiding movement to making a movement where there wasn't an obstacle, they often made unnecessarily curved movements even when they could have moved directly to the target. In this experiment, we want to know is if these unnecessarily curved movements can be avoided. So, what I want you to do when no obstacle appears on the screen is to move as directly to the target as you can. At the end of each set of trials, you'll be given a score based on three things: how quickly you complete the set of trials, how many times you run into the obstacle, and how straight you move when no obstacle appears. The score is highly weighted on how straight you move when no obstacle appears, however, so this should be your highest priority. What you want to do is get the lowest score possible*

*by moving quickly, avoiding collisions with the obstacle, and most importantly by moving straight to the target when no obstacle appears.*

At the end of each block, participants were given a score based on the formula, $S = V \times T(1 + C)$, where V was the average CI value of only the – trials in the block, T was the total time (in ms) to complete the block, and C was the number of obstacle collisions. Participants were urged to strive for ever-lower end-of-block scores, as in the previous experiments.

An additional 17 participants completed the A and N conditions with the instructions to move as straight as possible in the N condition. At the end of each N condition block, participants were given a feedback score, $S = V \times T$, where V was the average CI value of all movements in the block and T was the total time (in ms) to complete the block. This score was equivalent to the score given to participants in the mixed-trial conditions because no obstacle collisions were possible in the N condition blocks. In the A condition blocks, participants were given a feedback score, $S = T(1 + C)$, where T was the total time (in ms) to complete the block and C was the number of obstacle collisions. Before beginning the A condition blocks, participants were told that they did not have to make their movements as straight as possible. Instead, they were told to try to move quickly while avoiding obstacle collisions. Participants were informed that the way their score was calculated would be different between the two conditions, and they should therefore not compare their scores between the two block types.

## Results and Discussion

Trials in which any of the IREDs was out of view of the OPTOTRAK (approximately 2.1% of trials) were removed from analysis, as were trials in which an obstacle collision occurred (approximately 1.1% of trials).

*Hand Path Curvature of Outward Movements*

Hand path curvature of outward movements are shown in Figures 24 and 25 for the initial angular offset and CI measures, respectively. When instructed to move as straight as possible if no obstacle was present, hand path curvature on – trials decreased. However, there was still a reliable effect of previous trial type on curvature, such that movements on both trial types preceded by a + trial were more curved than those preceded by a – trial. Thus, even with instructions to do otherwise, the influence of preceding movement was not completely eliminated.

One unexpected finding was that hand paths on – – trials were *straighter* than the control condition in which no obstacle ever appeared. A possible explanation for this finding is that it may have been mentally effortful for participants to repeatedly make movements on obstacle-absent trials that were straighter than they would normally produce. If this was true, it would be more effortful to make straight movements when only obstacle-absent trials occurred (the N condition) than when obstacle-absent trials only sometimes occurred (the – condition). Because of the additional effort required in the N condition, participants may have sometimes been unable to move as directly as possible.

Although they were not instructed to do so, participants made straighter movements on + trials as well. This occurred even though the instructions explicitly stated that direct movements were only important on obstacle-absent trials. The feedback score given to participants also reinforced the importance of straight movements in only the obstacle-absent trials. The reduced curvature on + trials may have made it easier for the perceptual-motor system to adjust these curved hand paths when direct movements might be required in an upcoming trial. That is, the system may have used that fact that more completely modifying a previous hand path would easier if the difference between the previous and desired hand paths were more similar.

The initial angular offset measure was evaluated with a 2 (instruction type: none or move straight) x 2 (trial type: + or -) x 2 (previous trial type: + or – ) ANOVA, where all factors were manipulated within participants except for instruction type. The only reliable effects were the three main effects and the interaction between instruction type and previous trial type, $p < .001$ for all. For the interaction, the effect of previous trial type was weaker, but still present, in the move straight instruction condition than in the no-instruction condition. The final statistical tests compared trials in the mixed-trial blocks with their respective blocked-trial control conditions. Both + conditions had lower initial angular offset values than those in the A condition ($p < .05$, Bonferroni corrected). Initial angular offsets on – – trials were lower than those in the N condition and initial angular offsets on + – trials were higher than those in the N condition ($p < .05$, Bonferroni corrected).

The CI measure was also evaluated with the same ANOVA. All main effects and interactions were reliable, $p < .001$, except for the interaction between instruction type and trial type, $p = .68$. In the three way interaction, there was no effect of previous trial type on + trials for both instruction conditions, but the effect of previous trial type was weaker, but still present, in the move straight instruction condition than in the no-instruction condition. The final statistical tests compared trials in the mixed-trial blocks with their respective blocked-trial control conditions. Both + conditions had lower CIs than those in the A condition ($p < .05$, Bonferroni corrected). CI values on – – trials were lower than those in the N condition and CIs on + – trials were higher than those in the N condition ($p < .05$, Bonferroni corrected).

*Practice Effects*

As in the previous experiments, the evidence for plan reuse was robust over the levels of practice sampled. The only reliable effects of practice came from the CI measures of – + trials. As discussed in Experiment 1, this may have been caused by participants learning to give less clearance to the obstacle with practice.

For the + – trials of the instruction condition, the correlation between initial angular offset and block number was -.05 ($p = .07$) and the correlation between CI and block number was -.04 ($p = .17$). For – + trials, the correlation between initial angular offset and block number was -.03 ($p = .25$) and the correlation between CI and block number was -.14 ($p < .001$).

*Return Movements*

The influence of previous trial type was eliminated on the return movements of Experiment 5, as shown in Figures 26 and 27 for the initial angular offset and CI measures, respectively. For both trial types and both measures, the previous trial type did not influence hand path curvature on return movements. This finding was likely caused by the small effect that previous trial type had on the outward movement. If the return movement was planned using the previous outward movement's hand path, this slight additional curvature would be easy to modify.

On a movement-by-movement analysis, positive correlations were observed between the hand path curvature measures for outward and return movements, as in the other experiments. In the no-instruction condition, the correlations between outward and return movement curvature were .086 and .286 for – trials (as measured by initial angular offset and CI, respectively) and .24 and .45 for + trials ($p < .001$ for all). The weaker correlations for the – trials was likely caused by a reduced range of curvature values ( these trials were straighter and less variable than – trials in previous experiments).

The mean initial angular offsets were evaluated with a 2 (instruction type: none or move straight) x 2 (trial type: + or -) x 2 (previous trial type: + or – ) ANOVA, where all factors were manipulated within participants except for instruction type. All main effects and interactions were reliable, $p < .001$, except for the interaction between instruction type and trial type. In the three way interaction, there was an interaction between trial type and previous trial type in the no-instruction condition, but not in the move straight instruction condition. In this condition, only the main effect of trial type was reliable. The final statistical tests compared trials in the mixed-trial blocks with their respective blocked-trial control conditions. Both + conditions had lower initial angular offset values than those in the A condition ($p < .05$, Bonferroni corrected). Similarly, initial angular offsets on both – conditions were lower than those in the N condition ($p < .05$, Bonferroni corrected).

The mean CI measures were evaluated with the same ANOVA. All main effects and interactions were reliable, $p < .04$, except for the interaction between instruction type and trial type. In the three way interaction, there was an interaction between trial type and previous trial type in the no-instruction condition, but not in the move straight instruction condition. In this condition, only the main effect of trial type was reliable. The final statistical tests compared trials in the mixed-trial blocks with their respective blocked-trial control conditions. Both + conditions had lower CIs than those in the A condition ($p < .05$, Bonferroni corrected). Similarly, CI values on both – conditions were lower than those in the N condition ($p < .05$, Bonferroni corrected).

*Effect of Obstacle Recency for Outward Movements*

The effect of obstacle recency on hand path curvature for Experiment 5 is shown in Figures 28 and 29 for the initial angular offset and CI measures, respectively. Although the effect of previous trial type was reliable for both measures, the effects of obstacle recency were only reliable for the initial angular offset measure. Thus, when instructed to move straight, movements preceding the previous trial did not seem to affect hand path curvature. This finding is in contrast to the previously reported finding in other experiments that the influence of previous movements persisted for many trials. However, the result in the current experiment is consistent with the earlier conclusion that instructions reduced, but did not completely eliminate, the influences of preceding movements.

The initial angular offset measure was evaluated with a 2 (instruction type: none or move straight) x 2 (previous trial type: + or – ) x 3 (obstacle recency) ANOVA, where all factors were manipulated within participants except for instruction type. Separate ANOVAs were completed for the + and – trials. For the + trials, the only reliable effects were the three main effects, $p < .04$. For the – trials, the only reliable effects were the three main effects and the interaction between instruction type and previous trial type, $p < .001$. In this interaction, the effect of previous trial type was weaker, but still present, in the move straight instruction conditions than in the no-instruction condition.

The CI measure was evaluated with the same ANOVA. For the + trials, only the main effect of instruction type and previous trial type were reliable, $p < .008$. For the – trials, only the main effect of instruction type was reliable, $p < .001$.

*Angular Separation Between Targets In Successive Trials*

The effect of angular separation between targets in successive trials for Experiment 5 is shown in Figures 30 and 31 for the initial angular offset and CI measures, respectively. The effect of angular separation between targets in successive trials was weaker, but still present, in the move straight instruction condition than in the no-instruction condition. The overall pattern of generalizability for – + trials remained consistent across both instruction types, with hand paths generalizing equally across all values of angular separation. However, the pattern of generalizability changed for the + – trials in the move straight instruction condition. The pattern of generalizability was similar between the two instruction conditions for low values of angular separation. For example, curvature in both instruction conditions was higher for angular separations of 30° than angular separations of 90°. The amount of generalization was different for the two instruction conditions for higher values of angular separation, however. For example, curvature in the no-instruction condition was higher for angular separations of 180° than angular separations of 90°. This difference was not observed in the move straight instruction condition. Thus, there was less generalization from a preceding movement made in the same direction for the move straight instruction conditions than the no-instruction condition. This finding is consistent with the earlier conclusion that instructions reduced, but did not completely eliminate, the influences of preceding movements.

The effect of angular separation was evaluated with four 2 (instruction type: none or move straight) × 6 (angular separation) ANOVAs, performed separately for initial angular offset and CI measures as well as separately for – + and + – trials. For the initial angular offset measure of – + trials, neither main effect, nor the interaction between the two factors, was reliable, $p > .14$. For the + – trials, all effects were reliable, $p < .003$. For the CI measure of – + trials, all effect were reliable, $p < .01$. For the + – trials, all effects were reliable, $p < .001$.

*Reaction Time*

The foregoing analyses of hand path curvature show that when participants were instructed to avoid making unnecessarily curved movements when no obstacle was present, they made reliably straighter movements than in the earlier experiments. Having shown that participants followed the instructions, I next tested whether the observed sequential effects may be a tradeoff in the perceptual-motor system between the ability to completely modify a previously used hand path and quickly initiate movements. The prediction of this tradeoff hypothesis is that reaction times on + – trials would be longer in the move straight instruction condition than the no-instruction condition. This prediction was upheld, as shown in Figure 32. However, RTs in the move straight condition were longer than the no-instruction condition for almost all trial types. For example, RTs were longer in the move straight N condition than the no-instruction N condition. Thus, although the RT results for + – trials were in the predicted direction, the overall slowing of reaction times in the move straight condition makes it difficult to strongly support this prediction.

All of these conclusions were supported by a 2 (instruction type: none or move straight) x 2 (trial type: + or -) x 2 (previous trial type: + or – ) ANOVA, where all factors were manipulated within participants except for instruction type. The primary effect of interest was the main effect of instruction type, which was reliable, $F(1, 32) = 6.98$, $p = .013$. The only other effects that were reliable were the other two main effects and the interaction between instruction type and previous trial type.

*Correlations Between RT and Curvature*

The correlations between RT and hand path curvature in Experiment 5 were similar to those in Experiment 1. Again, the correlation relates to the hand-path reuse hypothesis' prediction that as participants take more time to initiate movements on trial-type switches, their performance should become more similar to performance on trials in which no trial-type switch occurred. The hand-path reuse hypothesis predicts that the relationship between RT and hand path curvature should be negative for + – trials (the more time taken, the straighter the path) and positive for – + trials (the more time taken, the more curved the path).

For the + – trials of the move straight instruction condition, both correlations between RT and hand path curvature were negative, as predicted by the hand-path reuse hypothesis ($r = -.45$, $p < .001$, for the correlation between RT and initial angular offset; $r = -.40$, $p < .001$, for the correlation between RT and CI). For the – + trials of the move straight instruction condition, both correlations between RT and hand path curvature were positive ($r = .23$, $p < .001$, for the correlation between RT and initial angular offset; $r = .28$, $p < .001$, for the correlation between RT and CI). This pattern of correlations between RT and hand path curvature is predicted by the hand-path reuse hypothesis.

## Summary of Experiment 5

When participants were instructed to avoid unnecessarily curved movements on trials when no obstacle was present, they were able to do so. However, instructions reduced, but did not completely eliminate, the influences of preceding movements. That is, obstacle-absent trials were still more curved when preceded by obstacle-present trials than when preceded by obstacle-absent trials. Finally, I tested the hypothesis that the observed effects of previous trial type on hand path curvature represented a tradeoff in the perceptual-motor system between the ability to completely modify a previously used hand path and quickly initiate movements. The results of Experiment 5 provide mixed support for this hypothesis. Reaction times in all conditions were longer in Experiment 5 than in Experiment 1, showing that additional planning time was required to make straighter movements. However, this increase in reaction time was not specific to the + –

condition, as predicted by the tradeoff hypothesis. Therefore, the tradeoff hypothesis was neither confirmed nor disconfirmed by the results of Experiment 5.

# CHAPTER 7

## GENERAL DISCUSSION

In this thesis I proposed the hand-path reuse hypothesis, which states that movement planning relies on the reuse and modification of previous hand paths. This hypothesis differs from existing models of motor control which rely on biomechanical cost minimization and fresh movement planning for each upcoming movement. The hand-path reuse hypothesis assumes, by contrast, that the ability to minimize biomechanical movement costs is limited by the perceptual-motor system's tendency to modify existing motor plans rather than to generate new plans for ensuing motor acts.

The results from five experiments in which participants performed reaching movements in the presence of or in the absence of an intervening obstacle supported the hand-path reuse hypothesis. When both movement types were required within a block, direct movements were *more* curved when preceded by obstacle–avoiding movements than by other direct movements. Thus, the cost of performing a direct movement was not fully minimized when its path differed significantly from the previous trial's path. In addition, obstacle-avoiding movements were *less* curved when preceded by direct movements than by other obstacle-avoiding movements. This second finding provides additional evidence for the reuse of previous movement plans. In general, the after-effects of the previous trial suggest that the perceptual–motor system reused a relatively high–level hand path representation that could be translated to other regions of space. Further experiments showed that the observed sequential effects were not anticipatory in nature (Experiment 2), that they persisted for many trials (Experiment 3), and that they were reduced when the time between movements was increased (Experiment 4) or when participants were instructed to move as straight as possible when no obstacle appeared (Experiment 5). Collectively, the results show that physical movement costs may not always be minimized if computational demands favor the reuse of movement plans.

The observed sequential effects seem, upon initial consideration, to represent an instance where the reuse of a previous plan is detrimental to performance, as in the parameter remapping effect (Rosenbaum et al., 1986). For example, the unnecessarily curved movements on obstacle-absent trials preceded by obstacle-present trials seem undesirable given the possibility of greater efficiency when straight movements were possible. The after-effects of the previous trial may be less detrimental if one does not assume that biomechanical cost minimization is the goal of movement planning. Instead, the perceptual-motor system may balance the reduction of movement costs with the reduction of computational costs. For example, the computational benefits of reusing the previous hand path on trial-type repetitions may outweigh the slight inefficiency of moving in an overly curved way on trial-type switches. This claim is akin to the idea of satisficing, the approach used for constraint satisfaction in the PB model (Rosenbaum et al., 2001). In effect, the perceptual-motor system may reduce computational demands of movement planning by reusing and modifying the previous hand path until it is "efficient enough." This approach would be less computationally costly than modifying the previous trial's hand path until it is as efficient as possible, or planning movements from scratch each time one is desired.

Although analyses of hand path curvature across experiments supported the hand-path reuse hypothesis, analyses of reaction time were less supportive of the hypothesis. The hand-path reuse hypothesis predicted that modifying the previous hand path would take longer on trial-type switches than on trial-type repetitions. The pattern of reaction time data did not support this prediction. Across experiments, no single reaction time pattern was observed. Instead, two general patterns emerged, which were grouped by how quickly participants initiated movements across conditions. The "fast" conditions were those in Experiments 1, 2, and 3 (shown in Figures 11 and 12) and the "slow" conditions were those in Experiments 4 and 5 (shown in Figures 23 and 32). In the fast conditions, reaction times were determined by the previous trial type. That is, reaction times were shorter on trials preceded by obstacle-present trials than on trials preceded by obstacle-absent trials, regardless of the current trial type. In the slow conditions, reaction times did not reliably depend on the current or previous trial type.

Within trial-type switches, however, the relationship between RT and influence of previous trial type was more consistent with the hand-path reuse hypothesis. When participants took more time to initiate movements on trial-type switches, their performance became more similar to performance on trials in which no trial-type switch occurred. Similar results were observed in the comparison between reaction times for Experiments 1 and 5. Reaction times were longer in Experiment 5, in which participants were instructed to produce hand paths that were as straight as possible on obstacle-absent trials, than in Experiment 1, in which no instructions about movement curvature were given. The "go-straight" instructions led to a reduced effect of the previous trial type on hand path curvature. The reason why the relationship between reaction time and influence of previous trial type was different at the trial and average levels is unclear. Future research is required to investigate this difference.

Aside from these issues, the most important finding is that the effects of the previous trial on hand path curvature were not predicted by current models of obstacle avoiding movements or, in fact, of direct movements. This is because all models assume that the cost of making a direct movement, or of moving around an obstacle, should depend only on the immediate task demands. How, then, could current models of movement planning be modified to account for the present results? Before answering this question, I will first summarize how the relevant models can, or cannot, account for the observed results. Because the current task required obstacle avoidance, I will focus on the two models of reaching that can predict obstacle-avoiding movements and that have been tested against human performance. These two models are the via point model of Hamilton and Wolpert (2002)[5] and the posture-based model of Rosenbaum et al. (2001).

The Hamilton and Wolpert (2002) via point model does not predict the observed sequential effects because it, like other cost minimization models, plans movements anew each time one is desired. The Rosenbaum et al. (2001) posture-based model, however, begins planning by searching through stored representations of recently completed movements. This property of the posture-based model may therefore seem more amenable to predicting the observed sequential effects. However, the posture-based model claims that only the previously planned *end postures* are stored, not the previous movement paths. Even if the previously planned bounce postures are stored (postures to which an additional movement is made when obstacle avoidance is required; see the introduction for details), the model predicts that the previous movement plan would not generalize to other regions of the workspace[1]. This limitation is problematic because the observed sequential effects did generalize to other regions of the workspace. Predicting generalization is easier for a model of hand path planning, like the via point model, if one adds the assumption that the via points can be translated to other areas of the workspace. Thus, one possible model that could account for the reported sequential effects would be one that combines the previous-plan-reuse approach of the posture-based model with the hand path planning of the via point model.

Although planning obstacle-avoiding movements to go through via points is intuitively appealing, and could be used to account for the observed sequential effects, some caution about this proposal is warranted. First, no direct evidence has been provided here or elsewhere that via points are used by humans when planning obstacle avoiding movements. The evidence that does exist for the via point planning comes from the finding that a model using via points can produce human-like hand paths around obstacles. However, human-like performance produced by computational models is not sufficient to show that the same planning mechanisms underlie human performance. (The same can be said for the bounce posture hypothesis of the posture-based model, of course.) More direct evidence for via point planning of obstacle avoidance would likely need to include assumptions about movement variability. For example, examination of the highly variable obstacle-avoiding hand paths shown in Figure 2 yields no obvious point in the workspace through which all hand paths passed. Thus, confirming that via point planning is used for obstacle avoidance by analyzing observed hand paths will likely be a difficult data analysis problem.

Even if evidence for via point planning of obstacle-avoiding movements can be developed, other issues remain. For example, even if a via point is selected, the perceptual-motor system must determine how to smoothly concatenate the movement from the start location to the via point and the movement from the via point to the desired end location. This issue has been taken up by Bullock et al (1999) and Wada and Kawato (2004), although not in the context of obstacle avoidance. Finally, the particular arm configuration at the via point would need to be determined. Because of the degrees of freedom problem, many possible arm configurations could be used to contact the via point during the movement.

These remaining challenges aside, the development of models for more complex movement tasks, such as obstacle avoidance, will likely continue in the future. The development of such models, along with additional behavioral data such as presented in this thesis, will help further our understanding of the power and flexibility of the human perceptual-motor system.

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**APPENDIX: FIGURES**

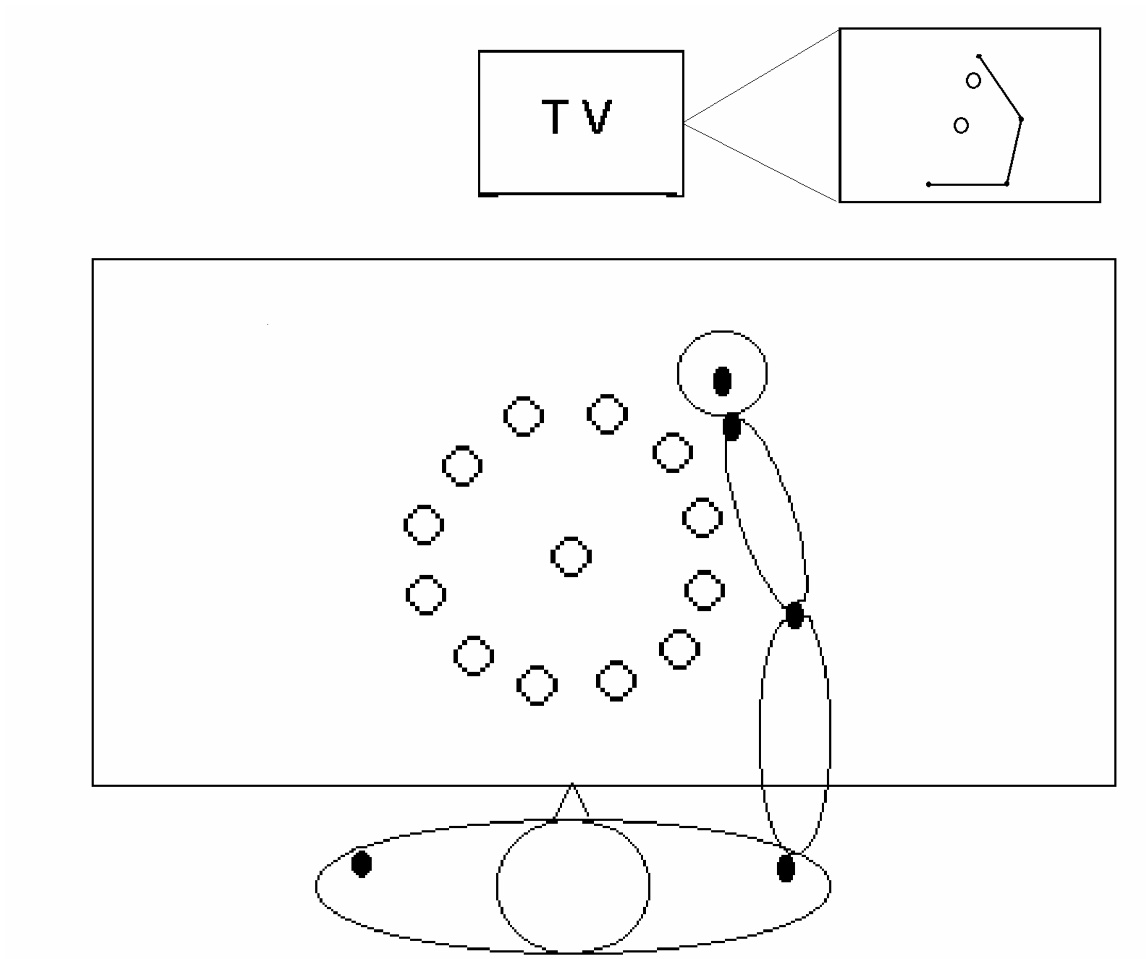



Figure 1.

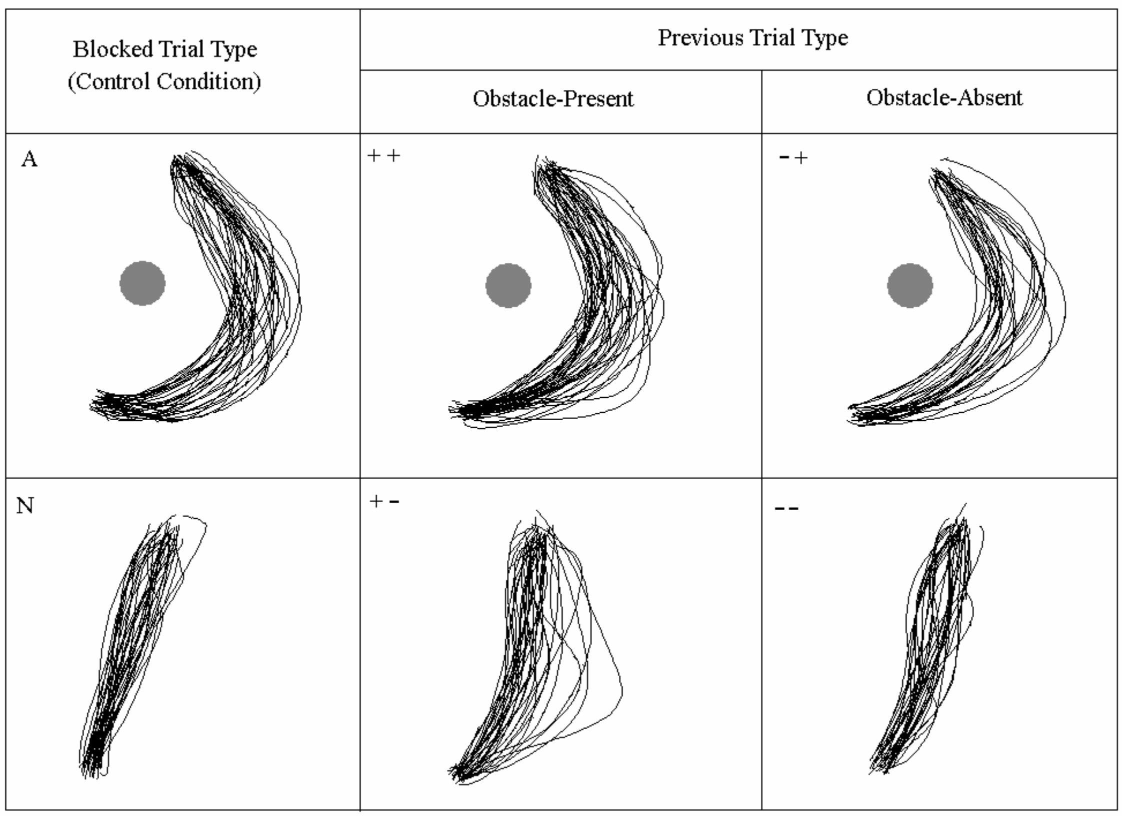

Blocked Trial Type
(Control Condition)
Previous Trial Type
Obstacle-Present
Obstacle-Absent
A
+ +
- +
N
+ -
- -

Figure 2.

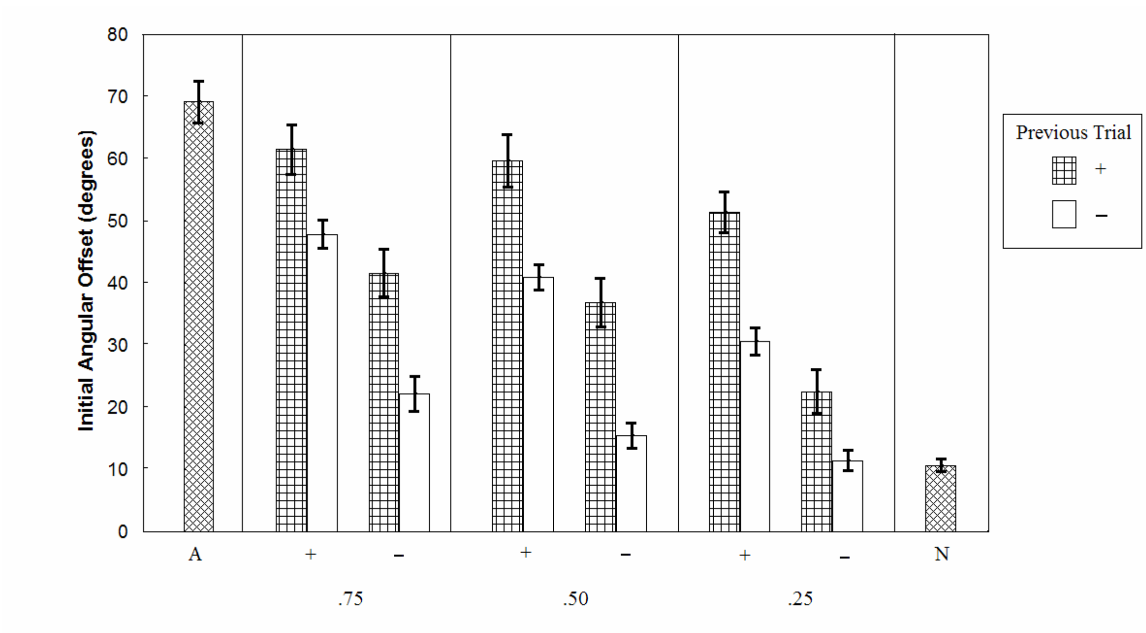

Initial Angular Offset (degrees)
0
10
20
30
40
50
60
70
80
A
+
–
+
–
+
–
N
.75
.50
.25
Previous Trial
+
–

Figure 3.

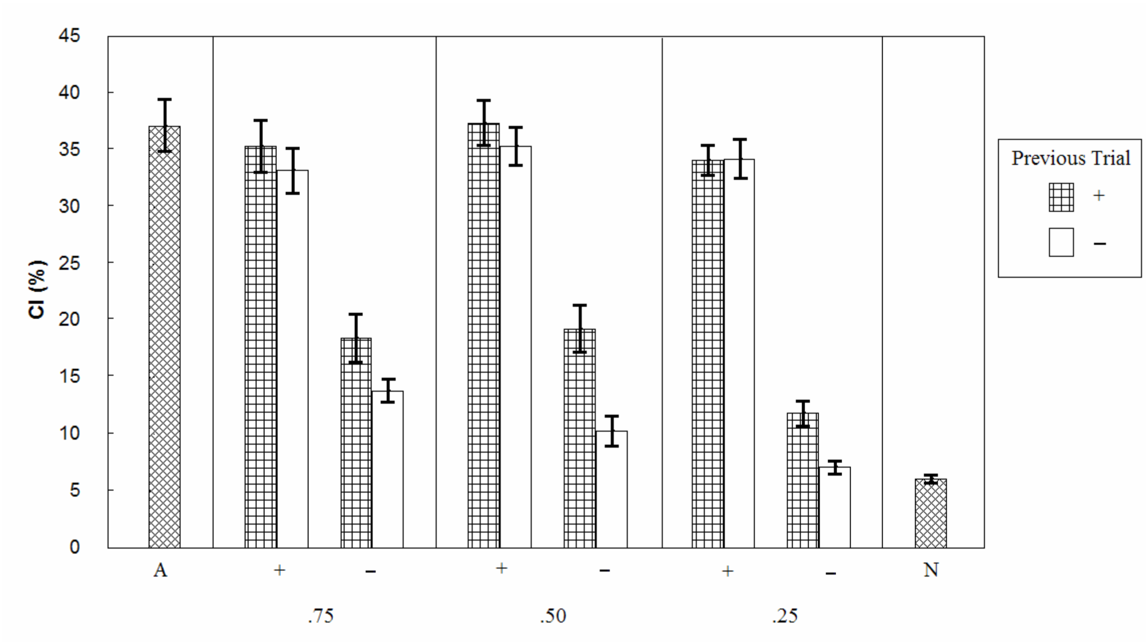
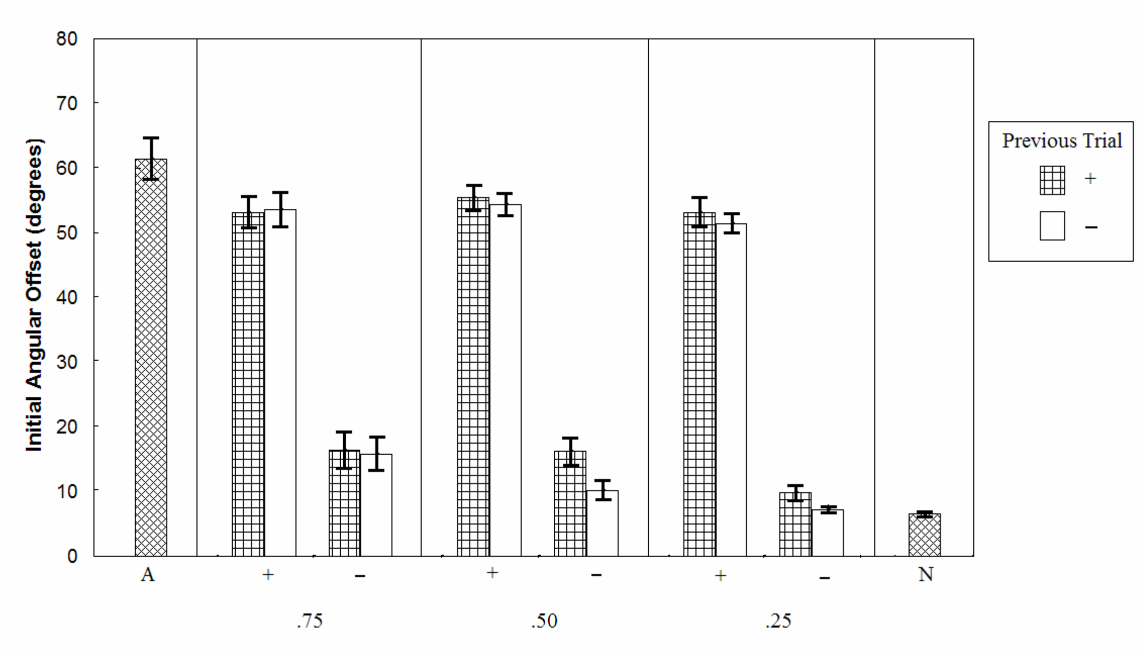



Figure 4.



Initial Angular Offset (degrees)
80
70
60
50
40
30
20
10
0
A
+
–
+
–
+
–
N
.75
.50
.25
Previous Trial
+
–


Figure 5.

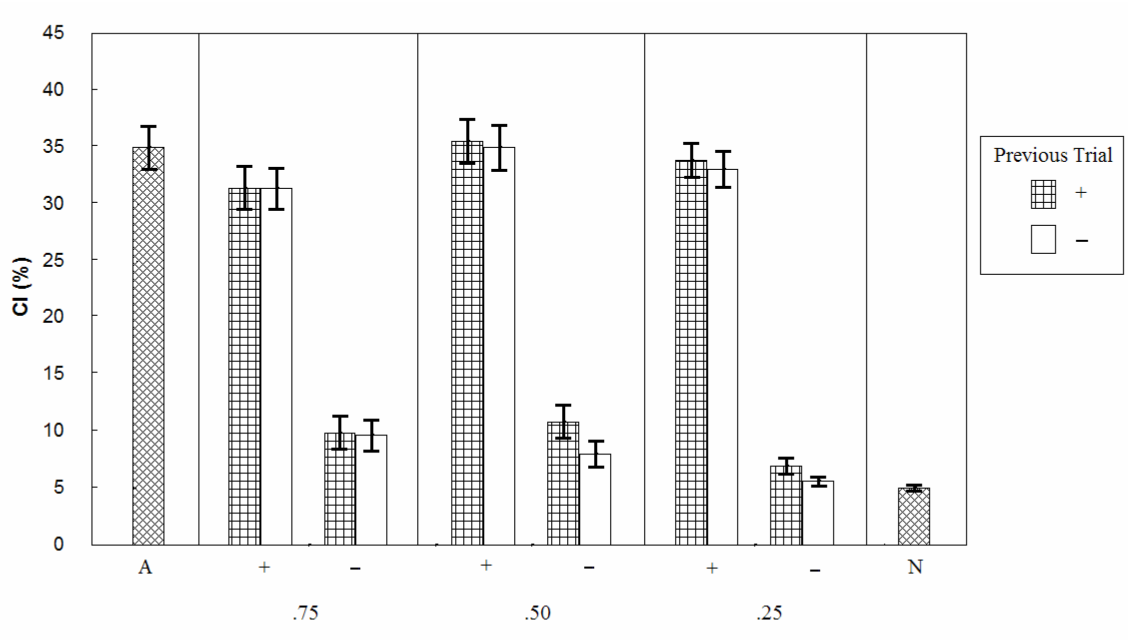



Figure 6.

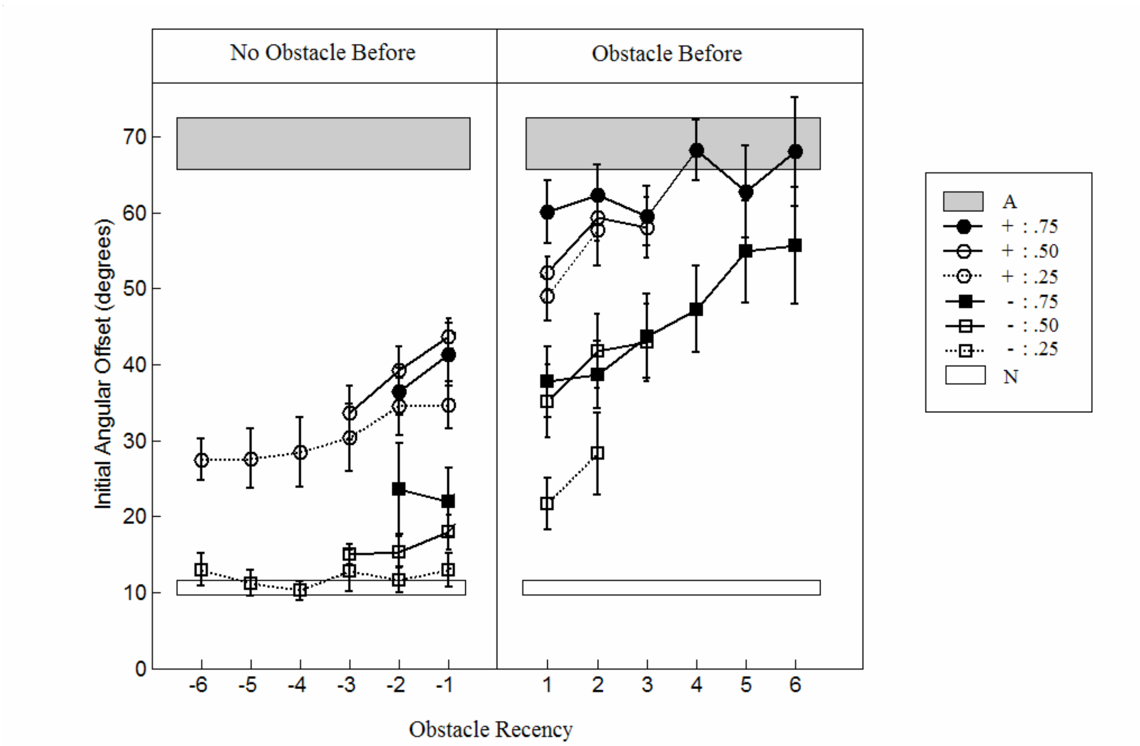
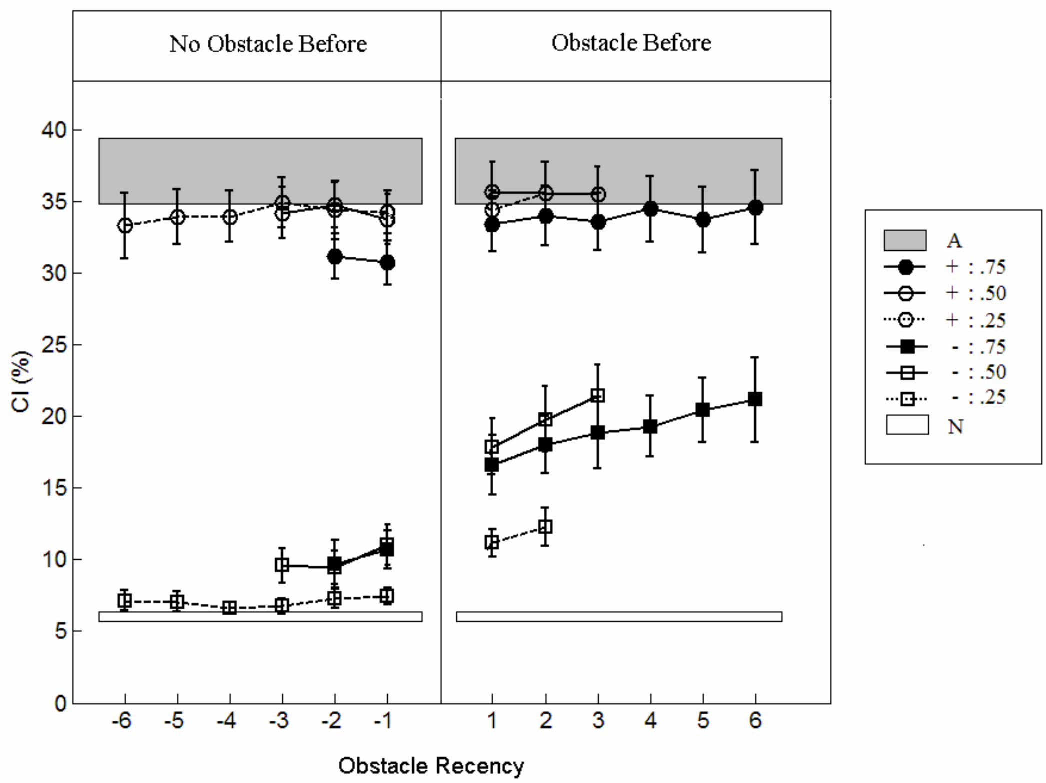
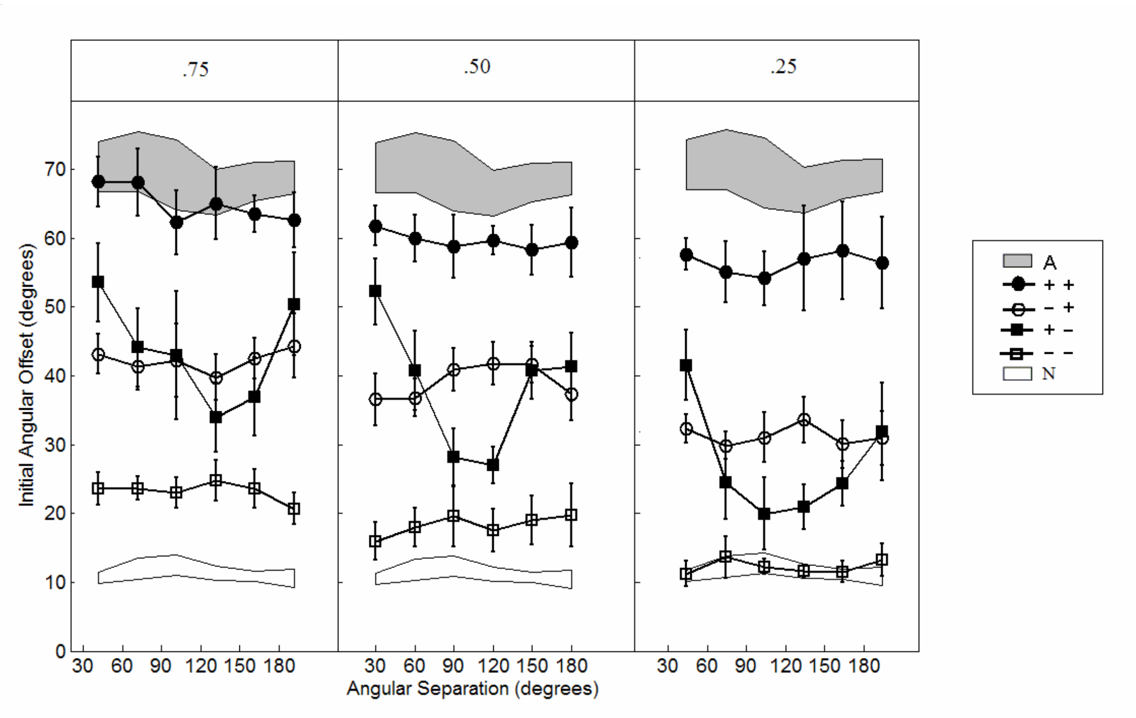

No Obstacle Before
Obstacle Before
Initial Angular Offset (degrees)
70
60
50
40
30
20
10
0
-6
-5
-4
-3
-2
-1
1
2
3
4
5
6
Obstacle Recency
A
+ : .75
+ : .50
+ : .25
- : .75
- : .50
- : .25
N

Figure 7.



No Obstacle Before
Obstacle Before
40
35
30
25
20
15
10
5
0
CI (%)
-6
-5
-4
-3
-2
-1
1
2
3
4
5
6
Obstacle Recency
A
+ : .75
+ : .50
+ : .25
- : .75
- : .50
- : .25
N


Figure 8.



.75
.50
.25
Initial Angular Offset (degrees)
0
10
20
30
40
50
60
70
30 60 90 120 150 180
Angular Separation (degrees)
A
+ +
− +
+ −
− −
N


Figure 9.

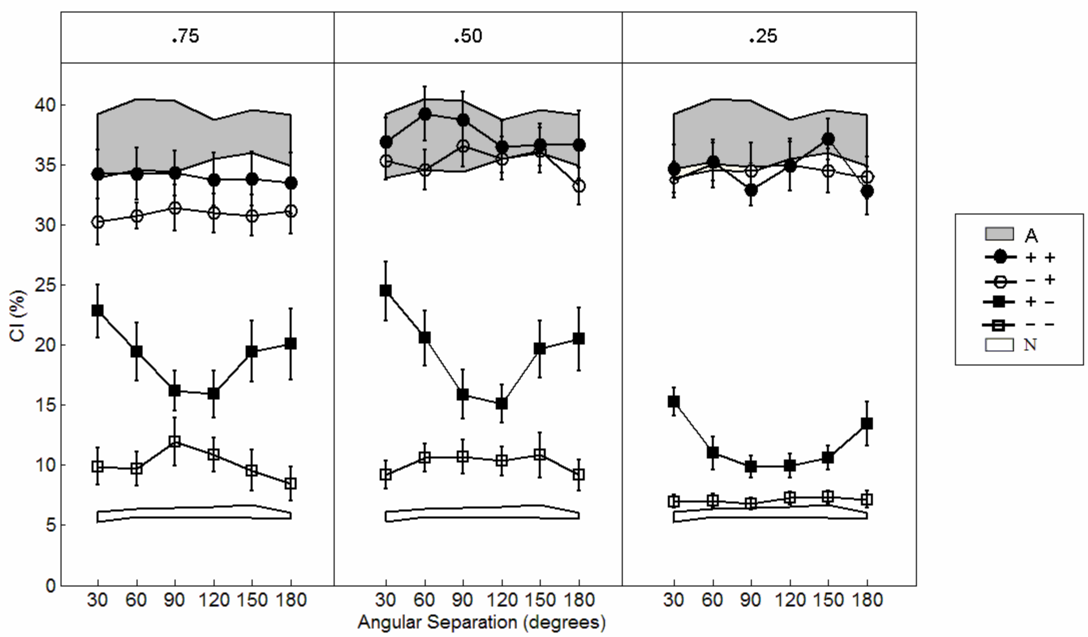



Figure 10.

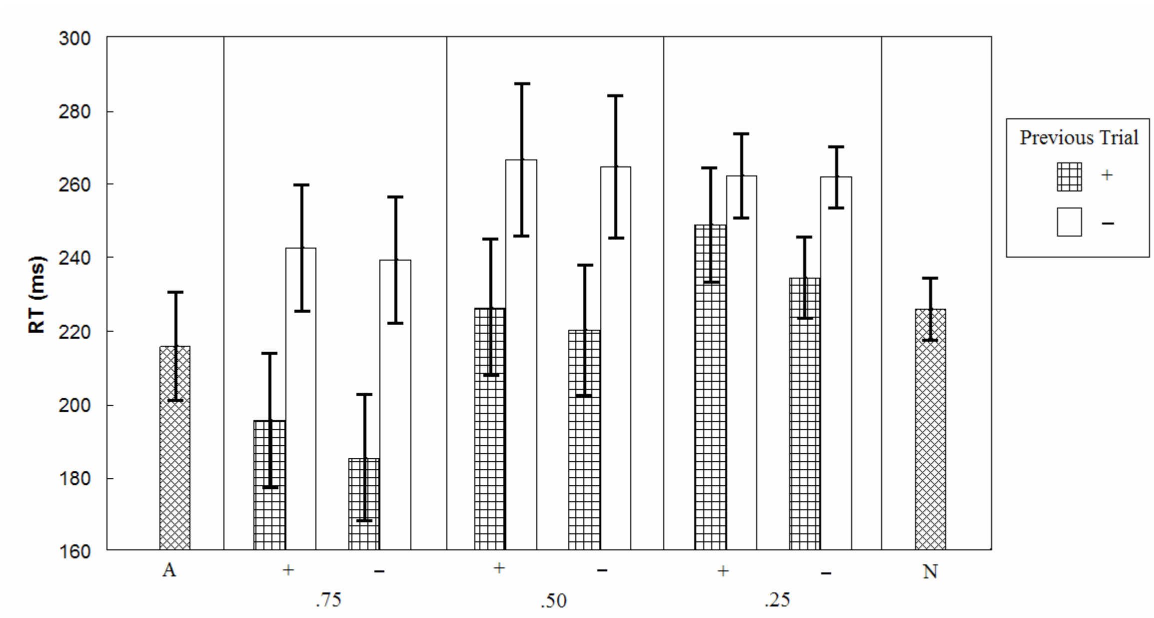
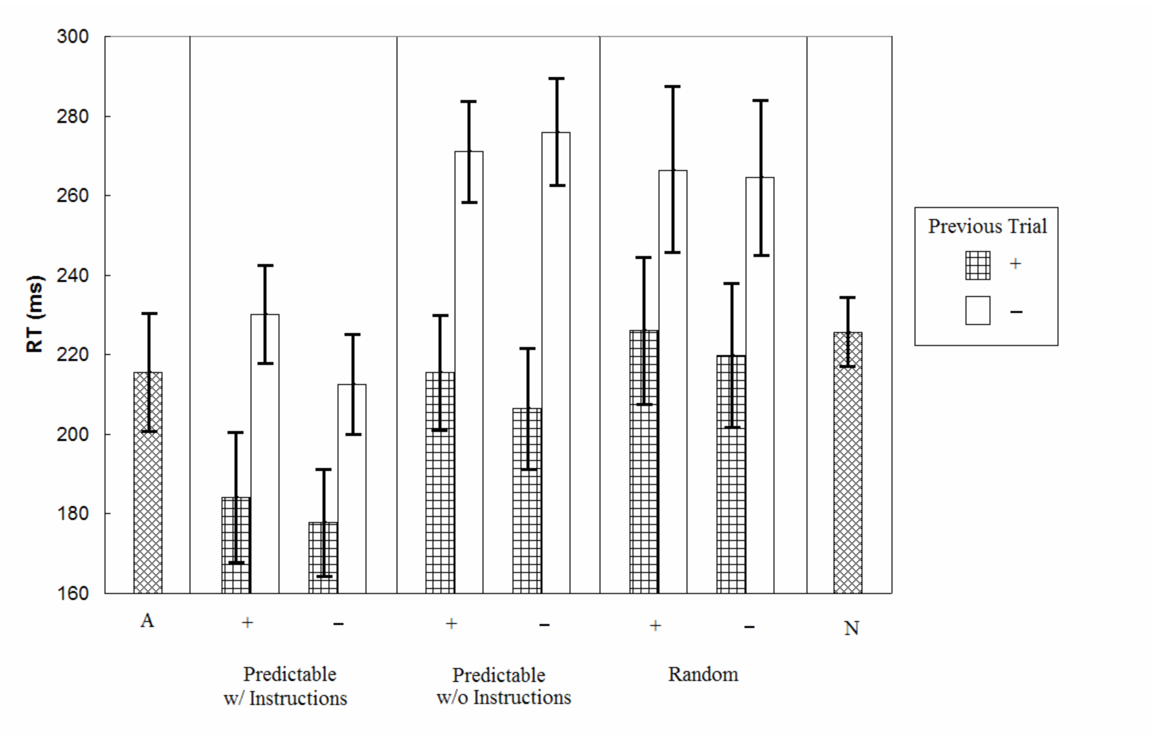
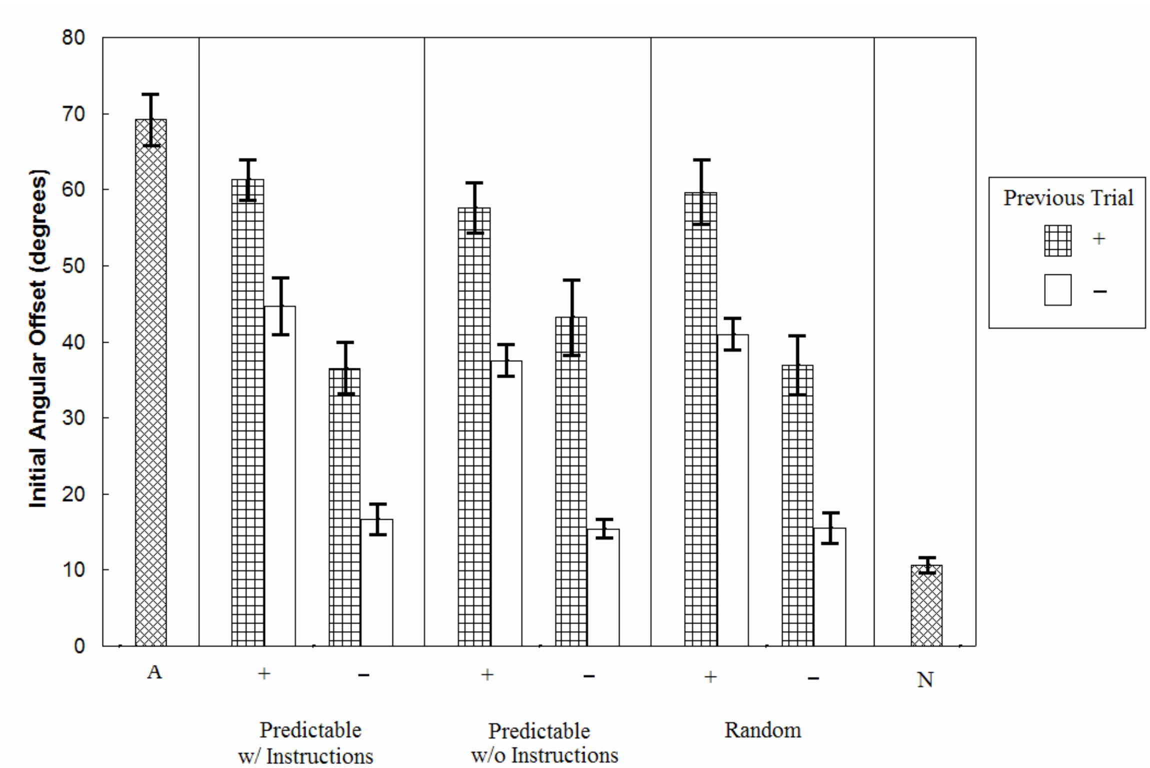



Figure 11.



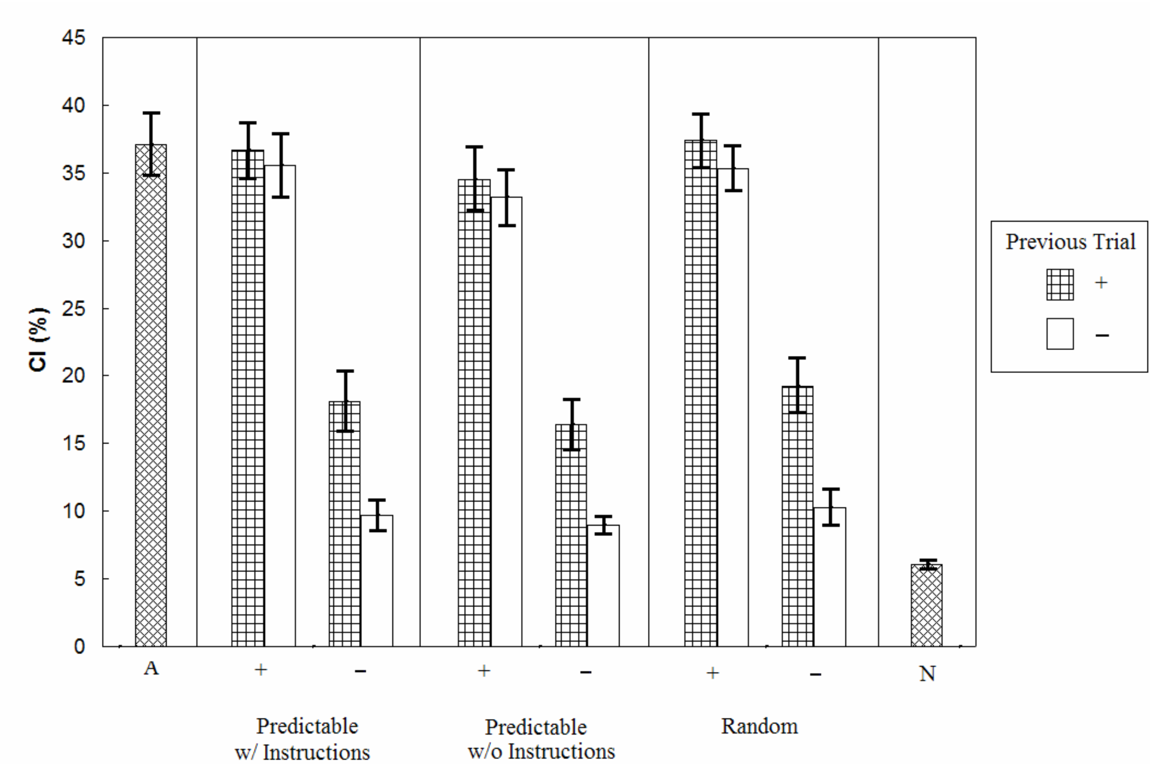
300
280
260
240
220
200
180
160
RT (ms)
A
+
–
+
–
+
–
N
Predictable
w/ Instructions
Predictable
w/o Instructions
Random
Previous Trial
+
–


Figure 12.



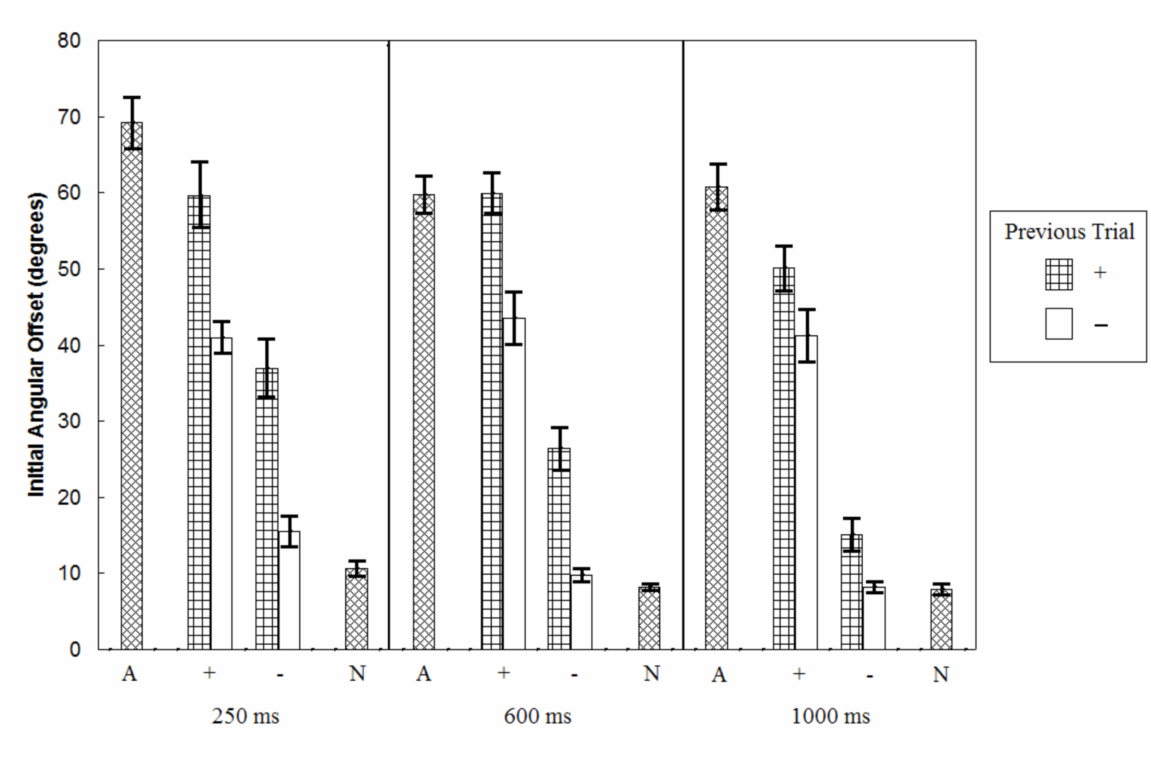
Initial Angular Offset (degrees)
80
70
60
50
40
30
20
10
0
A
+
–
+
–
+
–
N
Predictable
w/ Instructions
Predictable
w/o Instructions
Random
Previous Trial
+
–


Figure 13.



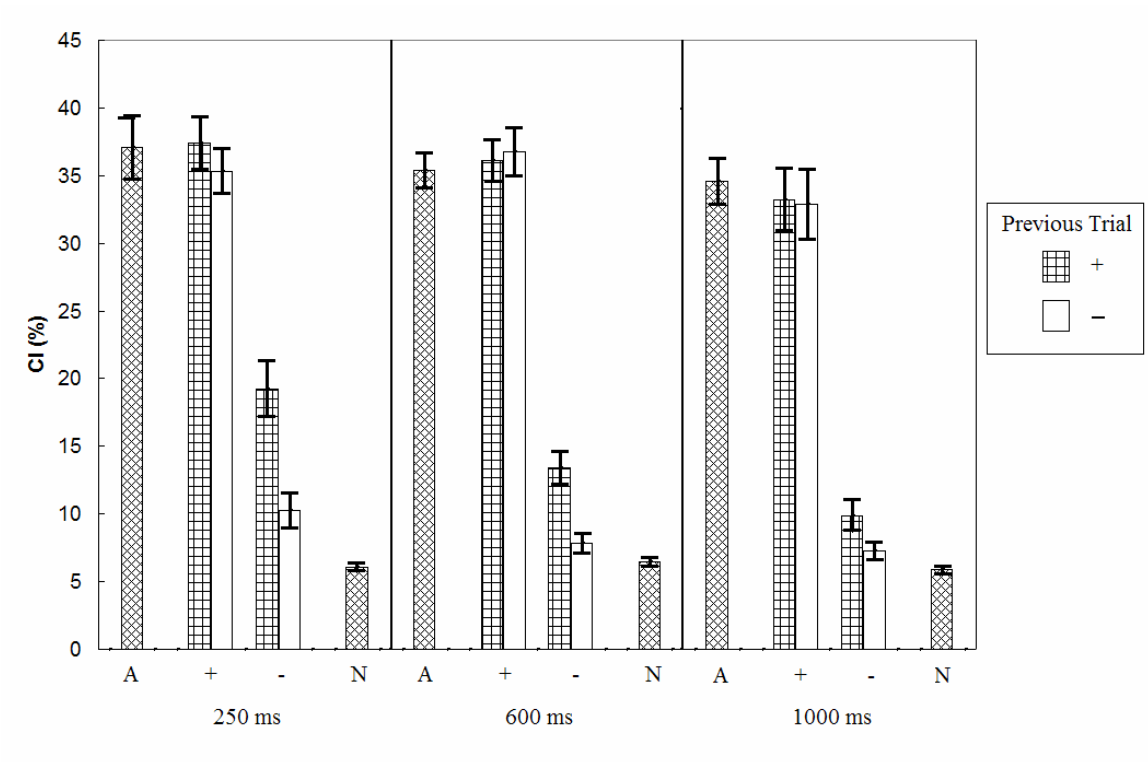
45
40
35
30
25
20
15
10
5
0
CI (%)
A
+
–
+
–
+
–
N
Predictable w/ Instructions
Predictable w/o Instructions
Random
Previous Trial
+
–


Figure 14.



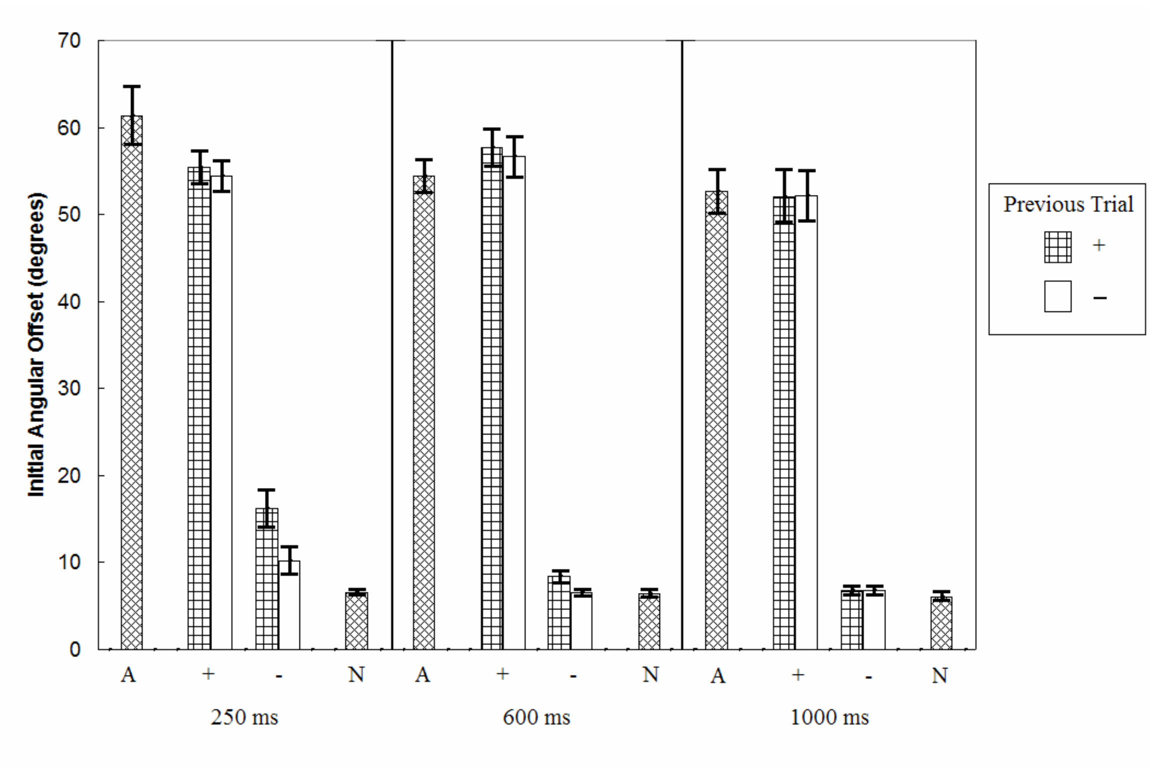
80
70
60
50
40
30
20
10
0
Initial Angular Offset (degrees)
A
+
-
N
A
+
-
N
A
+
-
N
250 ms
600 ms
1000 ms
Previous Trial
+
–


Figure 15.



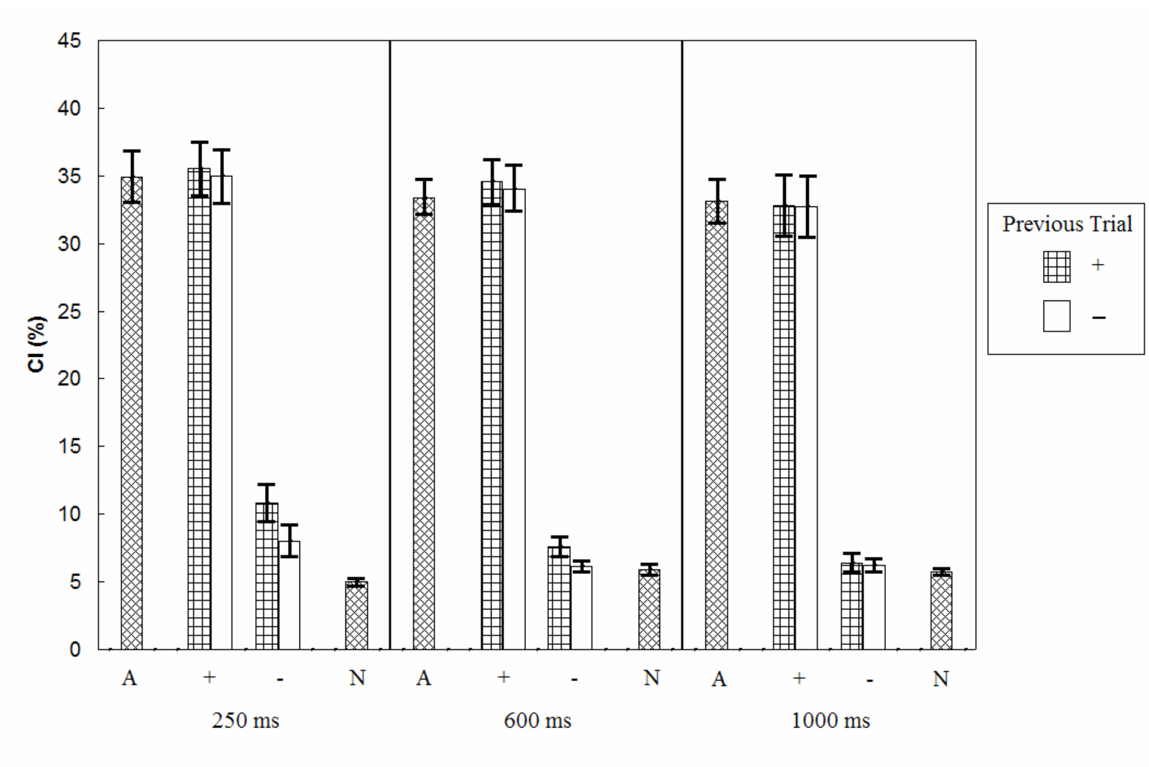
CI (%)
45
40
35
30
25
20
15
10
5
0
A
+
-
N
A
+
-
N
A
+
-
N
250 ms
600 ms
1000 ms
Previous Trial
+
–


Figure 16.



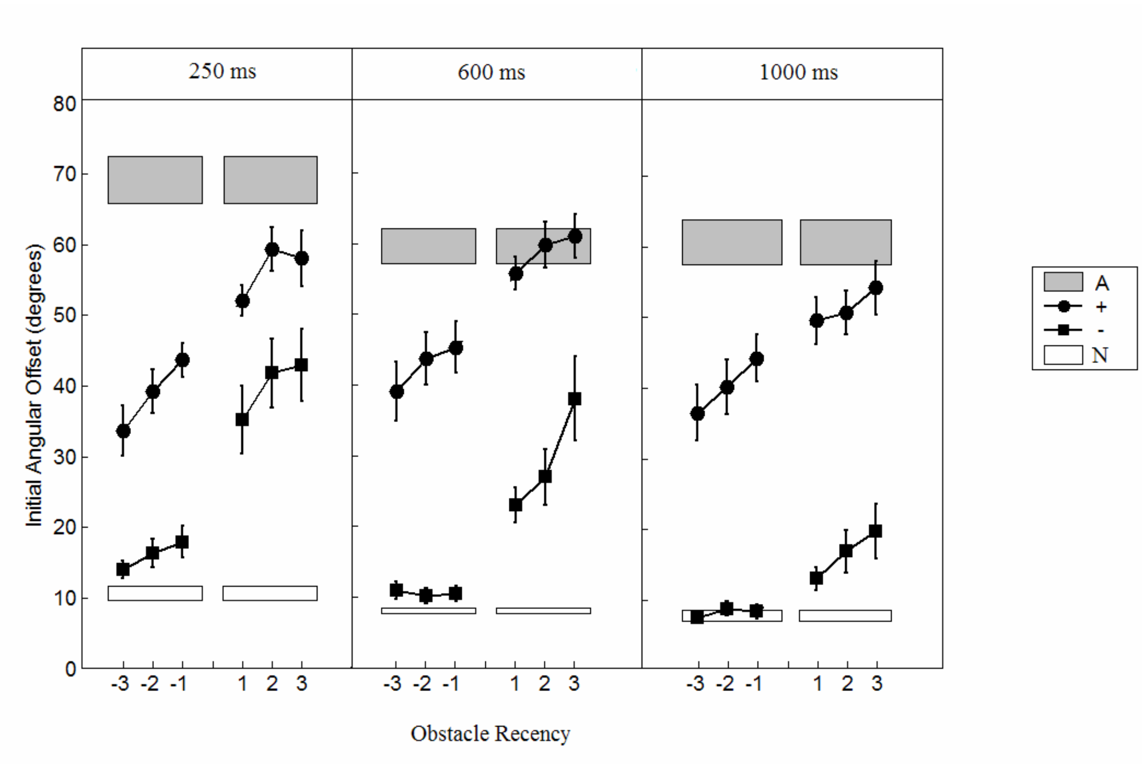
70
60
50
40
30
20
10
0
Initial Angular Offset (degrees)
A
+
-
N
A
+
-
N
A
+
-
N
250 ms
600 ms
1000 ms
Previous Trial
+
–


Figure 17.



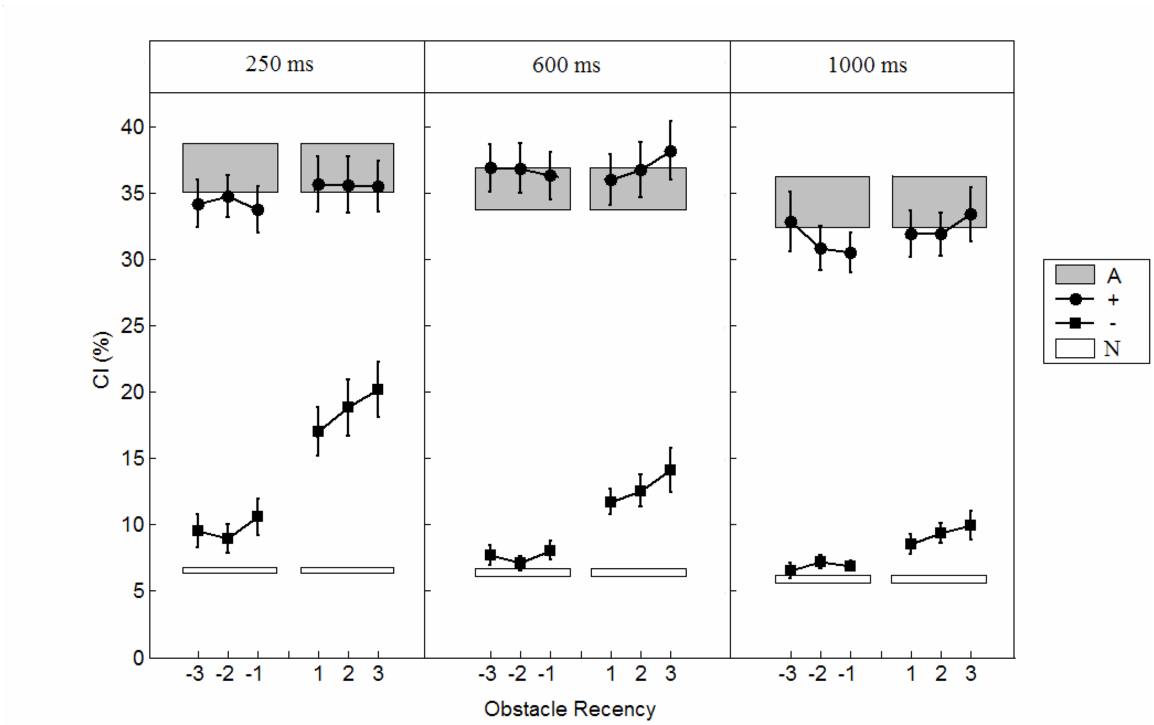
45
40
35
30
25
20
15
10
5
0
CI (%)
A
+
-
N
A
+
-
N
A
+
-
N
250 ms
600 ms
1000 ms
Previous Trial
+
–


Figure 18.



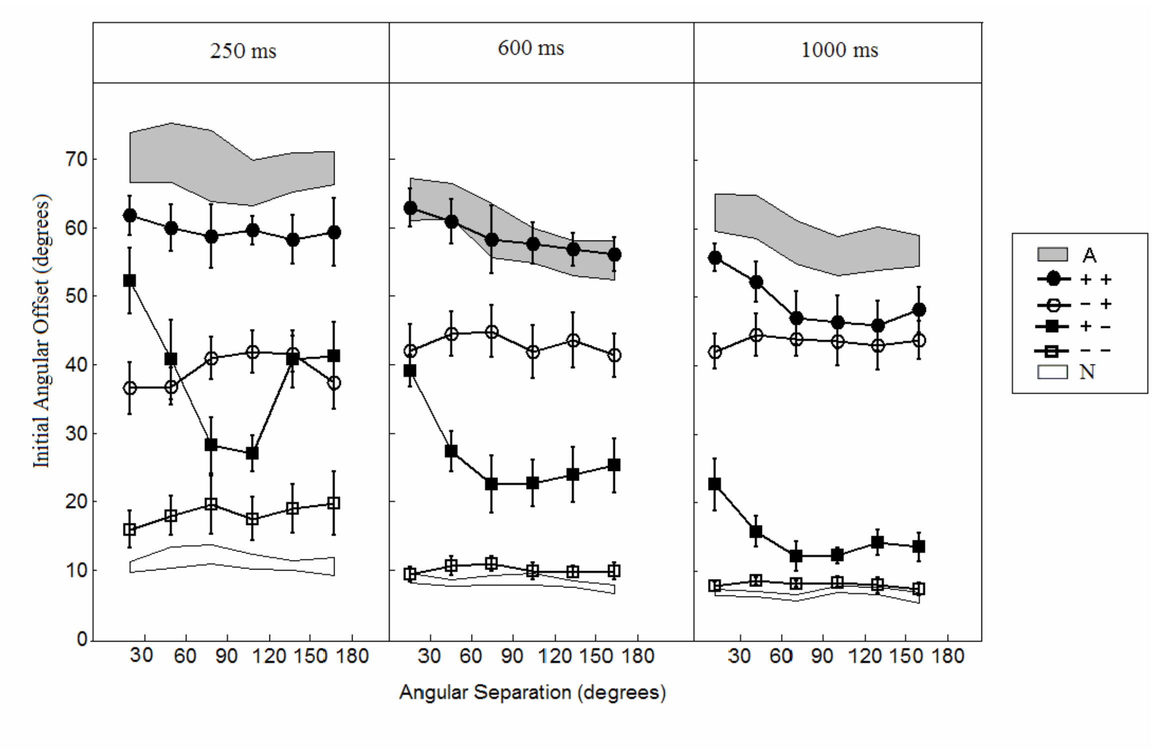
250 ms
600 ms
1000 ms
Initial Angular Offset (degrees)
80
70
60
50
40
30
20
10
0
-3 -2 -1 1 2 3
-3 -2 -1 1 2 3
-3 -2 -1 1 2 3
Obstacle Recency
A
+
-
N


Figure 19.



250 ms
600 ms
1000 ms
CI (%)
40
35
30
25
20
15
10
5
0
-3 -2 -1 1 2 3
Obstacle Recency
A
+
-
N


Figure 20.



250 ms
600 ms
1000 ms
Initial Angular Offset (degrees)
0
10
20
30
40
50
60
70
30 60 90 120 150 180
Angular Separation (degrees)
A
+ +
− +
+ −
− −
N


Figure 21.

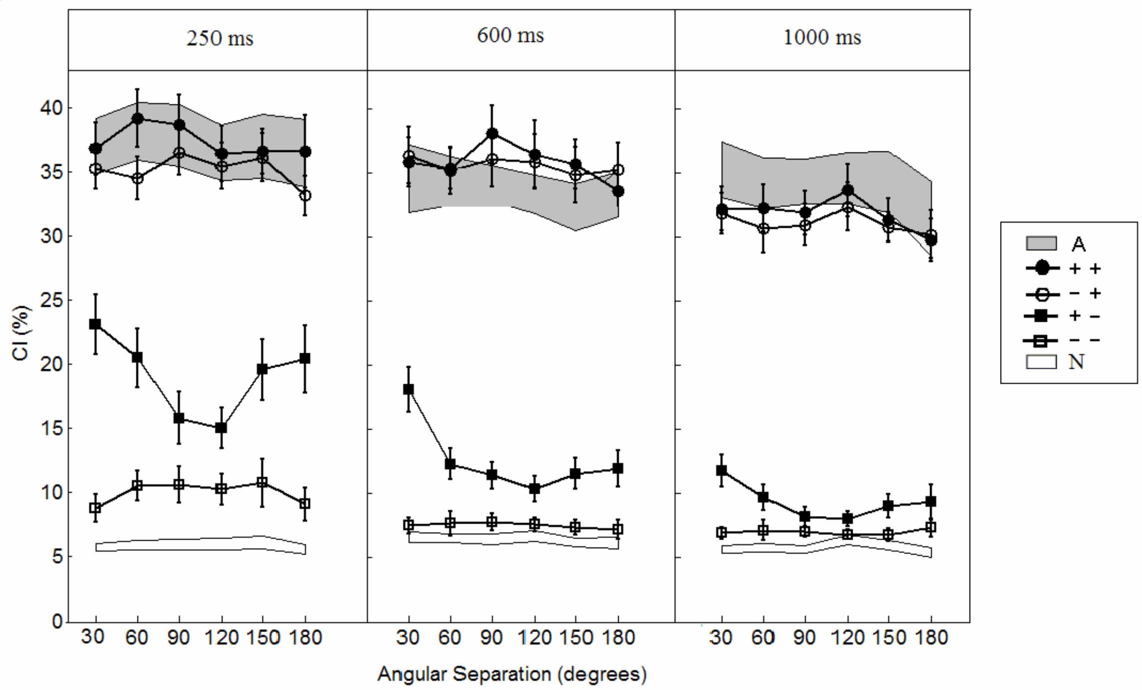
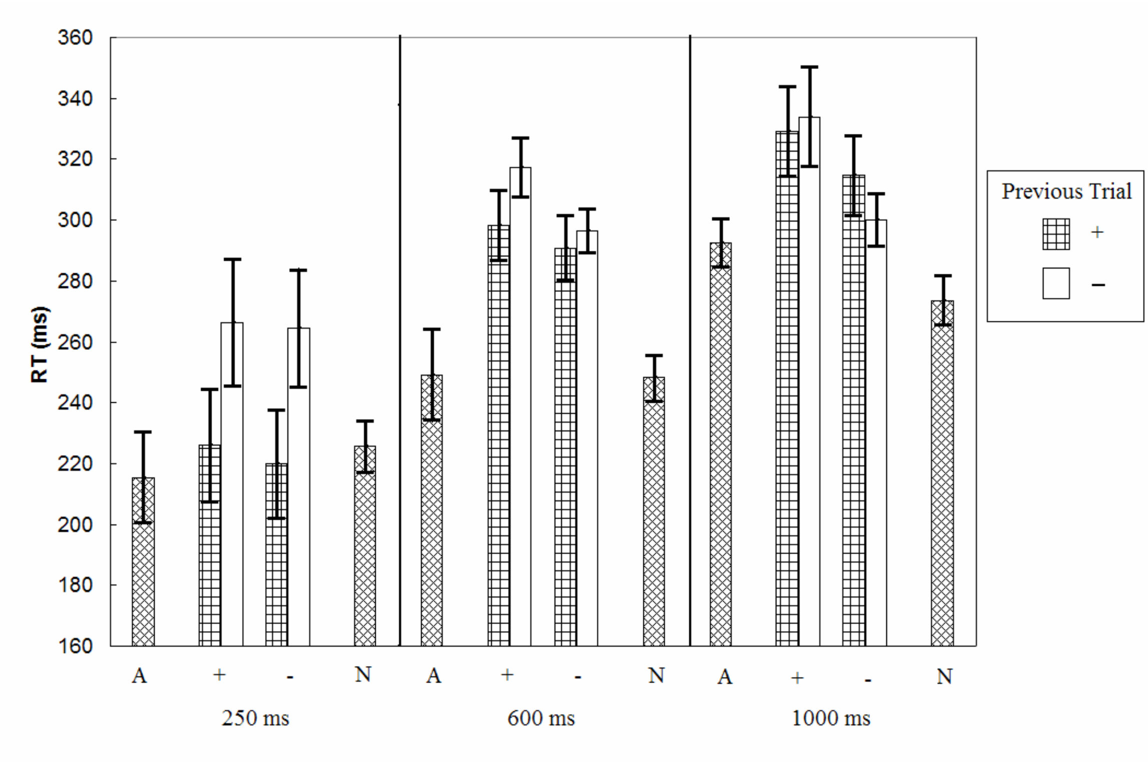
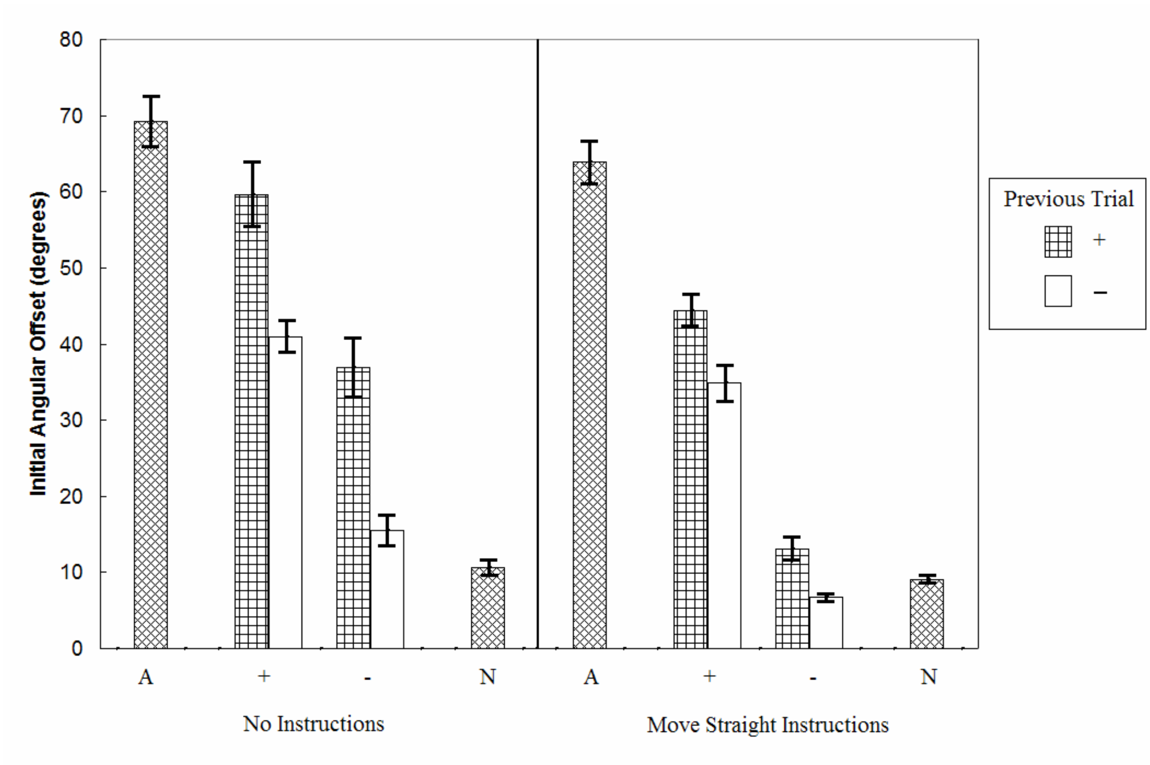

250 ms
600 ms
1000 ms
CI (%)
0
5
10
15
20
25
30
35
40
30 60 90 120 150 180
Angular Separation (degrees)
A
+ +
− +
+ −
− −
N

Figure 22.



360
340
320
300
280
260
240
220
200
180
160
RT (ms)
A
+
-
N
A
+
-
N
A
+
-
N
250 ms
600 ms
1000 ms
Previous Trial
+
–


Figure 23.



80
70
60
50
40
30
20
10
0
Initial Angular Offset (degrees)
A
+
-
N
A
+
-
N
No Instructions
Move Straight Instructions
Previous Trial
+
–


Figure 24.

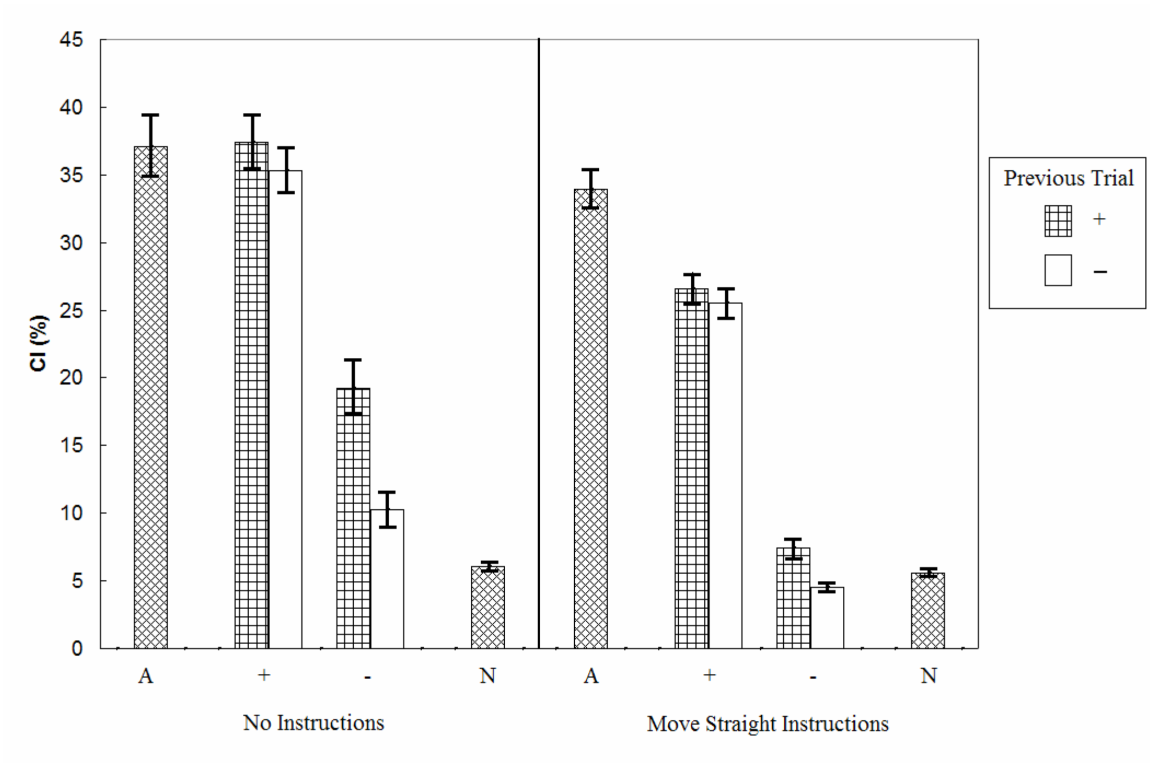

45
40
35
30
25
20
15
10
5
0
CI (%)
A
+
-
N
A
+
-
N
No Instructions
Move Straight Instructions
Previous Trial
+
–

Figure 25.

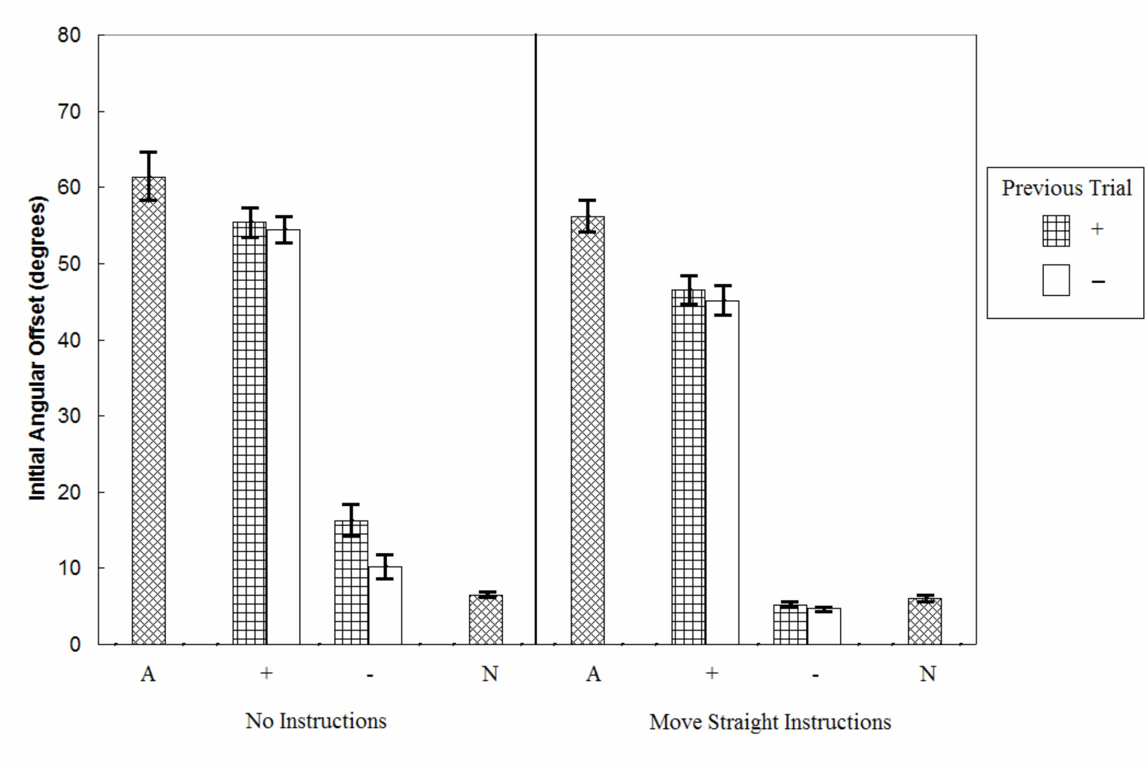
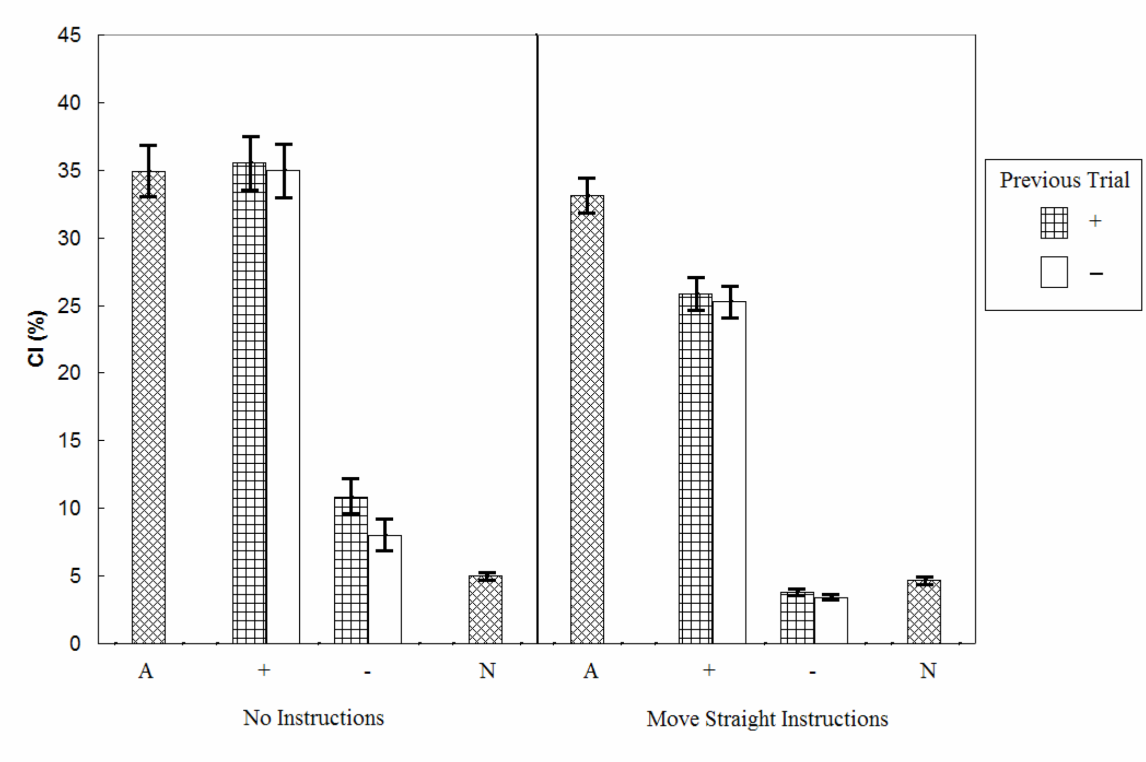
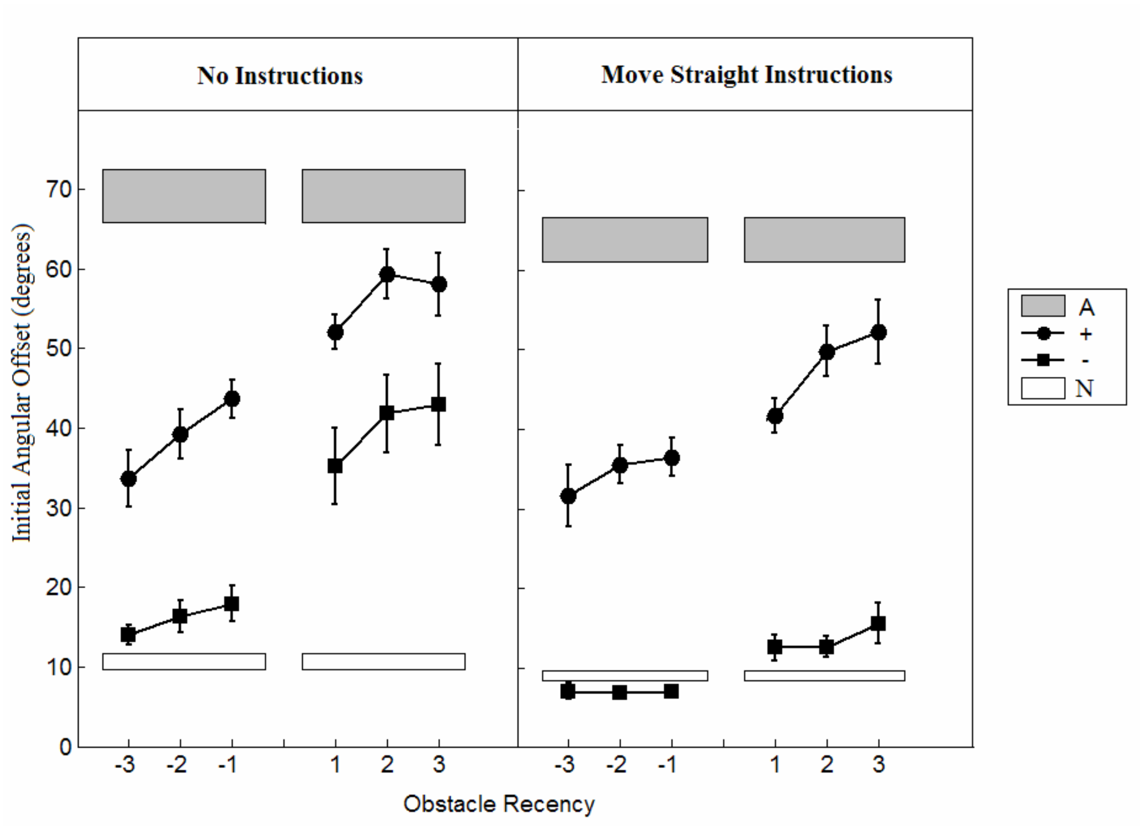

80
70
60
50
40
30
20
10
0
Initial Angular Offset (degrees)
A
+
-
N
A
+
-
N
No Instructions
Move Straight Instructions
Previous Trial
+
–

Figure 26.



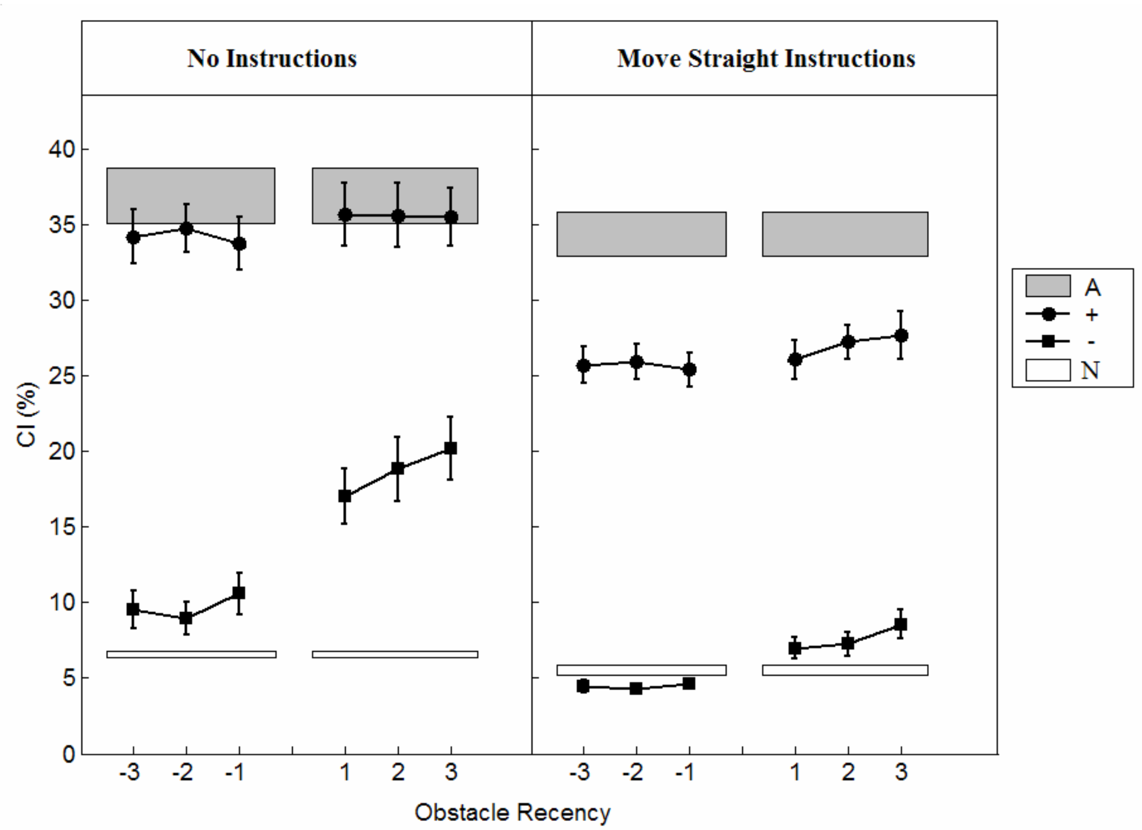
45
40
35
30
25
20
15
10
5
0
CI (%)
A
+
-
N
A
+
-
N
No Instructions
Move Straight Instructions
Previous Trial
+
–


Figure 27.



No Instructions
Move Straight Instructions
Initial Angular Offset (degrees)
70
60
50
40
30
20
10
0
-3
-2
-1
1
2
3
Obstacle Recency
A
+
-
N


Figure 28.



No Instructions
Move Straight Instructions
CI (%)
0
5
10
15
20
25
30
35
40
-3
-2
-1
1
2
3
-3
-2
-1
1
2
3
Obstacle Recency
A
+
-
N


Figure 29.

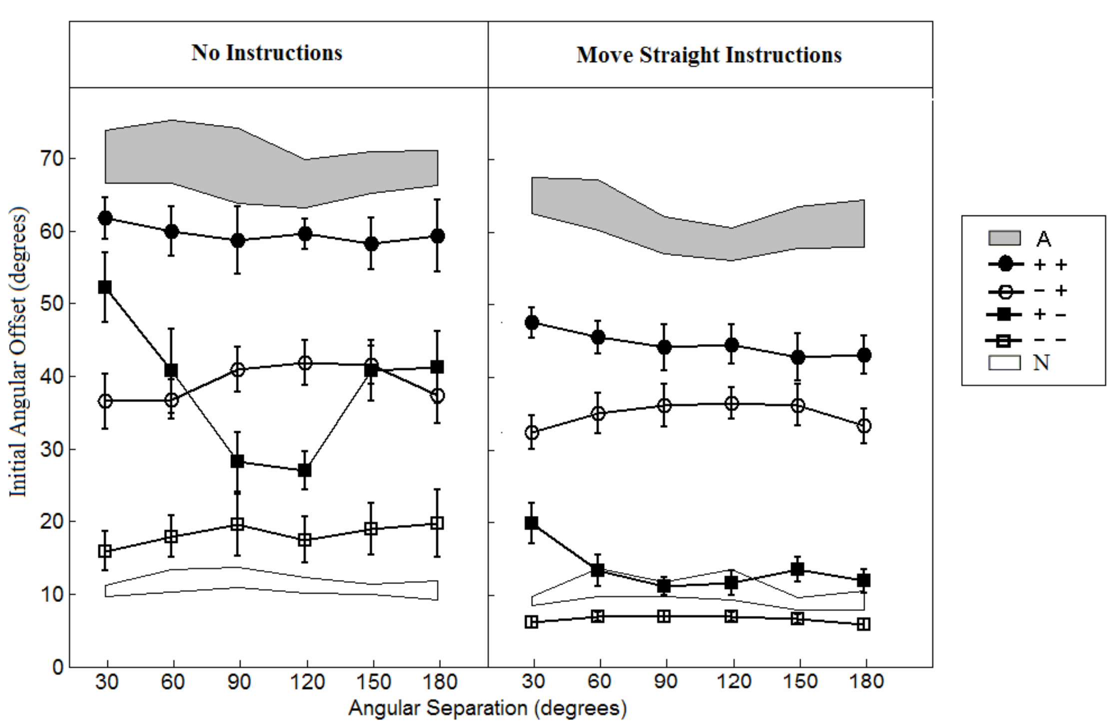

No Instructions
Move Straight Instructions
Initial Angular Offset (degrees)
70
60
50
40
30
20
10
0
30
60
90
120
150
180
Angular Separation (degrees)
A
+ +
− +
+ −
− −
N

Figure 30.

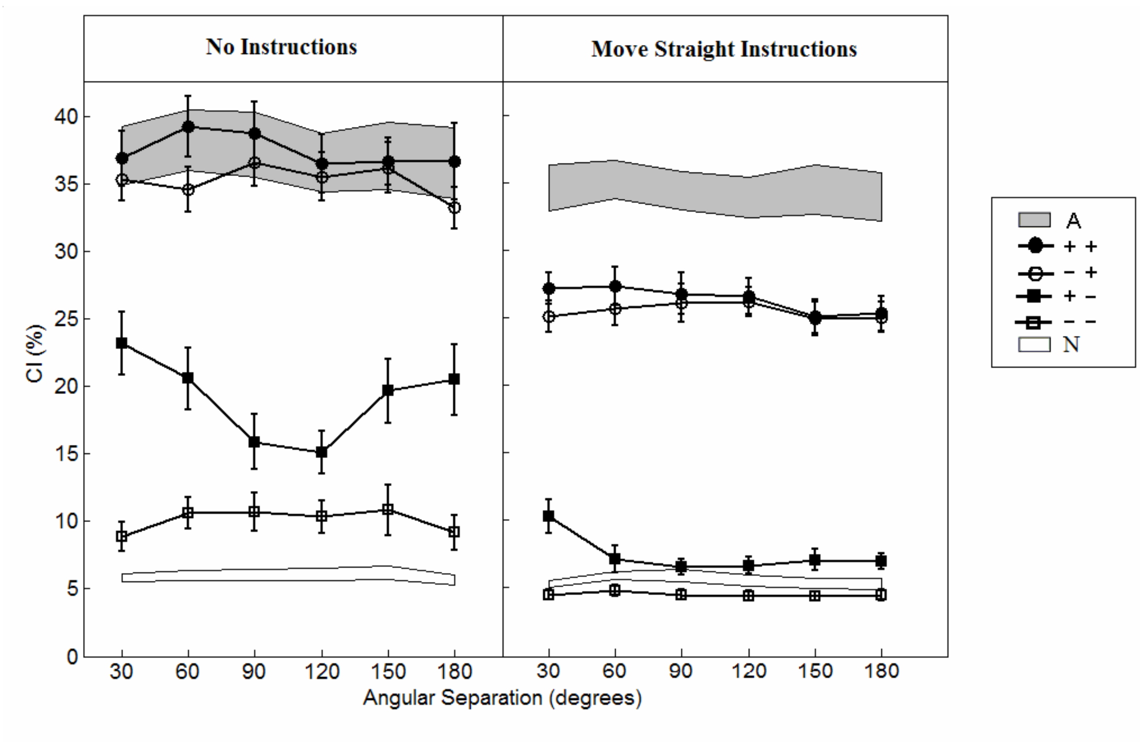
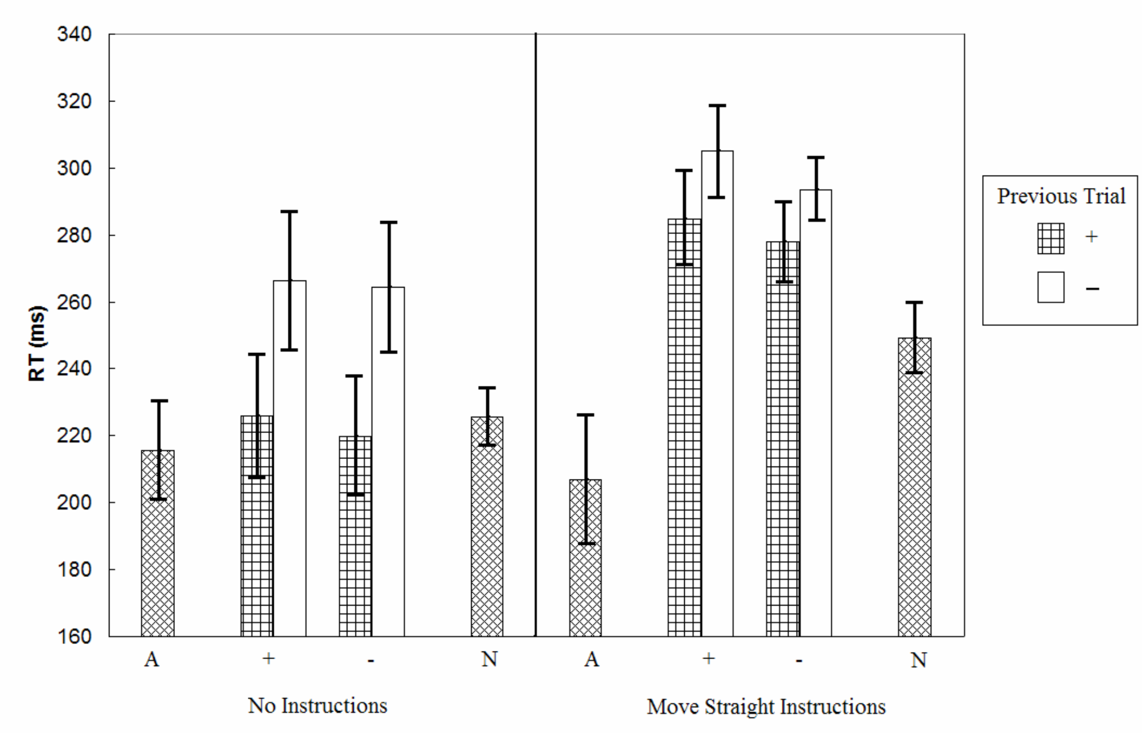

No Instructions
Move Straight Instructions
CI (%)
0
5
10
15
20
25
30
35
40
30
60
90
120
150
180
Angular Separation (degrees)
A
+ +
− +
+ −
− −
N

Figure 31.



340
320
300
280
260
240
220
200
180
160
RT (ms)
A
+
-
N
A
+
-
N
No Instructions
Move Straight Instructions
Previous Trial
+
–


Figure 32.

## NOTES

1. The reason for this lack of generalizability stems from the complex, non–linear relationship between intrinsic coordinates and extrinsic coordinates (Hogan, Bizzi, Mussa–Ivaldi, & Flash, 1987). For example, arm movements in different directions can be shown to require significantly different movement patterns at the shoulder and elbow joints (Barreca & Guenther, 2001). Therefore, the translation of an intrinsically defined trajectory to other areas of the work space would be computationally very complex to perform.

2. This method of analysis required the assumption that the reused hand path is not completely modified before movement initiation. This assumption is necessary because one can not differentiate between planning each movement anew and planning based on a completely malleable previous plan. For example, if movement planning minimizes the work required to complete a movement (as in Soechting & Flanders, 1995), movements would be predicted to be the same for a model that plans movements anew and a model that reuses a previous plan that can be completely modified so that work is minimized.

3. Another possible measure is the side of the obstacle around which the hand moved. I did not report this measure, however, because most movements circumvented the obstacle on the same side for any given target location. This similarity within and across participants was due to the constraint that the arm not collide with the obstacle. The location of many of the targets afforded only a single side on which the arm could avoid the obstacle. For example, the obstacles for targets located near the 12 o'clock and 6 o'clock positions could only be avoided by selecting a path to the right of the obstacle.

The lack of variability both within and across participants made this variable uninformative.

4. In the process of calculating these correlations, I discovered 12 trials (0.2% of the total number of trials) that had significantly longer RTs than most movements (> 5 standard deviations above the mean). These trials were removed from the RT correlation analyses because of the large influence outliers can have on correlations. These trials were also removed from the mean RT analyses, although the effect of their removal was negligible. However, these movements were not removed from the hand path analyses because their paths were not reliably different from the hand paths of other movements. This was done because of the vast amount of work required to do the reanalysis and the likely inconsequential effect these small number of trials would have on the reported hand path results.

5. The Hamilton and Wolpert (2002) model was selected as the exemplar model of via point planning because it was specifically developed for obstacle avoidance, unlike the via point models of Bullock, Bongers, Lankhorst, and Beek (1999), and Wada and Kawato (2004).

# Steven A. Jax

*Curriculum Vitae - February 7, 2005*

## Education

Ph. D. in psychology, Pennsylvania State University (expected May 2005)
M. S. in psychology, Pennsylvania State University, 2002
B.A. in psychology, *summa cum laude*, University of Minnesota, 1999

## Academic Awards and Honors

Phi Beta Kappa honors society member, 1999
Graduate Scholar Award, Pennsylvania State University, 1999
NIH Predoctoral National Research Service Award (1 F31 NS 047784-01), 2003

## Teaching Positions

Teaching Assistant, Pennsylvania State University

> *Introductory Psychology (3 semesters), Historical Perspective of Psychology, Introduction to Statistics (2 semesters), Sensation and Perception, Introduction to Research Methods (3 semesters), Personality and Social Development*

Lecturer, Pennsylvania State University

> *Introduction to Research Methods (2 semesters)*

## Publications

Jax, S. A., Rosenbaum, D. A., Vaughan, J., & Meulenbroek, R. G. J. (2003). Computational motor control and human factors: Modeling movements in real and possible environments. *Human Factors*, *45,* 5-27. (Special issue on "Quantitative Formal Models of Human Performance," M. Byrne & W. G. Gray, Eds.).

Fletcher, C. R. & Jax, S. A. (in preparation). *Memory for mathematical proofs and narratives.*

Jax, S. A., Lantz, K., Rosenbaum, D. A., & Vaughan, J. (in preparation). *Modeling reaching around obstacles.* [Note: Order of authors tentative, listed alphabetically until completed]

Jax, S. A., & Rosenbaum, D. A. (2004). *Sequential effects in reaching around obstacles.* Invited revision in preparation.

Rosenbaum, D. A., Augustyn, J. S., Cohen, R. G., & Jax, S. A. (in preparation). Perceptual-motor expertise. To appear in A. Ericsson (Ed.), *Cambridge Handbook of Expertise and Expert Performance*.