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THE FLEXIBLE USE OF REFERENCE FRAMES

IN HUMAN ACTION PLANNING

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ABSTRACT

The degrees of freedom problem refers to the problem of how people select their actions from infinite sets of possible actions. Addressing this question requires identifying which factors are taken into account in action planning. Possibly, the adopted solutions depend on the nature of the task, including factors such as task difficulty and experience. In general, the solution may depend on cognitive as well as biomechanical factors.

From a cognitive perspective, solving the degrees of freedom problem requires identifying which reference frame is used for action control. Actors may control physical actions relative to their bodies or relative to the external world. The origin of the adopted reference frames may be task-dependent.

To explore these possibilities, I conducted a series of experiments on how people manipulate two objects, one with each hand. I studied the influence of task difficulty and experience on performance through manipulations of start and target locations, timing of object grasps and object transports, number of repetitions that were performed, and object weight. These manipulations allowed me to determine which reference frame people used to plan their grasps.

Participants planned object grasps in cognitively efficient ways by adopting similar solutions for the two hands. Grasp selection was consistent with the use of an allocentric reference frame tied to the objects. The adoption of object symmetric grasps did not consistently depend on experience or grasp timing, but did depend on the similarity of the mass distribution of the two objects. In other words, symmetry in the mass distributions for the two objects appeared to drive the preference for symmetry in grasp selection. The results suggested that participants selected similar grasp locations because doing so allowed similar dynamics for the two hands during object transport. Breaking symmetry in allocentric dynamics resulted in changes in grasp selection.

The results are consistent with the notion that solving the degrees of freedom problem involves an interplay of representational and biomechanical efficiency.

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CHAPTER 1
INTRODUCTION

As long as we live, we move. Moving allows us to interact with the world. Without the ability to move, we would be spectators rather than agents to our surroundings. With actions we can give our thoughts a physical form.

Degrees of Freedom and Reference Frames

Owing to the importance of movement for psychology, a central aim for this field is to understand how movements are generated. What factors are taken into account in the planning of goal-directed physical actions?

First, there needs to be a goal that makes movement desirable. The term ‘goal’ refers to some desired outcome (Austin & Vancouver, 1996). Once a goal is appreciated and accepted, the actor needs to have some representation of the body and of the environment to determine what kinds of movements can and cannot be performed to achieve the goal. In most cases, many movements are possible, in which case just one solution must be selected from the set of solutions possible. Within the field of motor control, this selection problem is known as the degrees of freedom problem or redundancy problem (Bernstein, 1967).

To address the question of how people solve the degrees of freedom or redundancy problem for a particular task, an important consideration is which reference frame is used for the action planning. One possibility is that actions are planned with respect to the external world, using an allocentric reference frame for action planning. Alternatively, it could be that actions are planned with respect to the body, using an egocentric reference frame for action planning. Within these two broad classes of reference frames, many different possibilities exist. For example, in the case of humans, action planning in an egocentric reference frame might occur with respect to the eyes, hand, trunk, or left little toe. Similarly, action planning in an allocentric reference frame might occur with respect to an object, a room, or a coffee cup. Leaving the distinction between allocentric and egocentric reference frames aside, it could also be that multiple reference frames underlie task performance or that different reference frames underlie performance for different tasks.

Understanding action planning not only requires an understanding of which reference frame is used to plan actions in general but also the extent to which the use of particular reference frames depends on the context in which actions are performed. It could be, for example, that when people aim for targets, a different reference frame is used than when they grasp objects. In addition, it could be that the use of a particular reference frame depends on the difficulty of the task. Thus, a person might adopt a different reference frame to grasp a cup of coffee that is almost empty than a cup of coffee that is almost full. It could also be that the reference frame that people use changes with experience, so people plan their actions within one reference frame during early task performance but switch to a different reference frame when they become more experienced with a task. Thus, experts may use different reference frames than novices do.

In sum, the dominant reference frame that people use in a task could depend on the nature of the task, on task difficulty, and on experience. The experiments in this dissertation aim to address these possibilities. Doing so is of fundamental importance for theories of motor control (e.g. Bullock, Grossberg, & Guenther, 1993; Feldman, 1986; Flash & Hogan, 1985; Harris & Wolpert, 1998; Rosenbaum, Meulenbroek, Vaughan, & Jansen, 2001; Rosenbaum, Loukopoulos, Meulenbroek, Vaughan, & Engelbrecht, 1995; Uno, Kawato, & Suzuki, 1989).

Reference Frames are Task-Dependent

Previous research suggests that different reference frames underlie performance of different actions. For example, a recent study suggests that implicit motor sequence learning involves an egocentric reference frame (Witt, Ashe, & Willingham, 2008). Explicit sequence learning may rely on egocentric as well as allocentric reference frames (Liu, Lungu, Wechter, Willingham, & Ashe, 2007). Some studies of reaching movements suggest that reaching towards targets predominantly relies on an allocentric reference frame (e.g. Patchay, Haggard, & Castiello, 2006). In contrast, other studies indicate that reaching predominantly relies on an egocentric reference frame. Within the egocentric reference frame, reaching movements could be centered on an eye-centered or hand-centered reference frame (e.g. Beurze, van Pelt, & Medendorp, 2006; Batista, Buneo, Snyder, & Andersen, 1999; Colby & Goldberg, 1999). Other studies suggest that multiple reference frames underlie reach to grasp movements (e.g. Collucia et al., 2007; Graziano, 2001; Keulen, Adam, Fischer, Kuipers, & Jolles, 2002), depending, for example, on factors such as the availability of visual information (e.g. Ahmed, Wolpert, & Flanagan, 2008; Neely, Tessmer, Binsted, & Heath, 2007). Both intrinsic and extrinsic reference frames also appear to underlie perceptual-motor learning (e.g. Rosenbaum & Chaiken, 2001), and extrinsic reference frames appear to act at a higher level (e.g. Flanagan & Rao, 1995; Rogosky & Rosenbaum, 2000). Thus, the studies above suggest that different reference frames underlie performance of different tasks. Some argue, however, that action goals always rely on external or allocentric coordinates (e.g. Röder, Kusmierek, Spence, & Schicke, 2007), a claim that is at odds with some of the studies mentioned above.

Despite the differential involvement of alternative reference frames in different tasks, one would expect similar tasks to rely on similar reference frames. As already indicated above, however, different studies have reported different reference frames for tasks such as reaching. A possible reason for the discrepancies among the findings could be that tasks that may appear similar in nature in fact differ in their level of difficulty. Such differences in task difficulty could cause a shift in the reference frame used to perform it. To my knowledge, the possibility that task difficulty influences which reference frame is used to control action has not been considered in much detail. Investigating this issue could have important implications for theories of physical action control.

Reference Frames, Task Difficulty, and Experience

What does it mean for a task to be difficult? Clearly, if one thinks of a sport such as playing basketball, it is more difficult to score a three-point shot for most people than it is for an expert player such as Michael Jordan. A trivial reason for this difference is that most of us do not have the physical capacities of Michael Jordan. Leaving this individual difference aside, however, most of us also have not practiced basketball as much as Michael Jordan has. In other words, an important difference between novices and experts in a given task is the amount of experience with the task. But what is it about increased experience that makes a task easier over time? One possibility is that as people gain expertise in a task, they come to appreciate the appropriate reference frame to perform the task. If this assertion holds, one would expect to see differences in the reference frames that novices and experts adopt for certain tasks. By implication, a shift from one reference frame to another could be observed with increased expertise in such tasks, implying that the reference frames that underlie performance in a certain context are flexible rather than static.

The notion that people may bring different reference frames to bear based on their level of experience resonates with the seminal work of Edward Tolman on cognitive maps (e.g.

Tolman, 1948). In his experiments on rats, Tolman and colleagues demonstrated that rats learn a maze by developing a relatively abstract representation of the maze. Over time, rats were able to adjust their path to a food reward rapidly when certain passages in the maze were blocked. Thus, whereas the rats at first relied on the information that was immediately available to them in the environment, they shifted to the use of a more abstract cognitive map with increased experience. In other words, the adopted reference frame changed from being locally tuned to becoming more globally tuned.

In the context of human performance, the argument for flexible reference frames has recently been made for skill learning in golf. Lee and colleagues (Lee, Ishikura, Kegel, Gonzalez, & Passmore, 2008) suggested that with increasing expertise in golf putting, people shift from an allocentric reference frame to an egocentric reference frame. Lee et al. based this claim on the observation that for novices, there was a strong positive correlation between head displacements and putter displacement whereas for experts there was a negative correlation. Based on this difference, Lee et al. (2008) concluded that novices coordinated their putting behavior within an allocentric reference frame, whereas experts coordinated such actions within an egocentric reference frame. Thus, the authors argued that a shift in reference frames occurred with increased task experience. It is unclear, however, why a difference in the direction of the correlation between a golfer’s head and the putter implies the use of an egocentric or allocentric reference frame.

In general, shifts in reference frames with increased task experience have not been studied in much detail. For example, one basic question is whether such shifts in reference frames arise in tasks that are less complex than golf putting, such as moving objects. A first indication that such shifts may occur in more basic tasks comes from a recent study by

Ahmed, Wolpert, and Flanagan (2008). These authors investigated changes in reference frames with respect to properties of an object that participants displaced. In particular, these authors sought to determine how an object's dynamics (i.e. the object's force- and torque-related properties) are represented as a function of task complexity.

In the study by Ahmed and colleagues, participants held two short cylinders with their two hands, one in each hand. The cylinders were connected with an elastic band. The participants' task was to move the right hand to a target on a horizontal surface while keeping the left hand in a fixed position. The elastic band created the need to represent the dynamics of the system as a whole, because movements of one hand affected the dynamics that operated on the other hand. In the simple dynamics condition, the elastic band connected the two cylinders directly, but in the complex dynamics condition, a pulley system acted on the elastic band. As a result, the dynamics of the system were more difficult to represent. After a learning phase, the location of the right hand changed. This also changed the force vector of the elastic band that operated on the left hand by 30 degrees. By measuring the force vector generated by the left hand after this change, the use of an allocentric representation could be distinguished from the use of an egocentric representation. The use of an egocentric reference frame predicted alignment of the generated force vector with the orientation of the arm, whereas the use of an allocentric reference frame predicted alignment of the generated force vector with the orientation of the elastic band.

The results suggested that the representation of the dynamics of object manipulation was flexible and depended on task complexity. Whereas performance in the simple dynamics condition relied primarily on an object-centered reference frame, performance in the complex dynamics condition relied primarily on an arm-centered reference frame. When the elastic band was not visible, performance indicated the use of an intermediate reference frame. Thus, the use of a reference frame depended on task complexity. This finding raises the question whether a similar dependency for the use of a reference frame on task complexity arises in the selection of object grasps.

In addition to their findings, Ahmed et al. (2008) suggested that examining the use of reference frames as a function of task experience is an important direction for future research. In particular, the authors postulated that with experience, the representation of object dynamics may shift from an egocentric reference frame linked to the arm to an allocentric reference frame linked to the object. Note that this suggested hypothesis of a shift from an egocentric to an allocentric reference frame with increased task experience is opposite to what Lee and colleagues (2008) reported for novice versus expert golf putters.

Regardless of the direction of the shift in reference frames, finding that people shift from one reference frame to another with increased task experience has important theoretical implications. It suggests that the reference frame that people adopt in a particular task is not static but instead depends on the task as well as on experience. If that were the case in general, it would provide further evidence that the degrees of freedom problem does not involve a “one size fits all” solution.

Bimanual Actions and Cognition

If the latter hypothesis is viable, one needs to find a medium for analyzing which frame of reference is used and when each frame is used over the course of practice. The tack taken in this dissertation is to use bimanual object manipulation as a window into the involvement and stability of reference frames in action planning. It should be stated here that I will use the term reference frame to refer to the origin with respect to which actions are planned. Thus, I will not consider which coordinate system is used as the metric within reference frames.

Bimanual object manipulation occurs whenever one uses two hands to alter the physical properties of an object, including moving the object from one position to another or, in the simplest case, palpating the object to gather information about its properties. A number of findings concerning bimanual coordination which have emerged in the past thirty years will be reviewed here. Of central importance in this review is the notion that interference may arise at several levels in the action system, including a representational level related to the generation of action plans.

It is well known that some tasks in which people simultaneously perform actions with their two hands pose difficulties during initial performance. People's performance of such bimanual tasks shows decrements in performance reflected in the time to start moving to different locations with the two hands compared to moving to the same location with the two hands (e.g. Diedrichsen, Hazeltine, Kennerley, & Ivry, 2001; Ivry, Diedrichsen, Spencer, Hazeltine, & Semjen 2004; Weigelt, 2007) as well as increases in the time to complete the movements themselves when the characteristics of the movements of the two hands differ (e.g. Kelso, Southard, & Goodman, 1979). In addition, features of the kinematics of the movements that people produce suggest that planning two different movements with the two hands at the same time is, at least initially, difficult. For example, when people are asked to draw a circle with one hand while simultaneously drawing a square with the other hand, the circle tends to become square-like and the square tends to become circle-like (Franz, McCabe, & Zelaznik, 1991).

Bimanual interference effects can arise at multiple levels (Carson & Kelso, 2004; Oliveira & Ivry, 2008). Some bimanual interference effects appear to arise from interference at the level of planning of actions rather than at the lower level of generating motor commands. Evidence for this assertion comes from a study by Rosenbaum, Dawson, and Challis (2006) in which participants were equally well capable of moving in a circular pattern with one hand while the other hand produced a circle or a square. Critically, participants in this study were not responsible for generating the plans underlying these actions, but instead were allowed to haptically track two disks that were moved by two experimenters while the participants had their eyes closed. Haptic tracking is the task of maintaining contact with a felt object that is either still or is moving. In the study of Rosenbaum, Dawson, and Challis (2005), participants could simultaneously generate a circle and a square with their two hands when, at least by hypothesis, they did not have to actively plan such movements.

In like manner, Mechsner, Kerzel, Knoblich, and Prinz (2001) showed that bimanual interference is not likely to arise at the level of motor commands. They did so by showing that vastly different motor patterns can be generated with relative ease when the perceptual consequences of the generated actions are similar to one another. For example, Mechsner and colleagues showed that moving the fingers in an anti-phase pattern at high frequencies was a relatively stable coordination mode when the palm of one hand faced up while the palm of the other hand faced down. In contrast to the original interpretation of the finding by Kelso (1984) that greater stability of the in-phase versus anti-phase pattern for bimanual movements of the index fingers was due to the activation of homologous muscles, Mechsner and colleagues suggested that the stability of the coordination pattern emerged from perceptual symmetry. Thus, interference appeared to arise at a more abstract level than the level related to implementation of movements through motor commands sent to the muscles.

Results like those just summarized need not be taken to imply that bimanual interference only arises from interference at a cognitive level, for as stated above, interference is likely to arise at multiple levels (e.g. Oliveira & Ivry, 2008; Swinnen & Wenderoth, 2004). In fact, the experiments by Mechsner and colleagues (Mechsner et al., 2001; Mechsner & Knoblich, 2004) have been subject to debate (e.g. Riek & Woolley, 2005; Salter et al., 2004), in part because they may not apply to discrete bimanual movements (e.g. Obhi & Haggard, 2004). Nonetheless, such results do emphasize the possible importance of action plans on bimanual coordination. They suggest that bimanual movements can be performed relatively independently when actors do not have to generate two action plans simultaneously or when the production of different motor patterns leads to perceptual effects that can be conceived of in a single, integrated representation.

Object Manipulation and Cognition

Because the experiments in this dissertation aim to elucidate cognitive aspects of human action planning by using an object-manipulation task, it is important to demonstrate that examining how people manipulate objects could reflect cognitive processes and could provide insight into the question of which reference frames people use to plan their actions. For unimanual object manipulation, several studies reveal that grasp selection is sensitive to higher level planning mechanisms, as reviewed next.

Several studies indicate that people anticipate the body’s end state through the grasps they select. For example, whether people grasp a vertically-oriented cylinder with an overhand or underhand grip depends on the posture they would end in. People select grasps in such a way that they tend to end comfortably (Lam, McFee, Chua, & Weeks, 2006; Rosenbaum & Jorgensen, 1992; Short & Cauraugh, 1997). Similar end-state comfort consistent selection of overhand versus underhand grasps arises when people are asked to turn a handle to different locations (Rosenbaum, van Heugten, & Caldwell, 1996; Rosenbaum, Marchak, Barnes, Vaughan, Slotta, & Jorgensen, 1990). The ability to plan for end-state comfort has recently been shown to develop during childhood (Adalbjornsson, Fischman, & Rudisill, 2008), and is not specific to humans (Weiss, Wark, & Rosenbaum, 2007).

Cohen and Rosenbaum (2004) conducted a study of particular interest for this dissertation because the experimental methods formed the basis for the method used here. Similar to the studies reviewed above, Cohen and Rosenbaum (2004) demonstrated that healthy controls plan object grasps based on anticipation of the end-state that the body will adopt after object transport (see Figure 1). In their study, participants reached for and moved a bathroom plunger from a starting location to a target location. The height of the target location varied between trials. Cohen and Rosenbaum found an inverse relationship between the location of the hand on the cylinder (grasp height) and the height of the target location, such that participants grasped the plunger low when they would move it to a high target location and grasped the plunger high when they would move it to a low target location. By behaving in this way, participants ended in a relatively comfortable end position. The authors referred to this effect as the grasp height effect, a term I will use throughout this dissertation. One could view the grasp height effect as a form of end-state comfort. End-state comfort effects

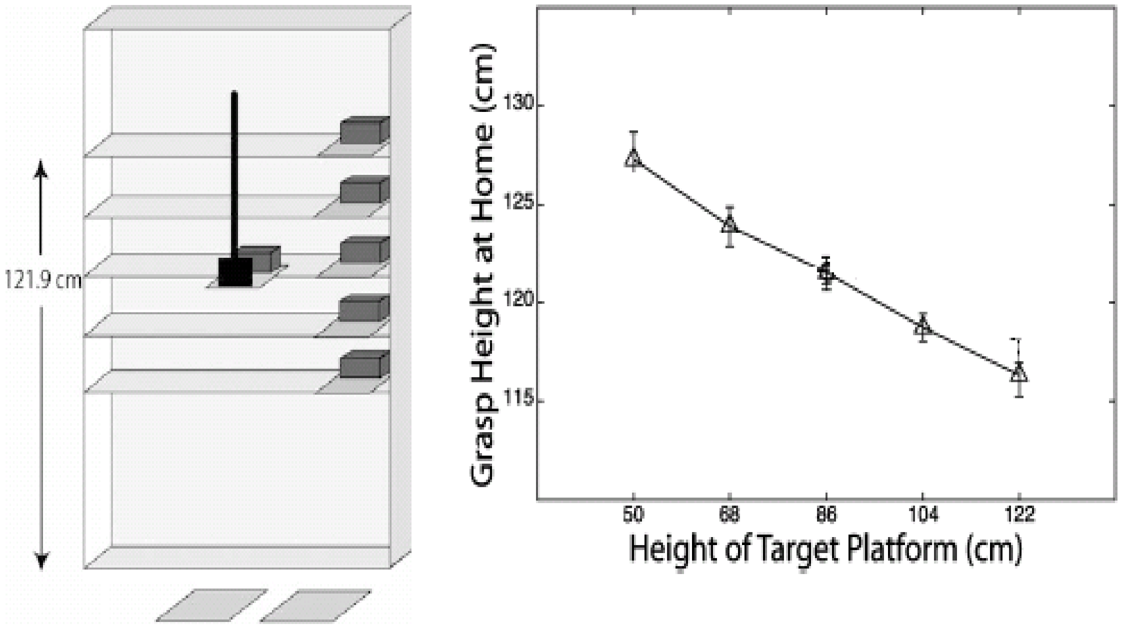

Figure 1. Left panel: Overview of Cohen & Rosenbaum's (2004) experimental setup. Right panel: Cohen & Rosenbaum's (2004) main result (figure modified from original print).

suggest that healthy controls anticipate forthcoming features of single transport movements. Research on grasp aperture provides a similar demonstration of anticipatory planning for object grasping (e.g. Jeannerod, 1981; 1984).

The grasp height effect is consistent with the hypothesis that action planning centers around action goals and that people plan with respect to the perceptual consequences of action. A number of studies provide further support for the notion that action goals and their perceptual effects are central to performance at the representational level (e.g., Bekkering, Wohlschläger, & Gatis, 2000; Blakemore, Goodbody, & Wolpert, 1998; Hommel, Müsseler, Ascherleben, & Prinz, 2001).

The finding that people anticipate forthcoming body postures when they grasp an object raises the question of which reference frame people use for such anticipation. For unimanual grasp selection, a recent study suggests that memory for recently executed grasps uses allocentric rather than egocentric coordinates (Weigelt, Cohen, & Rosenbaum, 2007). Based on this finding, one could hypothesize that unimanual grasps are also planned in an allocentric reference frame. Making such a claim assumes, however, that the memory for a generated grasp reflects the planning of that grasp rather than the perception of the grasp on the object. Aside from this assumption, another question is whether the same reference frame underlies the selection of a posture in a bimanual task and in a unimanual task.

Bimanual Grasping, Constraint Hierarchies, and Reference Frames

None of the studies discussed so far involved the manipulation of two objects, one with each hand. Only a few previous studies considered the issue of bimanual object manipulation in terms of grasp selection. The studies of bimanual grasp selection largely built on the methods used in the studies of unimanual object manipulation.

The few studies that have been conducted on the manipulation of two objects with the two hands provide contradictory results. From the results of these earlier studies, it is unclear whether an egocentric or allocentric reference frame underlies bimanual grasp selection. I will now review the studies that I am aware of concerning the manipulation of two objects with two hands. Central to these studies is the notion of a constraint hierarchy. This term refers to criteria (constraints) that people consider when performing a task, with the criteria differing in importance (hence the word hierarchy). The exact prioritization of criteria depends on the task as well as the action capabilities of the actor. Action planning based on a constraint hierarchy may rely on a method called elimination by aspects (Tversky, 1972). Here, possible actions are evaluated with respect to the most important constraint first, the second most important constraint second, and so on. At decreasing levels of the hierarchy, only the possible remaining actions are subsequently considered.

In a first study of bimanual grasping, Fischman, Stodden, and Lehman (2003) asked whether people would anticipate the end-state of their body following grasps of two objects, one with each hand, that were to be moved to targets at different heights. In this study, participants grasped two dowels. In each trial, they brought either the left end or the right end of the dowels to a vertically oriented target. In a trial, the target heights were the same for the two dowels -- both high or both low. The question of interest was whether people grasped the dowels with an overhand or an underhand grip, and whether such grip selection depended on the height of the target. Ending comfortably with both hands often required adopting an overhand grip with one hand and an underhand grip with the other hand.

The results indicated that people anticipated the end state of their body by changing their object grips based on the height of the target. For the lowest and highest target locations, people selected grips that allowed them to end comfortably in approximately 80 percent of the trials. This result contrasts with the results of a similar unimanual study by Rosenbaum and Jorgensen (1992), in which people exhibited end-state comfort in all the trials. Thus, although people showed anticipation of end state via selection of appropriate grips, such anticipation appeared to be weaker for bimanual object manipulation than for unimanual object manipulation.

In a second study of bimanual grasp selection, Weigelt, Kunde and Prinz (2006) examined bimanual end state comfort planning in a way that was similar to Fischman et al. (2003). Weigelt, Kunde and Prinz asked participants to grasp two dowels positioned horizontally at two start locations. Each dowel had one black end and one white end. The orientation of each dowel varied between trials. The participants' task was to grasp the two dowels and move the black or white end of each dowel to a black or white target. To achieve this task while maintaining end-state comfort, participants had to adopt different grasps with their two hands -- overhand with one hand and underhand with the other. The results of Weigelt et al. (2006) indicated that all the participants anticipated end state comfort in almost every trial. The authors concluded that action goals were of primary importance for action planning, while the movements to achieve those goals were of secondary importance.

Several important points can be raised about the studies by Fischman et al. (2003) and Weigelt et al. (2006). First, participants in both studies always moved their two hands to identical target heights. Thus, the task used in both of these studies allowed participants to produce movements for which compliance with end-state comfort necessarily implied ending in a body position that was symmetric for the two hands. An open question, therefore, is whether people would adopt end state comfort compatible grips when the body's end state is not symmetric. Second, it is important to note that the results of Fischman et al. (2003) and Weigelt et al. (2006) had similarities as well as differences. In both studies, participants displayed end-state comfort planning most of the time. However, in the Weigelt et al. study this tendency was much stronger than in the Fischman et al. study. A possible reason is that the task of Weigelt et al. was less difficult than the task of Fischman et al. because participants moved to the same target height in every trial in the Weigelt et al. study, whereas participants in the Fischman et al. study moved to different target heights in each trial though the two hands always moved to the same target height within a trial.

In a third study of bimanual grasp selection, Hughes and Franz (2008) asked people to grasp two dowels, one with each hand, and transport it to a target location as quickly as possible. The dowels were oriented in an upright position, and each dowel had one blue end and one yellow end. The initial position of the dowels was constant, but the required end orientation of the two dowels differed between trials. In addition, in some trials an obstacle was differentially introduced for one of the two hands. The obstacle was located between the initial position and the target position of the dowels. In each trial, the participants' task was to transport the two dowels from their initial locations to their target location such that the end of the dowels that touched the targets corresponded to the colors displayed on an index card by the experimenter. Thus, in some trials the orientations of the two dowels were identical and in some trials they differed (incongruent trials). Due to this manipulation, the grasps that people had to adopt to end comfortably either matched (in the congruent trials) or mismatched (in the incongruent trials).

The results revealed that participants took longer to initiate and complete the object transports in the incongruent trials than in congruent trials. This result replicated an earlier finding by Kunde and Weigelt (2005). In addition, participants grasped in end-state-comfort-consistent ways in 99% of the congruent trials that did not require object rotation, in 72% of the congruent trials that did require object rotation, in 58% of the incongruent trials that required rotation of the left hand dowel, and in 71% of the trials that required rotation of the right hand dowel. Thus, participants violated end state comfort for a substantial portion of the trials that required object rotation, and did so in particular in incongruent trials. Based on these findings, Hughes and Franz (2008) concluded that the constraint hierarchy underlying bimanual object manipulation is not static. Instead, end state comfort and movement symmetry both form important constraints for congruent trials, but movement symmetry is more important than end state comfort planning for incongruent trials in bimanual object manipulation.

In a fourth study of bimanual object grasping, Janssen, Beuting, Steenbergen, and Meulenbroek (2008) asked people to grasp two CD cases and transport them to two CD racks. The task was set up such that transporting the CDs to their racks sometimes required a horizontal end orientation and other times required a vertical end orientation. In addition, the initial orientation of the CDs at the start location varied between trials. In Experiment 1, participants received the instruction to adopt a particular grasp orientation with each hand. The end orientation for the two CDs was always congruent (either horizontal or vertical). Thus, transporting the CDs involved either bimanually symmetric or asymmetric movement trajectories. The results revealed a stronger degree of interlimb coupling for bimanual asymmetric movements than for bimanual symmetric movements. In Experiment 2, participants were free to select the way they grasped the CD cases to transport them to the CD racks. The results of this experiment indicated that the tendency to end comfortably with the two hands did not depend on whether the movements of the two hands were symmetric or asymmetric. The tendency to follow end state comfort was stronger for the right hand than for the left. The authors concluded that planning for end state comfort is a more important constraint than movement symmetry.

The conclusions of Janssen et al. (2008) and of Hughes and Franz (2008) appear to be at odds with one another. On the one hand, Janssen et al. (2008) concluded that end state comfort overrode movement symmetry for bimanual object manipulation in incongruent trials. In contrast, Hughes and Franz (2008) concluded that movement symmetry overrode end state comfort for bimanual object manipulation in incongruent trials.

How can these different conclusions be reconciled? One possibility is that the difference between the two studies was due to a difference in the number of trials participants performed. In the Hughes and Franz (2008) study, participants completed a total of eight incongruent trials, performing each condition only once. In contrast, participants in the Janssen et al. (2008) study completed a total of 120 trials, comprising 24 conditions. Of these conditions, four incongruent conditions created a conflict between end state comfort and movement symmetry. Participants repeated each of these four conditions five times, completing a total of 20 incongruent trials. Thus, participants in the Janssen et al. (2008) study completed many more trials in general, and more than twice as many incongruent trials.

How could the difference in the number of trials between the Hughes and Franz (2008) and Janssen et al. (2008) studies account for the differences in their findings? One possibility is that people attempt to plan for end state comfort in bimanual incongruent trials, but have difficulty doing so initially because adopting grasps that satisfy end state comfort in the incongruent conditions requires adopting a different grasp with each hand. Thus, bimanual symmetry needs to be broken for end state comfort to emerge. Possibly, people initially tend to adopt bimanual symmetric grasps, but start to display end state comfort grasps with increased experience in incongruent trials. In other words, increased experience with bimanual incongruent conditions allows people to break bimanual symmetry and to shift from such symmetry to adopting end state comfort with the two hands.

Taken together, then, it is possible that differences in the findings of the previous studies of bimanual object manipulation indicate that people tend to select grasps that comply with end state comfort planning more and more as they gain experience with the bimanual objection manipulation task to be performed. Consistent with this interpretation, the tendency to select grasps that comply with end state comfort planning decreases with increases in task difficulty. Thus, more experience helps compensate for differences in task difficulty. This general perspective underlies the research described in this dissertation.

Overview of the Experimental Method

To address the central questions of this dissertation, each of the conducted experiments used a task in which participants were asked to manipulate objects with their two hands. Each of the experiments used a bimanual variation of the plunger transport task of Cohen and Rosenbaum (2004). Figure 2 provides a schematic of the experimental setup. The basic task was to move pairs of plungers from a pair of start locations to a pair of target locations. In each trial, participants stood in front of the apparatus, which contained three shelves. The shelves differed in height, such that one shelf was positioned at table height (86.4 cm above the floor), one was

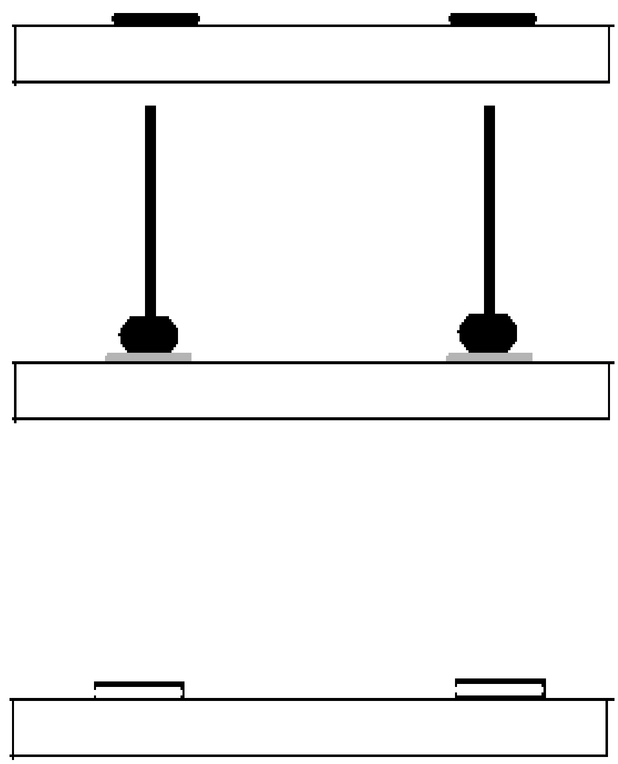

Figure 2. Overview of the experimental apparatus. The apparatus contains three shelves at different heights. The top and bottom shelves each contain one target location for the left and one for the right hand. Two objects (toilet plungers) will always sit on the middle shelf at the start of a trial.

positioned 34 cm above table height, and one was positioned 34 cm below table height. The shelves were shifted in depth relative to where the participant stood to prevent the shelves from forming a significant obstacle during object transport. Each shelf contained two target locations that differed in color. For example, the two target locations on the top shelf could both be black, whereas the two target locations on the bottom shelf could both be white, or vice versa. The plungers always started from the middle shelf, where they sat on a gray area that indicated the start location.

In each trial, the experimenter indicated the pair of targets that the plungers needed to be moved to by saying the color of the target for the plunger on the left first, followed by the color of the target for the plunger on the right. Thus, the experimenter said, for example, “Black White,” indicating that the plunger on the left needed to be moved to the black target on the left, and that the plunger on the right needed to be moved to the white target on the right. To ensure that participants were aware of the target sequence, they orally repeated the sequence back to the experimenter. After doing so, they moved the two plungers to their respective targets at a comfortable pace. The experimenter then returned the plungers to their initial locations, grasping them by their base. In all the presented experiments except Experiment 1, participants were instructed to grasp the plungers at the same time and to place them on the targets at the same time. Participants were told to prevent the plungers from sliding in their hands once they grasped the plungers. This instruction was included to ensure that the initial and final grasp locations were identical. Thus, grasp selection determined the body’s end-state after object transport.

The measure taken in each trial was where the two plungers were grasped. This measure afforded a continuous index of bimanual symmetry and end state comfort planning. In this regard, the presented experiments differed from previous studies of bimanual object manipulation, which used a discrete measure of end state comfort planning, namely, whether people used an underhand or overhand grip. The experiments in this dissertation measured grasp height along the two plunger shafts to determine to the extent to which people planned for bimanual symmetry and/or end state comfort. Studying grasp selection in such a continuous manner could provide insights that might not be obtained with a discrete measure. In particular, the use of a continuous measure could allow for an evaluation of the influence of different constraints on action planning. Arguably, people take several constraints into account when they plan their actions, with some related to the goals they want to achieve and some related to the means by which to achieve those goals. Thus, action planning could involve satisficing, such that people adopt a solution that is satisfactory but not necessarily optimal with respect to one or several costs during planning. Satisficing has been shown to play a key role in higher-level decision-making (Simon, 1955). Based on parsimony, it is an attractive as well as a plausible possibility that people rely on a similar mechanism when they plan their actions. Using a continuous measure could reveal whether grasp selection for bimanual object manipulation involves satisficing with respect to multiple constraints rather than planning based on one prominent constraint.

Hypotheses for Bimanual Object Manipulation

I will now consider possible hypotheses for some of the factors that people could plan for when manipulating objects with their two hands. These hypotheses concern only kinematic properties of the selected grasps. A consideration of hypotheses for grasp selection based on the dynamics of object displacement (forces and torques) is outside the realm of this dissertation.

Bimanual Symmetry Hypothesis

A first hypothesis about the way people select their bimanual object manipulation grasps is that they select their grasps to be symmetrical to one another. This hypothesis gives rise to the following prediction: *People will grasp the two objects in a similar location in a given trial.*

One version of the bimanual symmetry hypothesis states that people plan for symmetry with respect to their body, adopting an egocentric reference frame. Within this version, there are two possibilities. One is that people plan for symmetry between their hands at the start locations. The other is that people plan for symmetry between their hands at the end locations. I will refer to the first possibility as the *Body Initial State Symmetry (BISS)* hypothesis, and to the second possibility as the *Body End State Symmetry (BESS)* hypothesis.

The second version of the bimanual symmetry hypothesis states that people plan for symmetry with respect to the object, thus adopting an allocentric reference frame. I will refer to this version as the *Object Symmetry* hypothesis. According to this hypothesis, people will grasp the two objects in the same location along the object length. Thus, when one object starts at a higher location than the other, people should produce the same grasp heights along the objects for the two hands. There is only one version of this hypothesis because grasping the objects in an allocentrically symmetric way at the start locations necessarily produces allocentrically symmetric grasps at the target locations.

In general, finding that people plan for symmetry during bimanual grasp selection would be consistent with the argument that bimanual symmetry overrides end state comfort planning as a constraint (Hughes & Franz, 2008). This finding would also be consistent with the results of several bimanual aiming studies which showed that people tend to move their hands symmetrically when aiming for targets (e.g. Kelso, Southard, & Goodman, 1979; Spijkers & Heuer, 1995).

Bimanual End State Comfort Hypothesis

A second hypothesis is that people will pursue end state comfort when they move two objects with their two hands. At the level of performance, this translates to the following prediction:

People will grasp an object low when it needs to be brought to a high location and will grasp an object high when it needs to be brought to a low location. Where people grasp will not depend on the congruency of the target locations for the two hands.

This hypothesis would be consistent with earlier findings of Fischman et al. (2003), Weigelt et al. (2006), and Janssen et al. (2008), who argued that end state comfort overrides planning for symmetry as an action-planning constraint.

Conceptualization Hypothesis

Besides the question about the relative importance of bimanual symmetry versus end state comfort as a constraint for bimanual object manipulation, a third hypothesis can be formulated concerning the source of planning difficulties in bimanual tasks. According to this Conceptualization hypothesis, people display interference in grasp selection because their planning capacity is too limited to conceptualize the task of moving two objects to incongruent locations in a unified representation. Thus, the Conceptualization Hypothesis states that bimanual interference arises at a conceptual level rather than at a perceptual or motor level per se.

At the behavioral level, the Conceptualization hypothesis predicts the following: *People will show reduced end state comfort planning for both hands when they move to incongruent locations as compared to when they move to congruent locations, but with practice, this interference will reduce in strength.*

There is precedence for the notion that task conceptualization for the two hands influences the amount of bimanual interference. Franz, Zelaznik, Swinnen, and Walter (2001) argued that tasks that easily allow for a unified task representation tend to display weaker interference effects than do tasks that do not easily allow for a unified task representation.

Summary of Experiments to be Presented

In sum, the presented experiments are addressed to four central questions concerning the constraints and reference frames underlying bimanual object manipulation. The questions to be pursued are listed below and, for the sake of adumbrating the findings, the main results are also presented.

1. *Is symmetry or end state comfort a more important constraint for bimanual object manipulation?*

   The results of Experiment 1 will suggest that end state comfort and bimanual symmetry both influence grasp selection for the two hands. The results of Experiment 3 will indicate that with increased experience, participants continue to grasp both objects in similar locations in incongruent target conditions. The results of Experiment 4 will indicate that participants continue to do so when they grasp the objects one at a time and move them simultaneously.

The results of Experiment 5 will suggest that participants display a preference for symmetric grasps, but only when doing so produces a situation in which similar forces act on the two hands.

2. *Which reference frames do people use when they manipulate objects with their two hands?*

   The results of Experiment 2 will suggest that people use an allocentric reference frame. The results of Experiment 5 will suggest that this reference frame may mainly be used when grasping in object symmetric locations gives rise to similar dynamics for the two hands.

3. *Does the reference frame that people use for bimanual object manipulation depend on task experience?*

   The results of Experiment 3 will suggest that participants do not change their performance appreciably with increased task experience. In contrast, the results of Experiment 5 will suggest that participants do change their grasp selection with increased experience when the two objects to be moved have different inertial properties.

4. *Does the reference frame that people use for bimanual object manipulation depend on the difficulty of the task?*

   The results of Experiment 1 will suggest that the origin of the adopted reference frame could depend on the difficulty of the task, causing participants to adopt an egocentric reference frame in congruent conditions and an object-centered reference frame in the simultaneous incongruent condition. However, the results of Experiments 3, 4, and 5 make it unlikely that such a difference in the adopted reference frame is strictly due to differences in task difficulty. The results of Experiments 3 and 4 will indicate that participants continue to adopt grasps in similar locations in incongruent conditions even when they perform the task many times. In addition, the results of Experiment 5 will suggest that participants tend to adopt an egocentric reference frame in simultaneous incongruent conditions a relatively small number of repetitions. Thus, it may be that participants adopt different reference frames due to differences in task difficulty for the first few repetitions, but this effect of task difficulty strongly weakens after a relatively marginal increase in task experience.

CHAPTER 2
BIMANUAL GRASP SELECTION

Experiment 1

Two hypotheses were addressed with Experiment 1. The first was referred to as the bimanual end state comfort hypothesis; it said that people select the grasps for their two hands to end their movements close to the center of the range of motion of the two arms. The second hypothesis was referred to as the bimanual symmetry hypothesis; it said that people select the grasps for their two hands that are symmetrical with respect to one another. The primary aim of Experiment 1 was to decide between these hypotheses, something that was important because earlier studies did not do so. Studies by Fischman et al. (2003), Weigelt et al. (2006), and Janssen et al. (2008) suggested that end state comfort planning is a more important constraint for bimanual object manipulation than is adoption of bimanual symmetry. By contrast, Hughes and Franz (2008) suggested that bimanual symmetry is a more important constraint for bimanual object manipulation than is planning for end state comfort.

Experiment 1 used a continuous measure of end state comfort planning to evaluate the possibility that bimanual symmetry and end state comfort both influence performance when participants moved two objects to different locations. Figure 3 shows the grasp locations that the Bimanual Symmetry hypothesis and the Bimanual End State Comfort hypothesis predicted for the simultaneous conditions. Whereas the two hypotheses are not identifiable based on the congruent simultaneous conditions (panel on the left in Figure 3), they are in the incongruent simultaneous conditions (panel on the right in Figure 3). When participants were required to move the object on the left to a high location while simultaneously moving the object on the right to a low location, the Bimanual End State Comfort hypothesis predicted that participants would grasp the left object near the bottom while grasping the right object near the top. In contrast, the Bimanual Symmetry hypothesis predicted that participants would grasp both objects in the same location.

In sum, Experiment 1 addressed the following questions: Does performance suggest that people plan for end state comfort for bimanual grasp selection? Does the adoption of end-state comfort grasps occur regardless of the congruency in target locations for the two hands? If people do not show an end state comfort effect, do they grasp for bimanual symmetry? Does the weighing of bimanual symmetry and end state comfort during grasp selection depend on whether people produce the two movements at the same time (simultaneously) or in close succession (sequentially)?

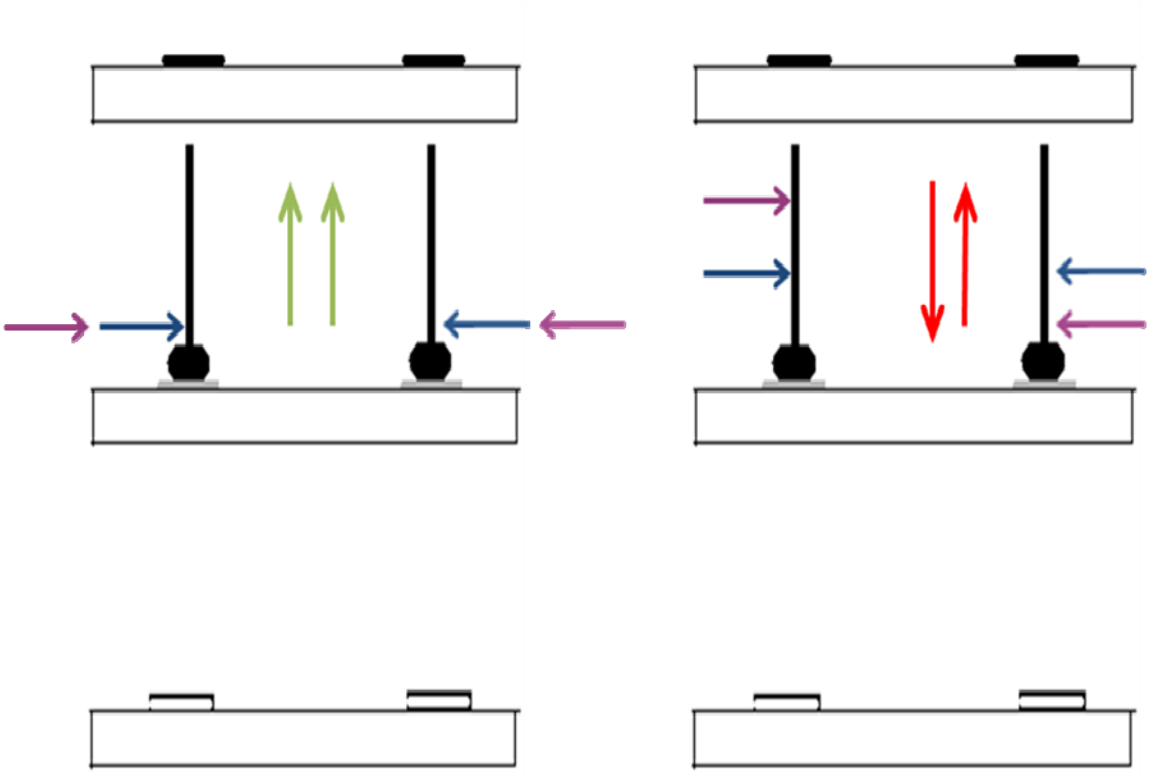

Figure 3. Predictions for Experiment 1. The vertical arrows indicate the target locations for the two hands in a congruent (left panel) and incongruent (right panel) condition. The horizontal arrows indicate the predicted grasps based on end-state comfort (blue arrows) and bimanual symmetry (purple arrows).

Method

Participants

Eight participants first completed an informed consent form and filled out two questionnaires. One pertained to demographic characteristics and any neurological deficits. The other was the short form of the Edinburgh handedness inventory (Oldfield, 1971). None of the participants reported any neurological deficits and all the participants were right-handed, ranging in age from 18 to 22 years. All participants were tall enough to comfortably reach the top of the cylinder when it was on the top platform. The Penn State University Institutional Review Board approved the experiment and the rights of all participants were protected.

Procedure

Participants performed the basic task of grasping two plungers, one with each hand, and moving them from two start locations to two target locations. Participants completed two variations of this task with four conditions each. Thus, each participant completed a total of 8 experimental conditions. Each condition was performed once and the order of conditions was counterbalanced across participants.

The conditions in one variation required participants to move the left plunger first to its target position and then to move the right plunger to its target position. These sequential conditions provided a baseline measure to determine whether people planned for end state comfort when moving one plunger at a time. In the other variation, participants moved the two plungers simultaneously from their start location to their respective target locations. The four conditions in each of the variations consisted of moving both plungers to locations of the same height (both up or both down) or to locations of different heights (one up and one down).

After the participant filled out the forms, s/he was directed to the experimental setup and asked to stand in front of it. The setup consisted of three platform heights. The bottom platform was 52.4 cm above the floor, the middle platform was 86.4 cm above the floor, and the top platform was 120.4 cm above the floor. The platforms were each 21 by 26 cm, and oriented with the longer edge perpendicular to the participants. The top and bottom platforms had two target areas, one black and the other white. In Experiment 1, the start platform was always the middle one. The start platform contained two gray areas of 21 by 26 cm. The platforms were shifted relative to one another in depth relative to the participants' position, such that the bottom platform was 10 cm away, the middle platform was 31 cm away, and the top platform was 52 cm away from where the participant stood at the onset of a trial. The reason for positioning the platforms in this way was to minimize the curvature that participants needed to move with to avoid hitting the platforms during the transport movements.

At the beginning of each trial, two bathroom plungers stood on the start platform, one aligned with the participant's left hand and one aligned with the participant's right hand. Both plungers had a wooden shaft, 51 cm in length and 23 mm in diameter. The plungers had a sturdy rubber base, 13 cm in diameter and 8 cm high, attached to the shaft handle. The mass of each plunger was 135 g, and the mass of each rubber base was 178 g.

Each of the two target platforms (top and bottom) had two targets on them, one for each hand. The targets were either black or white. The colors of the two targets on a platform always matched, such that either the top targets were both black and the bottom targets white, or vice versa. The assignment of target colors to target locations stayed constant throughout the experiment for each participant, but was randomized across participants.

Participants always started with both of their arms hanging by the side of their bodies. Their body was positioned in such a way that their shoulders approximately lined up with the target pairs. Participants aligned the toes of their feet with a line on the floor that was 10 cm away from the experimental setup.

On each side of the experimental setup stood a webcam (Logitec Ultra Vision 5000, 30 Hz. frame rate) that focused on the cylinders on the start platforms. The webcam to the left of the participant recorded grasps of the plunger on the left side of the participant, and the webcam to the right of the participant recorded grasps of the plunger on the right side of the participant. The webcams were placed at approximately the same height as the start platform in such a way that the bottom of the rubber base was on the very bottom of the webcams' field of view, and the top of the plunger shaft was at the very top of the webcams' field of view.

At the beginning of the session, the experimenter told participants that the study focused on how well people could memorize sequences of movements. Participants were told that they were in the easy condition, such that they would always make one movement with each hand, and report the target sequence back to the experimenter before and after moving. The experimenter told the participants this cover story to encourage them to perform without being self-conscious of how they took hold of and moved the plungers. This instruction was important because the webcams stood on a tripod to the left and in full view of the participant. In addition, it ensured that participants moved to the correct target pairs in a trial. The experimenter also told participants to grasp the plungers with a power grip (by indicating that a power grip is similar to how one grasps a tennis racquet) and to maintain this grip throughout the movement. The experimenter gave this instruction to ensure that participants would not let the plungers slide through their hands during object transports. Finally, the experimenter told participants that they could move at a pace that felt comfortable to them. Thus, the task was not speeded. The exact instructions that participants were given appear in Appendix A.

To indicate what participants had to do in a trial, the experimenter told the participant to move sequentially or simultaneously, followed by the target order. The experimenter indicated the target order through the color of the targets and by specifying the left hand target first and the right hand target second. Thus, the experimenter would, for example, say “Simultaneously, Black White” in a trial, indicating that the plungers should be moved at the same time, moving the plunger on the left with the left hand to the location of the black target on the left side, and moving the plunger on the right with the right hand to the location of the white target on the right side. None of the participants appeared to have trouble understanding these instructions. When participants did not follow the instruction in a particular trial, they were immediately reminded of the instructions by the experimenter. This happened infrequently, and if it did it was mostly in the first few trials of the experiment. In such cases, the experimenter repeated the particular trial immediately.

Data Analysis

Two webcams captured each participant’s performance on a computer. The webcams recorded the position of the hands on the plungers at the starting positions when the participant took hold of the plungers before moving them to the target positions. I used the video records of one webcam to analyze grasps performed with the left hand and the video records of the other webcam to analyze grasps performed with the right hand. Given the instruction that participants received not to let the plungers slide in their hands (which was carefully checked during performance), it is safe to assume that the positions of the hands on the plungers at the end of the object-transports was the same as the positions of the hands on the plungers when participants first grasped the plungers at the starting positions.

To measure grasp heights, I used a video playback device that permitted frame-by-frame inspection of individual video frames. During the analysis I froze the frame of interest for each measurement. In a second step, I then measured the distance from the bottom of the plunger shaft to the judged highest point of thumb contact on the plunger by clicking on these locations with a computer mouse. A second measure taken for each frozen frame was the length of the plunger shaft. This measure was taken as an extra precaution, because the distance of the plunger from the webcam could vary slightly from trial to trial if the participant did not set the base down exactly on the middle of the platform every time. I obtained this measure by clicking on the base and the top of the plunger shaft. I used a customized Matlab routine to measure grasp height as a proportion of the length of the plunger by dividing the distance from the bottom of the plunger shaft (above the plunger base) to the highest point of thumb contact on the plunger by the distance from the bottom of the plunger shaft to the plunger's top. Thus, the values for the resulting measure of proportional grasp height range from 0 (grasping right above the plunger base) to 1 (grasping at the very top of the plunger).

The proportion grasp heights for the hands were taken to compute the strength of the grasp height effect, the main dependent measure in each of the experiments. Calculation of the strength of the grasp height effect was done differently for congruent and incongruent conditions. For congruent conditions, the strength of the grasp height effect for each individual hand was calculated by taking the proportional grasp heights when both plungers were moved to low target locations (expected to be a relatively large value), and subtracting from this the proportional grasp heights when both plungers were moved to high target locations (expected to be a relatively small value). Thus, the calculation of the grasp height effect for congruent conditions occurred across trials. The calculation of the grasp height effect for incongruent conditions in contrast was done within a trial. For this measure, the proportional grasp height for the hand that moved a plunger to a high location was subtracted from the proportional grasp height for the hand that moved a plunger to a low target location.

Each participant performed each experimental condition once, resulting in one recorded proportional grasp height for each hand in each condition.

Results of Experiment 1

To determine whether participants displayed an effect of congruency and simultaneity of the movements for the two hands on their grasp selection, I subjected the proportional grasp heights

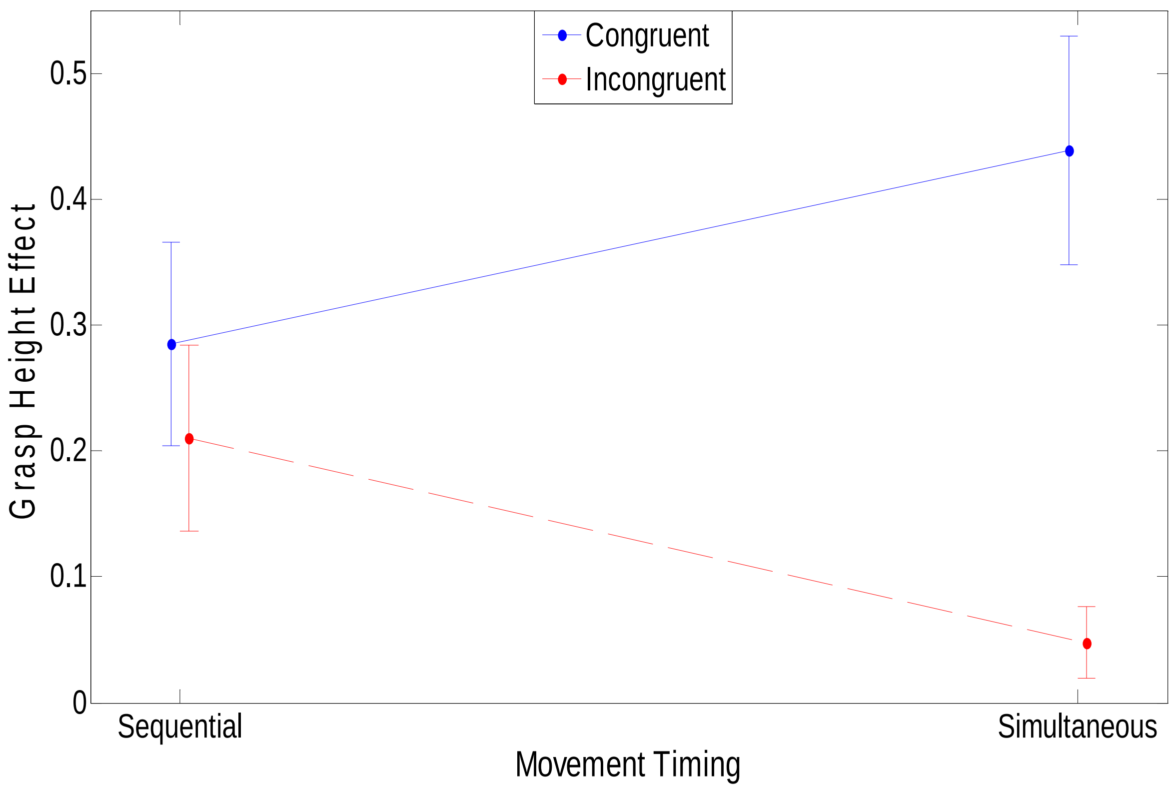

Figure 4. Mean grasp height effect (± 1 SE) of Experiment 1 for congruent and incongruent conditions when moving the objects one at a time (sequential) or at the same time (simultaneous).

for the left hand and the grasp heights for the right hand to two separate repeated-measures ANOVAs whose design was 2 (target height, low or high) x 2 (congruency, referring to whether the other hand moved to the same or a different target height) x 2 (simultaneity of movement, either simultaneous or sequential).

Figure 4 shows the grasp height effect for the congruent and incongruent target conditions averaged for all participants. The results of the congruent conditions are averaged for the left and right hand. The results for the incongruent conditions are averaged for cases in which participants moved the object on the left up and the object on the right down, and vice versa. For the congruent conditions, I calculated the magnitude of the grasp height effect for each hand by subtracting the proportional grasp height when moving the plunger to a high target from the proportional grasp height when moving the plunger to a low target. Positive values indicated the presence of the grasp height effect, with the numerical difference indicating the strength of the effect. For the incongruent conditions, I calculated the magnitude of the grasp height effect by subtracting the proportional grasp height that participants adopted on the plunger that needed to be moved to a high target location from the proportional grasp height that participants adopted on the plunger that needed to be moved to a low target location. Again, positive values indicated the presence of the grasp height effect, and the numerical difference indicated the strength of the effect.

The results of the ANOVAs for the left and right hand revealed a significant three-way interaction between target height, congruency, and timing, $F(1,7) = 8.860$, $p < .05$ for the left hand, and $F(1,7) = 6.395$, $p < .05$ for the right hand, such that participants grasped according to end state comfort in the congruent conditions but not in the incongruent conditions while moving the objects simultaneously. Thus, in congruent conditions participants grasped the plungers close to the base when moving them to the high locations, and close to the top when moving the plungers to the low locations. In contrast, the results displayed no effect of congruency on proportional grasp height when participants moved the objects sequentially. The results for both hands also showed a two-way interaction between target height and congruency, $F(1,7) = 19.509$, $p < .05$, for the left hand, and $F(1,7) = 13.241$, $p < .05$, for the right hand, such that participants grasped closer to the bottom of the plunger shaft for displacements to a high target in congruent versus incongruent trials, and closer to the top of the plunger for displacements to a low target in congruent versus incongruent trials. Finally, the results also revealed a significant main effect for target height for both hands, $F(1,7) = 21.445$, $p < .01$ for the left hand and $F(1,7) = 19.879$, $p < .01$ for the right hand, such that participants grasped the object more towards its top when they transported it to a low location, and more towards its bottom when they transported it to a high location.

Discussion of Experiment 1

The results of Experiment 1 indicated a reduction of end state comfort planning when participants performed the task of moving two objects simultaneously (one with each hand) to incongruent target locations (Figure 4). When participants moved two objects to two low or to two high targets simultaneously, they anticipated end-state comfort with both hands by grasping the objects high for low targets and by grasping the objects low for high targets. However, when they moved one object to a low location while simultaneously moving the other object to a high location, participants displayed an attenuation of the grasp height effect. Instead of grasping the object low for a high target and high for a low target, they grasped both objects in close proximity. Thus, participants adopted near symmetric grasps that would not be expected based on end state comfort planning. When participants moved the objects one at a time, they did show a grasp height effect for incongruent conditions.

The results of Experiment 1 are consistent with the notion that goals play a primary role in action planning, and that concurrently coordinating two opposing action goals within a single representation is difficult. Thus, coordination of an object transport to a low or high target location simultaneously with both hands could have been relatively easy because the same goal representation could be applied to both hands. In contrast, different goal representations were required when one hand displaced an object to a low location while the other hand simultaneously displaced an object to a high location. The timeline of such incongruent goal representations was important, as reflected in the finding that participants adopted near symmetric grasps when the hands moved simultaneously to two opposing locations, but much less so when one hand moved to a location first, followed by a movement of the other hand to an opposing location.

The results of Experiment 1 suggest that people may plan object manipulation actions differently depending on the difficulty of the task. The results do not indicate however how participants planned their object grasps. Because the two objects always started at identical heights, the results of Experiment 1 provide no information on whether the origin of the reference frame that participants relied on during action planning was allocentric or egocentric. I designed Experiment 2 to address this question.

CHAPTER 3
BIMANUAL OBJECT MANIPULATION AND REFERENCE FRAMES

Experiment 2

Previous studies of bimanual grasp selection indicated that participants adopted grasps that complied with end state comfort and bimanual symmetry when the start and end locations for transporting the two objects were similar (e.g. Fischman et al., 2003; Hughes & Franz, 2008; Janssen et al., 2008; Weigelt et al., 2006). From these previous studies, the influence of end state comfort and bimanual symmetry on performance in trials in which transporting the two objects required different start and/or end postures for the two hands was less clear. In one study, bimanual symmetry appeared to override end state comfort planning (Hughes & Franz, 2008). In other studies, end state comfort appeared to be an important constraint for action planning in incongruent trials (Janssen et al., 2008; Weigelt et al., 2006). Experiment 1 of this dissertation suggested that symmetry for the two hands formed an important constraint for bimanual grasping.

A question that cannot be addressed on the basis of these earlier studies is which reference frame participants predominantly used for the planning of bimanual object grasps. Each of the previous studies used symmetric objects that started at the same height for each hand and ended at the same height for each hand. As a result, it is impossible to determine whether participants used an allocentric reference frame or an egocentric reference frame to plan their grasps. In particular, a central question is whether the origin of the reference frame that participants rely on is grounded in their body or in the external world. Experiment 2 addressed this issue through a manipulation of the height of start and target locations.

Experiment 2 allowed for tests of three different forms of the bimanual symmetry hypothesis that I introduced earlier. The *Body Initial State Symmetry (BISS)* hypothesis stated that people plan for symmetry between their hands at the start locations. The *Body End State Symmetry (BISS)* hypothesis stated that people plan for symmetry between their hands at the end locations. The *Object Symmetry* hypothesis stated that people always grasp the two objects in the same location along the object length.

Figure 5 shows the predictions of the different bimanual symmetry hypotheses. The critical conditions to distinguish between the BISS and BESS hypotheses are those in which the objects start at different heights and need to be moved to the same target height. For these conditions, the BISS predicts that people will grasp the two objects such that their hands occupy egocentrically symmetric positions when they first grasp the objects. Doing so leads to body asymmetric end states when the two objects start at different heights and need to be moved to the same target height. In contrast, the BESS predicts that people will grasp the objects such that they end the

A. B.

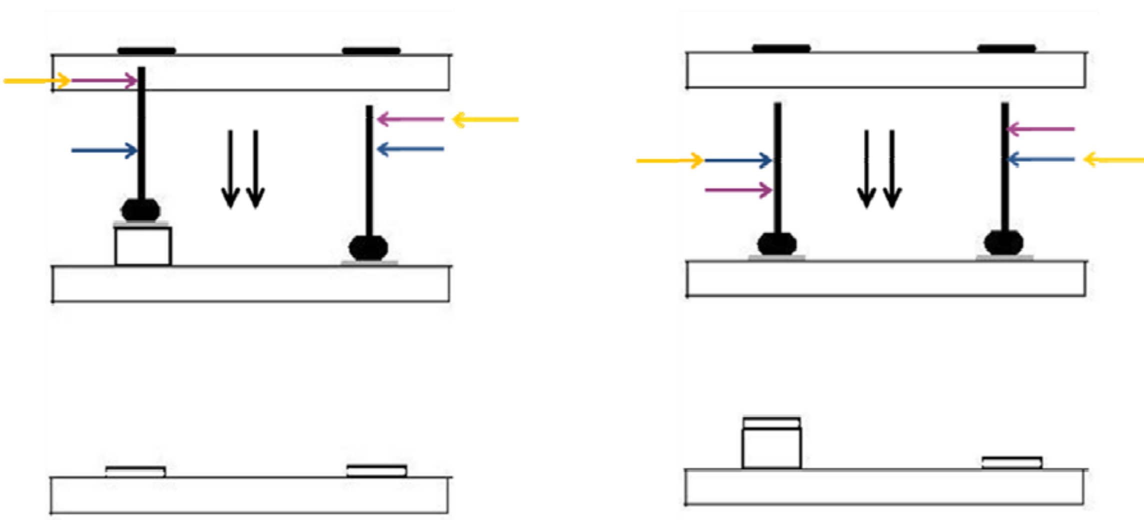

Figure 5. Predictions for Experiment 2. Panel A and B show different conditions. The vertical arrows indicate the target locations for the two hands. The horizontal arrows indicate the predicted grasps based on BISS (blue arrows), BESS (purple arrows), and Object Symmetry (orange arrows). See text for explanation.

object transports with their hands occupying body symmetric positions. Doing so requires body-asymmetric initial grasps when the two objects start at different heights and need to be moved to the same target heights.

The BESS hypothesis and the Object Symmetry hypothesis make the same prediction when the two objects start at slightly different heights and are moved to the same target heights. For people to end in a body symmetric way at the same target heights mean that they must adopt object symmetric grasps. The two hypotheses make different predictions for the conditions in which people move the objects from the same start heights to slightly different target heights however. The BESS hypothesis predicts in that case that people will adopt asymmetric grasps for the start locations that cause them to end in an egocentrically symmetric posture at the target locations. The selected grasps would be symmetric with respect to their body but not with respect to the object in that case. In contrast, the Object Symmetry hypothesis predicts that people will adopt grasps that are symmetric with respect to the object. Because the target locations differ in height, this would cause them to complete the object transports in an allocentrically symmetric but egocentrically asymmetric way at the target locations.

Method

Participants

Twenty eight participants first completed an informed consent form and filled out two questionnaires. One pertained to demographic characteristics and any neurological deficits. The other was the short form of the Edinburgh handedness inventory (Oldfield, 1971). Two of our participants reported neurological deficits and one participant was left-handed. Their data were not used for further analysis. All of our remaining participants were right-handed. They ranged in age from 18 to 24 years. All participants were tall enough to comfortably reach the top of the cylinder when it was on the top platform. The Penn State University Institutional Review Board approved the experiment, and the rights of all participants were protected.

Procedure

Experiment 2 consisted of 28 conditions, each of which each participant performed once. Four conditions were identical to the four conditions in Experiment 1 in which participants moved the two plungers simultaneously, and no height was added to the start platform and target platforms. There were 24 additional conditions; 3 (starts even, left start raised, or right start raised) x 2 (left target raised or not) x 2 (right target raised or not) x 2 (congruent or incongruent; hands moving in the same or opposite direction). The order of conditions was counterbalanced between participants.

After participants filled out the forms, they were directed to the experimental setup and asked to stand in front of it. The setup was the same as in Experiment 1, except that an additional height was differentially added to the start and/or target locations in different conditions. For this purpose, the experimenter differentially added platforms of 11 cm in height and with the same dimensions as the target locations to the start and/or target locations.

At the beginning of Experiment 2, the experimenter told participants that the study focused on how well people could time the movements they made with their two hands. This instruction diverted the focus from where participants grasped and encouraged participants to move the plungers simultaneously. The experimenter also told the participants to grasp the plungers with a power grip (by indicating that a power grip is similar to how one grasps a tennis racquet), to not let the plungers slide through their hands during transport, and to move at a comfortable pace. The experimenter repeated any of these instructions as needed throughout the experiment. When participants did not follow the instruction in a particular trial, they were immediately reminded of the instructions by the experimenter. The vast majority of such cases occurred in the first few trials of the experiment, and the experimenter repeated the particular trial immediately in such cases.

As in Experiment 1, at the beginning of each trial, two plungers stood on the start platform, one approximately aligned with the participants' left hand and one approximately aligned with their right hand. The plungers were identical to those used in Experiment 1. In each trial, participants moved the two plungers simultaneously from their start location to their respective target locations. In each trial, the experimenter told the participant the target order for that trial. The target order was indicated through the color of the targets and by specifying the left hand target first and the right hand target second. For example, the experimenter aid "Black White" in a trial to indicate that one plunger should be moved with the left hand to the black target on the left side and the other plunger should be with the right hand to the white target on the right side. The experimenter asked participants to repeat the target sequence before moving. None of the participants appeared to have trouble understanding these instructions. The exact instructions that participants received appear in Appendix A. Analysis of the video data followed the same procedure as in Experiment 1.

Results of Experiment 2

To analyze the data of Experiment 2, I conducted a series of analyses. The goal of the first analysis was to determine whether or not people selected end state comfort grasps (reflected in higher grasp heights for object transports to low targets than to high targets). The goal of the second analysis was to determine whether people planned their grasps in ways that reflected

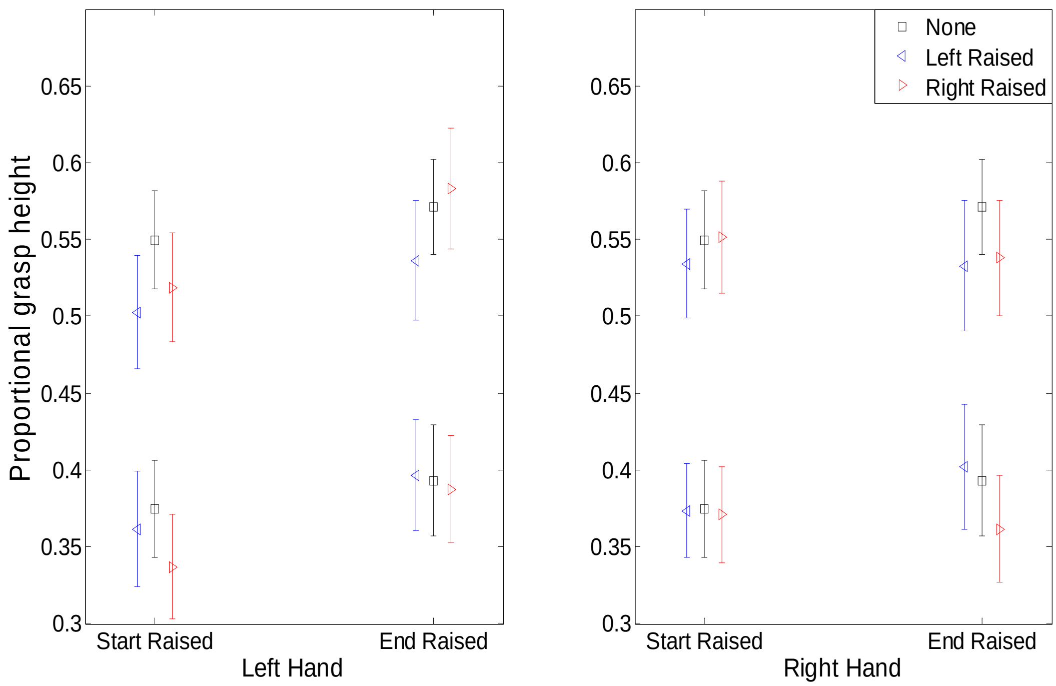

Figure 6. Mean proportional grasp heights (± 1 SE) for the left hand (left panel) and right hand (right panel) when moving both plungers to a low target (plotted in the upper parts of both panels) and high target (plotted in the lower parts of both panels). Different symbols correspond to different raised start and target (end) locations.

planning for symmetric grasps with respect to the initial state of the body (grasping the objects at their initial location), with respect to the end state of the body (placing the objects on their target locations), or with respect to the objects themselves.

Analysis of End State Comfort

To determine whether participants displayed the grasp height effect in congruent trials, I first ran an ANOVA to compare the grasp heights that were adopted when participants moved both plungers to a high location with the grasp heights adopted when participants moved both plungers to a low location. For this analysis, I only included trials in which there were no differences in the start and target heights. Figure 6 shows these conditions. The 2 (target combination) x 2 (hand) ANOVA revealed a main effect for target height on grasp height, $F(1, 24) = 93.76$, $p < .01$, such that participants grasped the plungers higher when they moved them to a low location than when they moved them to a high location. The results revealed no main effect for hand or a hand-related interaction, $p > .10$.

Analysis of Symmetry

To determine whether and what type of symmetric grasps participants tended to adopt when transporting the two plungers, I first obtained difference values for each trial by subtracting the proportional grasp heights for the left hand from the proportional grasp heights for the right hand. I performed this calculation on a subject-by-subject and trial-by-trial basis. Resulting values close to zero indicated that participants grasped the two plungers in approximately the same location on the plunger shafts, whereas deviations from zero indicated that one of the hands grasped at a higher location on one of the plunger shafts than the other hand on the other plunger shaft. Higher grasps for the right hand than the left hand resulted in positive difference values, and higher grasps for the left hand than for the right hand resulted in negative difference values.

Figure 7 shows the mean difference values for each experimental condition. To analyze these data statistically, I conducted a 2 (target combination; both up or both down) x 2 (raised location; one of the start locations or one of the target locations) x 2 (side of the raised location; left or right) ANOVA on the difference values for the conditions in which participants moved the plungers to similar target heights. Thus, I included only the conditions in which either one of the

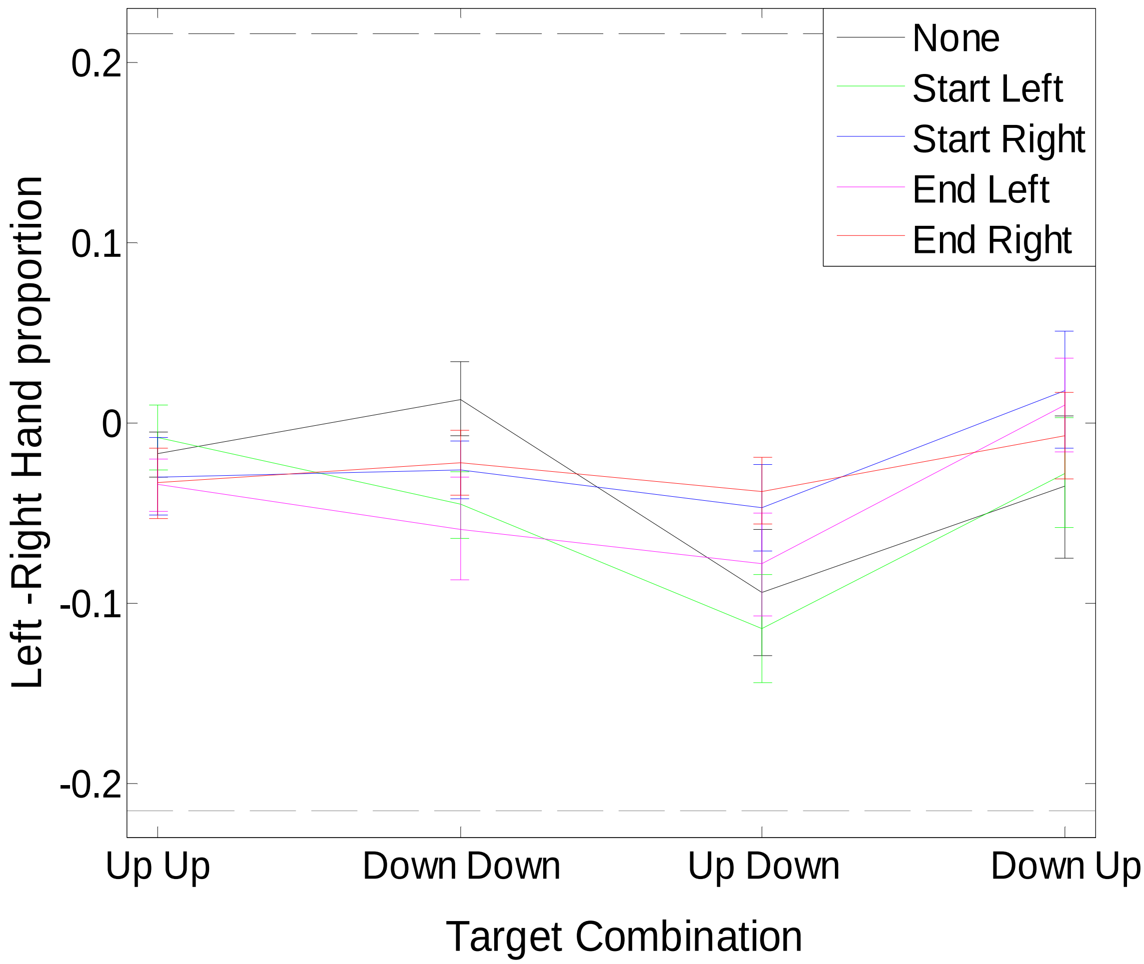

Figure 7. Mean difference values (± 1 SE) based on proportional grasp heights for the left hand minus the right hand. Different lines indicate different conditions in which one of the start or target locations were raised. The dotted lines on the top and bottom indicate the grasp height differences that would have been adopted if participants planned for start or end state symmetry.

start locations or one of the target locations was raised. The reason for selecting these eight conditions was that they formed the critical conditions for evaluation of the different hypotheses concerning the type of symmetry for which participants planned. Whereas the BISS and BESS hypotheses predicted differences in the values among these eight conditions, the Object Symmetry hypothesis predicted no differences among them. In addition, the Object Symmetry hypothesis predicted the difference values to be close to zero in each of the conditions.

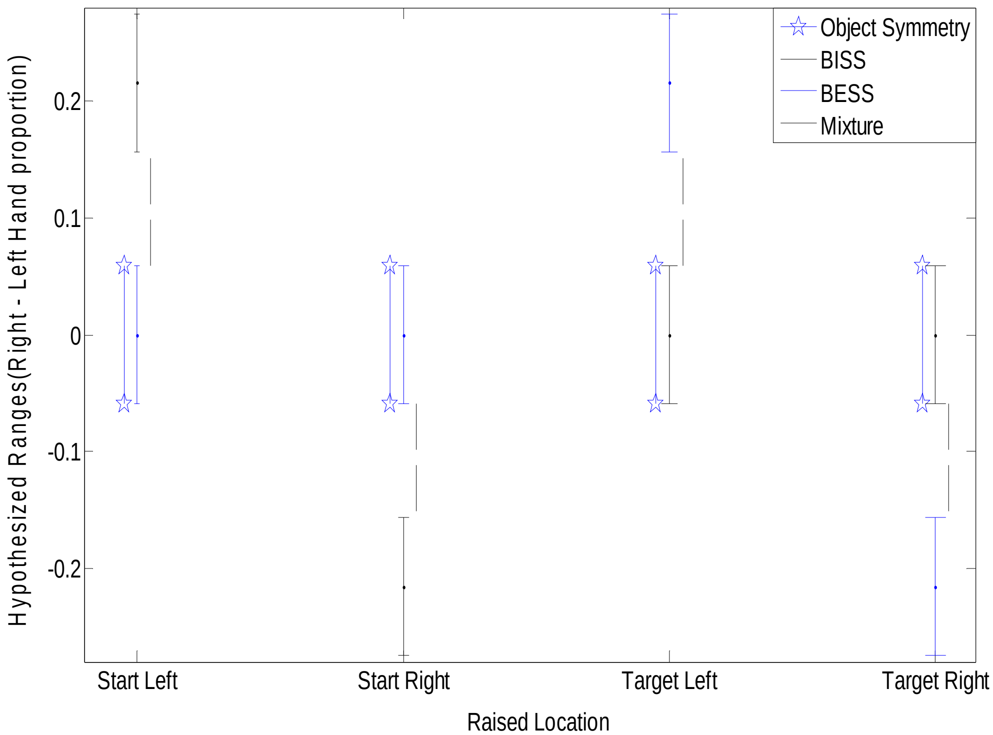

Figure 8. Predicted difference values (± 3 cm) in proportional grasp heights for the right hand minus the left hand for different hypotheses.

Hypothesis	<u>Supporting observations</u> Possible observations	Percent support
Object symmetry	138/200	69.0
Object symmetry without Initial State Symmetry	63/100	63.0
Object symmetry without End State Symmetry	75/100	75.0
Initial state symmetry	81/200	41.5
Initial state symmetry without Object symmetry	6/100	6.0
End state symmetry	64/200	32.0
End state symmetry without Object symmetry	1/100	1.0
Mixture hypothesis	23/200	11.5
No hypothesis	32/200	16.0

Table 1. Observed support for each of the hypotheses of Experiment 2.

Figure 8 shows the criterion ranges I used for each of the hypotheses. For the Object Symmetry hypothesis, the range always fell around zero (± 3 cm). For the BISS and BESS hypotheses, the range sometimes fell around zero, and at other times it fell around the predicted (positive or negative) proportional difference value corresponding to the height of the added platform (the platform height, 11 ± 3 cm, divided by the length of the plunger shaft, 51 cm). Within each raised start or target location, the predicted difference values for conditions in which both plungers needed to be moved to a low or high location are identical. As one could see in Figure 8, in some cases different hypotheses made identical predictions. However, the required critical conditions exist to distinguish between each of the hypotheses.

Table 1 shows the proportion of grasps consistent with each of the hypotheses. The Object Symmetry hypothesis accounted for a larger proportion of the adopted grasps than one would expect by chance. As shown in Table 1, the data predominantly supported the Object Symmetry hypothesis (69.0 percent of cases). The BISS hypothesis was supported for 41.5 percent of grasps, but only in 6.0 percent of the cases in which the Object Symmetry hypothesis predicted difference values other than those predicted by the BISS hypothesis. Similarly, the BESS hypothesis was supported for 32.0 percent of grasps, but only in 1.0 percent of the cases in which the Object Symmetry hypothesis predicted different difference values than the BESS hypothesis. Participants adopted grasps that fell between the predicted difference values in 11.5 percent of cases, suggesting that grasp selection could sometimes arise due to a mixture of planning for different constraints.

Discussion of Experiment 2

The results of Experiment 2 suggest that participants planned their grasps with respect to an allocentric reference frame for which the origin was tied to the objects to be moved. Participants predominantly grasped the plungers in approximately the same locations along the plunger shafts regardless of differences in the start or target locations of the object transports. Thus, participants favored object symmetric grasps. However, the results also suggested that a mixture of body and object symmetry constraints could underlie bimanual grasp selection, because a substantial percentage of grasps fell between the predicted values of the different hypotheses.

The finding that participants predominantly used an allocentric reference frame for bimanual grasp selection is consistent with recent work on the use of reference frames for unimanual grasp selection. As mentioned before, Weigelt, Cohen, and Rosenbaum (2007) found that memory for recently executed unimanual grasps relies on an allocentric rather than on an egocentric reference frame. The current findings extend this observation by showing that not only did memory for grasp selection use allocentric coordinates, but that planning of bimanual object grasps did so as well.

Why might people use an allocentric reference frame for bimanual grasp selection? One advantage of grasping both objects in the same location is that representing the dynamics of object displacement is similar for both hands. Positioning the hands in the same location relative to the objects' center of mass could make coordination of the forces required to grasp and displace the objects less complex. In line with the proposition that people may select bimanual object symmetric grasps to adopt similar positions of the hands relative to the center of mass of the objects, Ahmed, Wolpert, and Flanagan (2008) recently proposed that the dynamics of objects with simple (or familiar) dynamics are represented in an object-centered reference frame. Based on this notion, a possible hypothesis for why people tended to adopt similar grasp locations along the plunger shafts is that doing so made representing object dynamics easier.

This hypothesis cannot be inferred from the results of Experiment 2, but it constitutes a plausible possibility.

Sensitivity of the planning of object grasps to the location of the center of mass of the object has been demonstrated for unimanual grasp selection. Lederman and Wing (2003) showed that people select grasps to fall very close to the center of mass when they were asked to lift an object and put down. The observation that grasp selection was sensitive to the location of the center of mass could not be the only factor that people plan for, however, because Experiment 1 and 2 in this dissertation showed that where people grasped the objects in congruent conditions depended strongly on the height of the target locations.

Another reason why people may gravitate towards adopting allocentric, object symmetric grasps is that it is well-known that object symmetry plays an important role in visual perception. For example, people prefer symmetric forms for perceived (e.g. Pashler, 1990) as well as mental shapes (e.g. Feldman, 2000). Faces that are symmetrical tend to be perceived as more attractive (e.g. Rhodes, 2006). Symmetry is an important factor in the creation and perception of art (e.g. Ramachandran & Hirstein, 1999). The preference for visual symmetry is not exclusively human, but has been demonstrated for many species, including apes, bees, birds, and dolphins (cf. Giurfa, Eichmann, & Menzel, 1996). Recently, an area in the extrastriate cortex showed sensitivity to symmetry of perceived shapes in humans and macaque monkeys (Sasaki, Vanduffel, Knudsen, Tyler, & Tootell, 2005). Thus, to observe that people gravitate towards grasps that are symmetric in terms of the visual perception of the hands on the objects is perhaps not surprising based on these earlier findings.

To observe that people adopt object symmetric grasps in incongruent conditions need not imply that they continue to do so with increased experience in a task. It could be that the tendency to adopt symmetric grasps is initially predominant, but that people break such symmetry with increased task experience if it is beneficial to do so. Alternatively, symmetry could remain a prominent constraint with increased task experience. Experiment 3 addressed this possibility.

CHAPTER 4
REFERENCE FRAMES AND TASK EXPERIENCE

Two important issues that were raised in the introduction could not be addressed with Experiments 1 and 2. A first issue was whether people display changes in performance as a function of task experience. Experiment 2 indicated that planning of bimanual object grasps predominantly relied on an allocentric reference frame. However, whether this reference frame would remain prominent with increased task experience is an open question.

A second issue that could not be addressed by Experiments 1 and 2 is the Conceptualization hypothesis. This hypothesis refers to the notion that people initially have difficulties with planning in the incongruent conditions because it is difficult to conceive of the body's end posture when transporting two objects to different locations at the same time. According to this hypothesis, people would initially fail to adopt grasps that comply with end state comfort planning in the incongruent trials because planning to do so is difficult. If this hypothesis is correct, one would expect people to start displaying grasps that comply with end state comfort planning as they gain more experience with the task.

If people change their performance for bimanual grasp selections, one can infer that they were sensitive to factors related to performance that they were not sensitive to before, or if they were, they could not address their concerns via planning or plan execution. Demonstrating that people show increased sensitivity to end state comfort planning with increased task experience would reconcile discrepancies in the previous findings on bimanual object manipulation. If people show no changes in performance as a function of experience, this could be due to several possibilities. One is that selecting grasps to comply with end-state comfort is not worth the effort of planning because the end position that the body is in after object transport is tolerable. In other words, people would not show end state comfort planning with increased experience in the incongruent conditions because the costs of planning for end-state comfort exceed the benefits gained from it. A second possibility is that even with practice, people cannot conceive of the task of moving two objects to different locations as single, integrated representation. As a result, people continue to display reduced end state comfort planning with increased task experience.

Experiment 3A

Method

Participants

Sixteen participants first completed an informed consent form and filled out two questionnaires. One pertained to demographic characteristics and any neurological deficits. The other was the short form of the Edinburgh handedness inventory (Oldfield, 1971). None of the participants reported any neurological deficits and all the participants could be classified as right-handed. The participants ranged in age from 18 to 23 years. All participants were tall enough to comfortably reach the top of the cylinder when it was on the top platform. The Penn State University Institutional Review Board approved the experiment and the rights of the participants were protected.

Procedure

The method of Experiment 3 was very similar to the method of Experiment 1, with some differences. A first was that participants always moved the two plungers simultaneously from their start locations to their respective target locations. The four conditions in each of the variations consisted of moving both plungers to the same (up or down) or to different (left up/right down, or left down/right up) target locations. Participants completed two blocks of 15 trials each. In each block, participants first completed 13 trials in which the two plungers started at the same initial height. For these trials, participants completed 5 trials of the congruent conditions, and 8 trials of the incongruent conditions. In the last two trials of each block, one plunger started at a slightly higher location than the other plunger. To achieve this different in initial start location, a platform of 11 cm in height was differentially added to one of the start locations.

To investigate possible effects of practice on the way participants manipulated the objects, I had half of the participants complete blocks of the same incongruent condition and I had the other half of the participants complete blocks containing a mixture of the different conditions. The order of the conditions was randomized over participants and blocks.

Another difference between Experiment 3 and Experiment 1 was that plunger lift-off and placement times were recorded in each trial. Electric switches recorded when participants lifted the objects from the start locations and placed them on the target locations. To obtain these data, I placed an electric switch under each of the start and target locations. Placement of a plunger on a switch caused the switch to close. To achieve this switch closure, I covered the bottom of the base of each plunger with a circular disk that was inserted into the plunger base in such a way that it reliably caused the switches to close without making the plunger unstable when it sat on any of the switches.

I used a digital input/output card (DIO 6356, National Instruments, Inc.) to record the opening and closing of the six switches. I also developed a customized MATLAB routine to register the opening and closing times. The data for each trial were written to an Excel file that was used for later analysis. The recording of pick up and placement times allowed for the analysis of the asynchrony of pick-up times and placement times, as well as movement times for the two hands.

Behind the experimental setup stood two webcams that focused on the cylinders on the start platforms. The webcams recorded grasps of the plunger for the left and right hand. The webcams were placed at approximately the same height as the target platform on the top in such a way that the bottom of the rubber base was on the very bottom of the webcams' field of view, and the top of the plunger shaft was at the very top of the webcams' field of view. A first webcam (Logitec UltraVision 5000) was connected to the digital input/output board. This webcam collected a still frame at each moment one of the plungers was lifted from one of the two start platforms. A second webcam (Logitec UltraVision 5000, 30 Hz. frame rate) continuously recorded images throughout the experiment. This recording was included to ensure that a still frame for each grasp would be recorded in the event that the first webcam failed to do so. Based on the collected still frames, extracting a still frame from the recorded videos was necessary for approximately 6% of the trials. In these cases, I used the same procedure for extracting still frames as described in the method section of Experiment 1.

Another difference between Experiment 3 and Experiment 1 was that the experimenter told participants that the study focused on how well participants could time the object displacements to different locations. The experimenter told the participants this cover story to encourage them to perform without being self-conscious of how they took hold of and moved the plungers. This instruction was important because the webcam stood in full view of the participant. None of the participants appeared to have trouble understanding these instructions. The complete instructions that participants received appear in Appendix A.

Results

I now present the results concerning the adopted grasp heights followed by the results concerning timing. For each analysis, I applied a Greenhouse-Geisser correction to the degrees of freedom if appropriate.

Grasp Height Results

Figure 9 shows the mean grasp height effect (± 1 SE) as a function of repetition number for the congruent and incongruent conditions. The results of the congruent conditions are averaged for the left and right hand. The results for the incongruent conditions are averaged for cases in which participants moved the object on the left up and the object on the right down, and vice

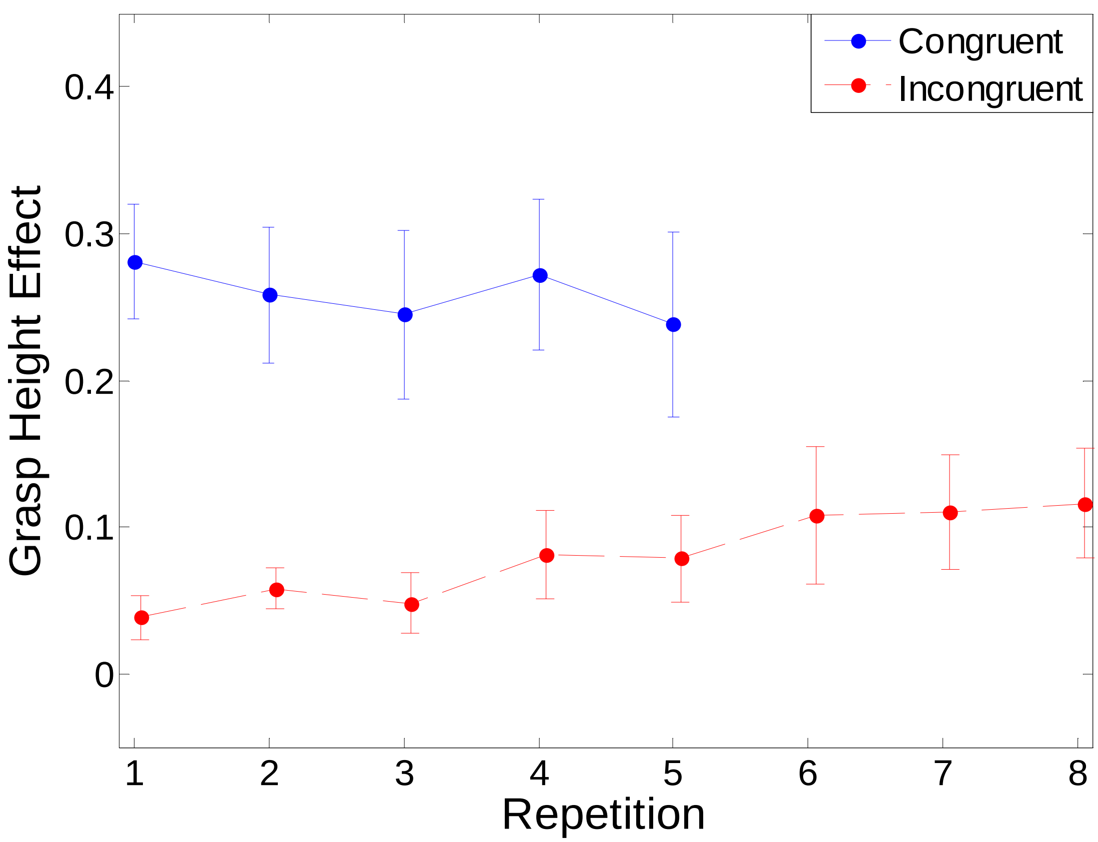

Figure 9. Mean grasp height effect (± 1 SE) for congruent and incongruent conditions of Experiment 3a.

versa. The calculation of the strength of the grasp height effect in different conditions was the same as that used in Experiment 1.

To analyze whether and how congruency of the target locations and task experience influenced the adopted grasps, I performed a 2 (hand; left or right) x 4 (target combination; High/High, Low/Low, High/Low, Low/High with the left target indicated first) x 5 (repetition) repeated-measures ANOVA on the proportional grasp heights. The results indicated a main effect of target combination, $F(1.704, 20.449) = 32.978$, $p < .01$, such that participants grasped the plungers at a low location when they moved both plungers to a high target ($M = .331$), they grasped the plungers at a high location when they moved both plungers to a low target ($M = .589$), and they grasped the plungers close to the middle when they moved one plunger to a low location and the other plunger to a high location ($M = .464$ for High/Low, and $M = .477$ for Low/High). Post-hoc comparisons revealed significant differences between each of the conditions except between the two incongruent conditions.

The results also indicated a significant interaction between hand and target combination, $F(1.403, 16.834) = 10.631$, $p < .01$, such that the grasp height effect for congruent conditions was stronger for the right hand ($M = .261$) than for the left hand ($M = .257$). In contrast, the grasp height effect for the incongruent conditions was stronger for the left hand ($M = .074$) than for the right hand ($M = .048$). In general, the grasp height effect was much stronger for congruent than for incongruent conditions, but present in both cases. The results revealed no other significant main effect or interactions, $p > .10$.

To further explore the grasp height effect in the incongruent conditions as a function of task experience, I performed a 2 (hand; left or right) x 2 (target combination; High/Low or Low/High) x 8 (repetitions) repeated-measures ANOVA. If participants increasingly showed the grasp height effect in the incongruent conditions, one would expect to find a significant three-way interaction in this analysis. The results did not reveal this interaction, $p > .1$. However, the results did reveal a significant main effect of target combination on the adopted proportional grasp heights, $F(1,12) = 17.451$, $p < .01$, such that participants grasped the plunger higher when they moved it to a low location ($M = .494$) than when they moved it to a high location ($M = .415$). Thus, the results revealed a grasp height effect with an average magnitude of about 8%, or 4 cm for the incongruent conditions. It is important to note that the magnitude of the grasp height effect was much smaller for the incongruent than for the congruent conditions. In the congruent conditions, the average magnitude of the grasp height effect was about 26%, or 13 cm.

Timing Results

Based on the opening and closing times of the electric switches, I calculated the onset asynchrony, target asynchrony, and movement times for each trial. The onset of a movement corresponded to the opening of the electric switch located beneath the plunger on the start location. The completion time of a movement corresponded to the closing of the electric switch at the target location. I calculated the asynchronies by computing the absolute difference between the onset and target times of the two hands. I computed the movement time for each hand in each trial by subtracting the onset time from the completion time of each movement.

Start Asynchronies

Figure 10 shows the mean start asynchronies (± 1 SE) for the conditions in Experiment 3A. To determine whether participants timed the onset of their movements differently for the congruent and incongruent conditions, I first conducted a 4 (target combination; High/High, Low/Low, High/Low, Low/High with the left target indicated first) x 5 (repetition) repeated-measures ANOVA on the start asynchronies. The results of this analysis revealed a significant

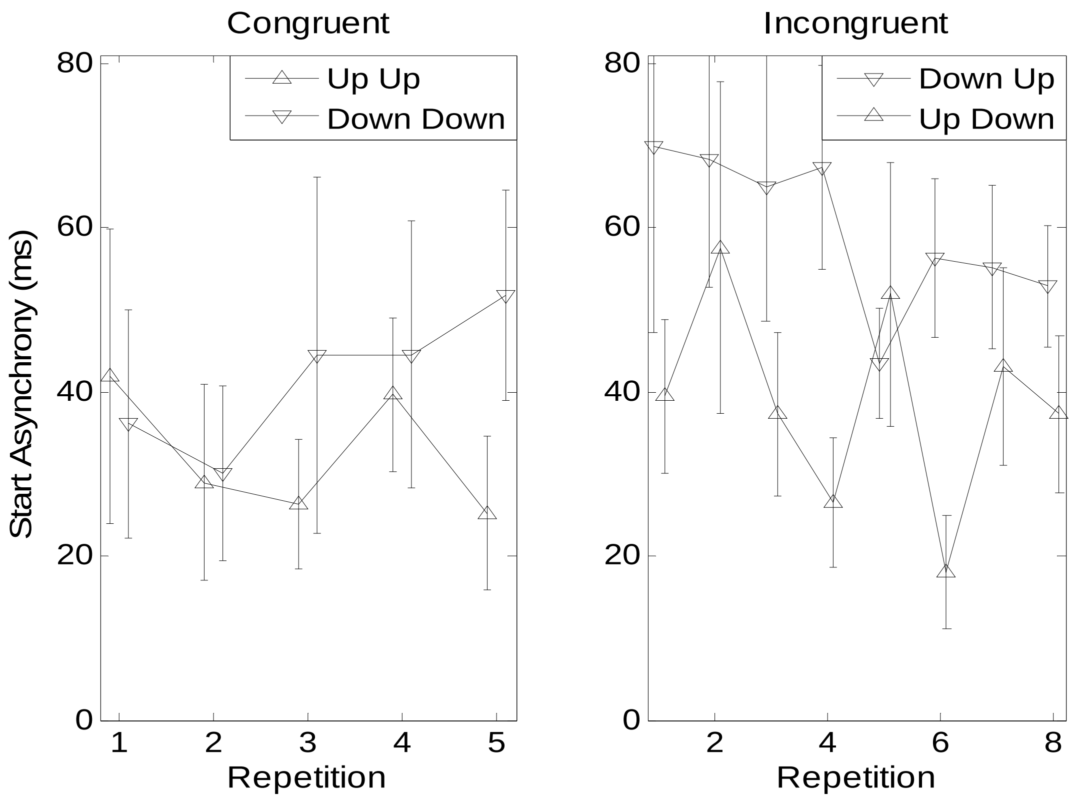

Figure 10. Mean start asynchronies (± 1 SE) for Experiment 3A.

main effect of target combination on start asynchronies, $F(3,36) = 3.271$, $p < .05$, such that participants started their movements closest to synchrony when moving both plungers to a high location (M = 37 ms) compared to moving both to a low location (M = 41 ms), the left plunger to a high location and the right plunger to a low location (M = 43 ms), and the left plunger to a low location and the right plunger to a high location (M = 63 ms). The results revealed no other significant main effects or interactions, $p > .10$.

Target Asynchronies

Figure 11 shows the mean target asynchronies (± 1 SE) for the conditions in Experiment 3A. To determine whether participants timed the completion of their movements differently for the congruent and incongruent conditions, I conducted a 4 (target combination; High/High,

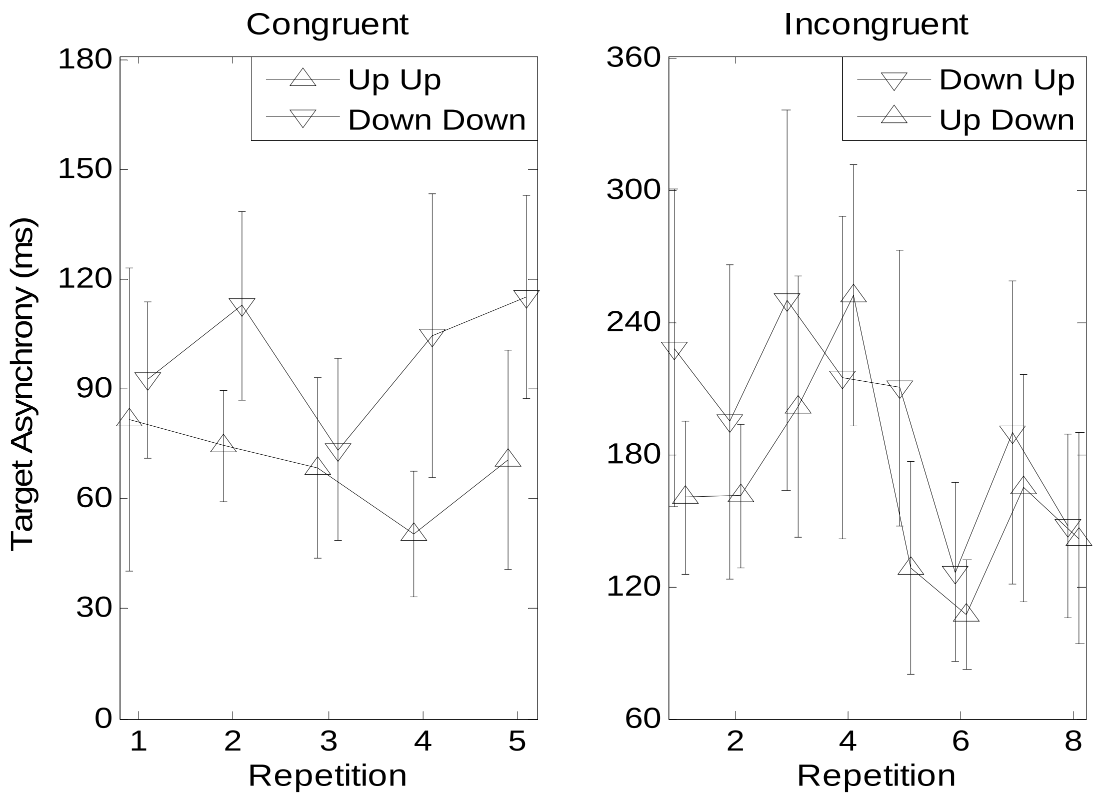

Figure 11. Mean target asynchronies (± 1 SE) for Experiment 3A.

Low/Low, High/Low, Low/High with the left target indicated first) x 5 (repetition) repeated-measures ANOVA on the target asynchronies. The results of this analysis revealed a significant main effect of target combination on target asynchronies, $F(3,36) = 8.060$, $p < .01$, such that participants completed their movements closest to synchrony when moving both plungers to a high location (Mean Asynchrony $M = 69$ ms) than when moving both to a low location ($M = 100$ ms). The mean target asynchrony was $M = 187$ ms when moving the left plunger to a high location and the right plunger to a low location, and it was $M = 227$ ms when moving the left plunger to a low location and the right plunger to a high location. Post-hoc analyses revealed that participants' timing for the congruent conditions was significantly better than for the incongruent conditions. The differences between the two conditions in each of these cases did not reach significance. The results revealed no other significant main effects or interactions, $p > .10$.

Movement Times

Figure 12 shows the mean movement times (± 1 SE) for the conditions in Experiment 3A. To determine whether there were differences in movement times for the two hands and between the experimental conditions, I performed a 2 (hand; left or right) x 4 (target combination; High/High, Low/Low, High/Low, Low/High with the left target indicated first) x 5 (repetition) repeated-measures ANOVA. The results of the analysis revealed a significant main effect for hand, $F(1,12) = 19.589$, $p < .01$, such that object transports for the left hand (M = 1742 ms) took longer to complete than object transports for the right hand (M = 1637 ms). The main effect for target combination also reached significance, $F(3,36) = 7.168$, $p < .01$, such that object transports took shortest when moving both objects to a high location (M = 1436 ms), followed by moving both objects to a low location (M = 1611 ms), moving the left plunger to a low location while moving the right plunger to a high location (M = 1796 ms), and moving the left plunger to a high location while moving the right plunger to a low location (M = 1916 ms). Finally, the results revealed a significant interactive effect of hand and target combination on movement times, $F(1.606, 19.278) = 4.119$, $p < .05$, such that the general pattern for the two hands was similar, except that object transport with the right hand was appreciably shorter when moving to a high target while moving to a low target with the left hand (M = 1690 ms) than vice versa (M = 1923 ms).

The results of Experiment 3A revealed a reduced grasp height effect for incongruent conditions compared to congruent conditions. This effect did not appear to increase with increased task experience. However, in Experiment 3A participants performed a total of 8 repetitions of each incongruent condition, and half the participants completed the conditions in a randomized fashion. As a result, it could be that the grasp height effect would increase with

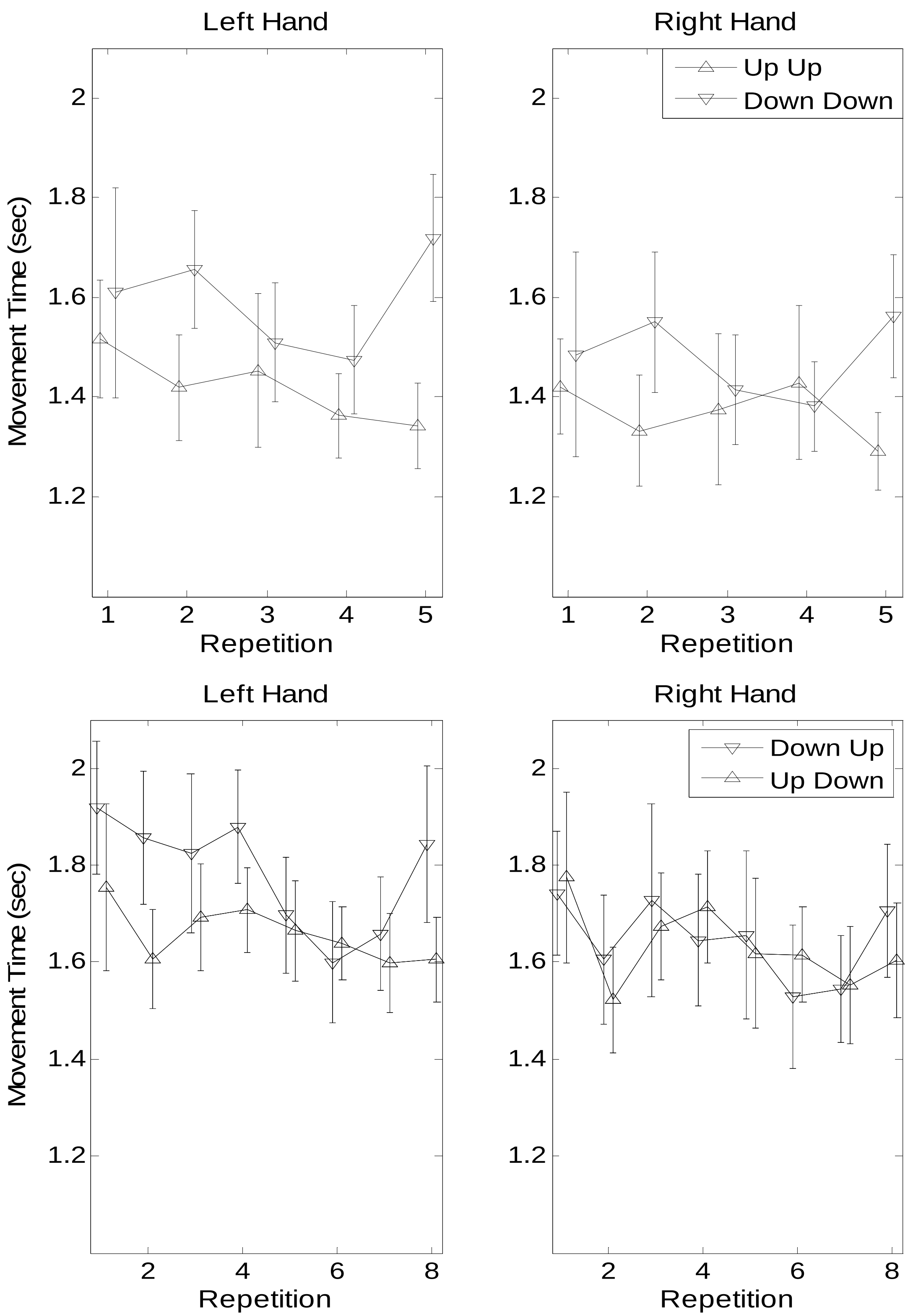

Figure 12. Mean movement times (± 1 SE) per hand and condition for Experiment 3A.

increased task experience if participants completed more repetitions and did so in a blocked design. Experiment 3B addressed this possibility.

Experiment 3B

Method

Participants and Procedure

Ten new participants between the ages of 19 and 22 followed the same general procedure as Experiment 3A, except that they completed 6 repetitions of each of the congruent conditions, and 16 repetitions of each of the incongruent conditions. Participants completed two blocks of trials. In the first block, they first completed two trials of each of the congruent conditions, followed by 16 trials of one of the incongruent conditions. Participants again completed one repetition of each congruent condition in trials 21 and 22 of a block. The final two trials in a block consisted of the incongruent target combination that they completed throughout that block, except that the left or right target was raised 11 cm. The second block was identical to the first block, except that participants completed 16 trials of the other incongruent condition.

Grasp Height Results

Figure 13 shows the magnitude of the grasp height effect (± 1 SE) as a function of repetition number for each of the experimental conditions. The results of the congruent conditions are averaged for the left and right hand. The results for the incongruent conditions are averaged for cases in which participants moved the object on the left up and the object on the right down, and vice versa. The calculation of the strength of the grasp height effect in different conditions was the same as that used in Experiment 1.

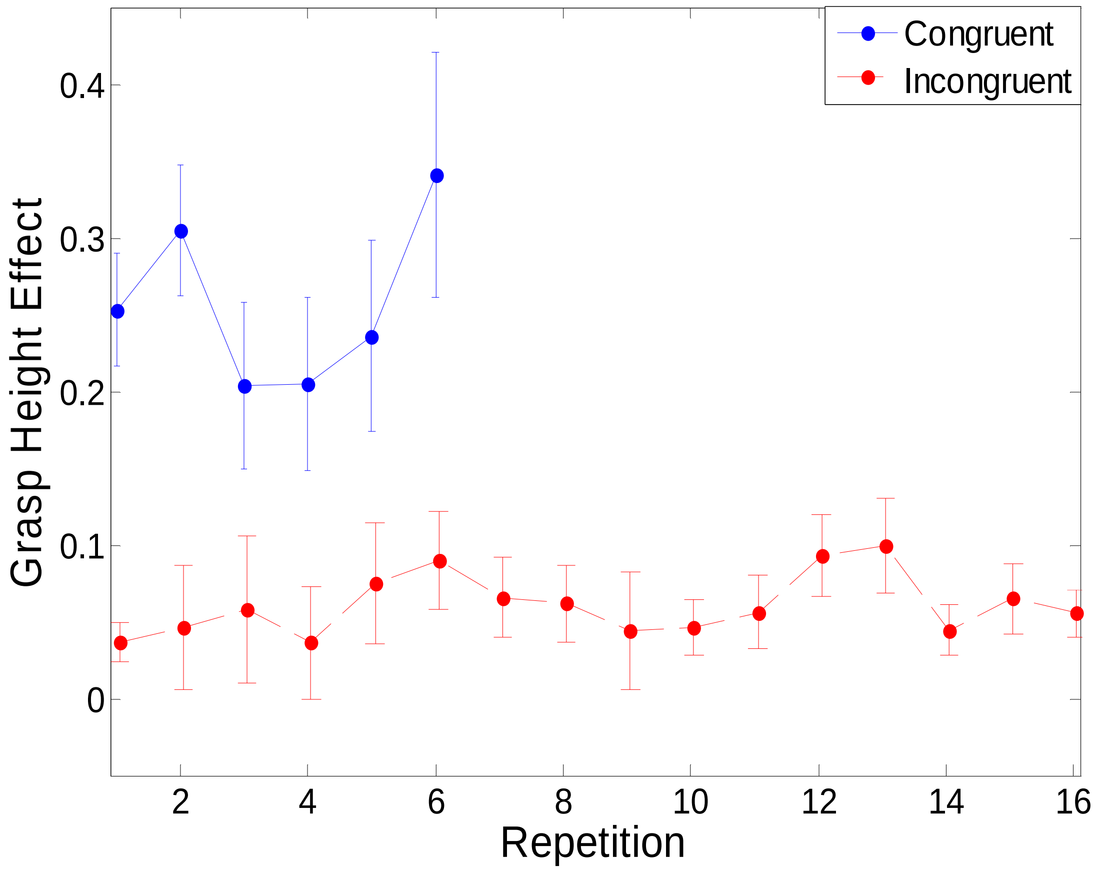

Figure 13. Mean grasp height effect (± 1 SE) for congruent and incongruent conditions in Experiment 3B.

To analyze the proportional grasp heights, I performed a 2 (hand; left or right) x 4 (target combination; High/High, Low/Low, High/Low, Low/High with the left target indicated first) x 6 (repetition) repeated-measures ANOVA. The results indicated a main effect of target combination, $F(3,27) = 18.497$, $p < .01$, such that participants grasped the plungers at a low location when they moved both plungers to a high target ($M = .037$), they grasped the plungers at a high location when they moved both plungers to a low target ($M = .628$), and they grasped the plungers close to the middle when they moved one plunger to a low location and the other plunger to a high location ($M = .423$ for High/Low, and $M = .479$ for Low/High). Post-hoc comparisons indicated significant differences between each of the conditions except between the two incongruent conditions and between the High/High and High/Low target combinations. The results revealed no other significant main effect or interactions, $p > .10$.

To determine whether the grasp height effect would strengthen the incongruent conditions as a function of task experience, I performed a 2 (hand; left or right) x 2 (target combination; High/Low or Low/High) x 16 (repetitions) repeated-measures ANOVA. The results of the analysis indicated a significant interactive effect of hand and target combination on proportional grasp heights, $F(1,9) = 7.230$, $p < .05$, such that participants tended to grasp the plunger higher with the left hand than with the right hand when the target pair was Low/High ($M = .505$ for the left hand and $M = .417$ for the right hand). In contrast, participants tended to grasp the plunger higher with the right hand than with the left hand when the target pair was High/Low ($M = .417$ for the left hand and $M = .451$ for the right hand). Thus, participant showed a grasp height effect in the incongruent conditions. Again, the magnitude of the grasp height effect was much smaller than for the congruent conditions. The results revealed no other significant main effects or interactions, $p > .10$.

Timing Results

Start Asynchronies

Figure 14 shows the mean start asynchronies (± 1 SE) for the conditions in Experiment 3B. To determine whether participants timed the onset of their movements differently for the congruent and incongruent conditions, I performed a 4 (target combination; High/High, Low/Low, High/Low, Low/High with the left target indicated first) x 6 (repetition) repeated-measures ANOVA. The results indicated a main effect of target combination on start asynchronies, $F(3,27) = 7.379$, $p < .01$, such that participants started their movements most synchronously when moving both plungers to a high location ($M = 31$ ms) compared to moving both to a low location

(M = 43 ms), moving the left plunger to a high location and the right plunger to a low location (M = 48 ms), and moving the left plunger to a low location and the right plunger to a high location (M = 56 ms). The results revealed no other significant main effects or interactions, $p > .10$.

To determine if start asynchrony decreased over repetitions in the incongruent trials, I performed a 2 (target combination; High/Low or Low/High) x 16 (repetition) repeated-measures ANOVA for the incongruent conditions. The results revealed no significant main effects or interactions, $p > .10$.

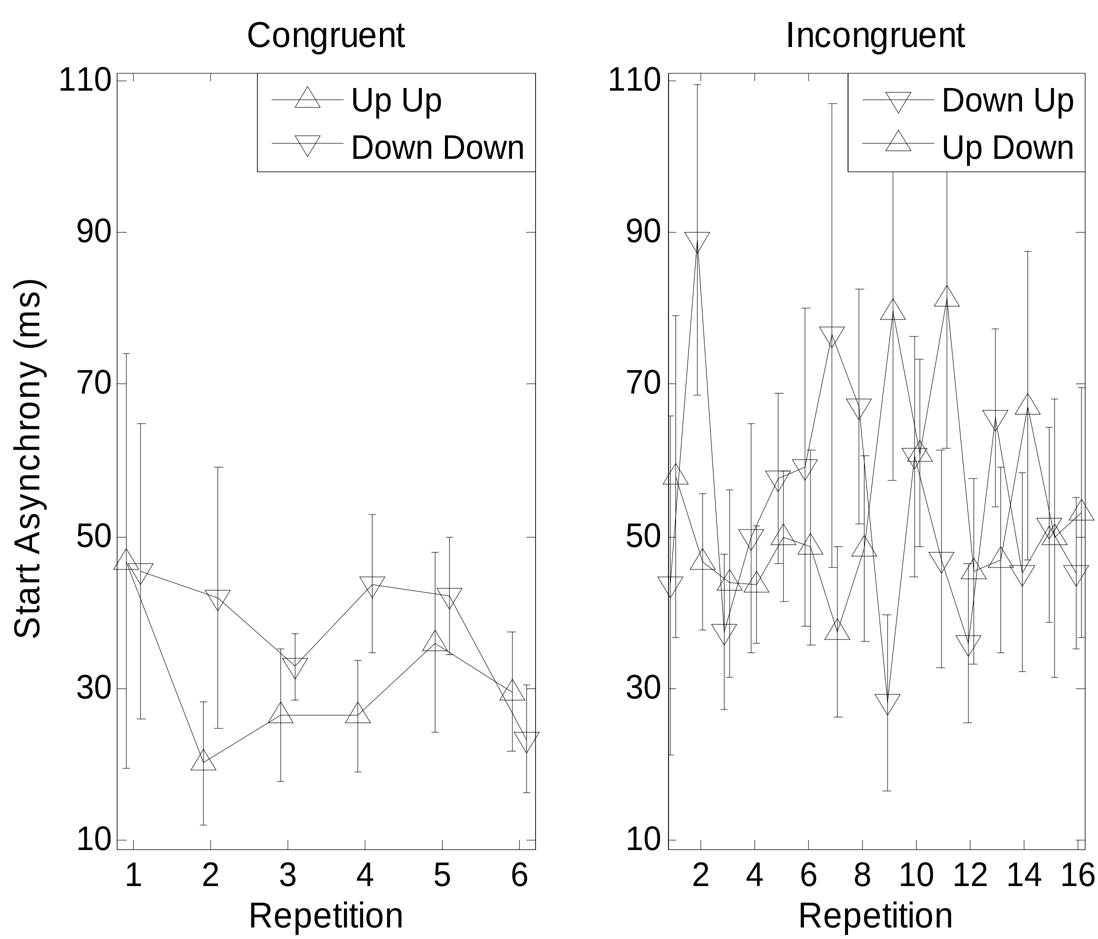

Figure 14. Mean start asynchronies (± 1 SE) for Experiment 3B.

Target Asynchronies

Figure 15 shows the mean target asynchronies (± 1 SE) for the conditions in Experiment 3B. I conducted a 4 (target combination; High/High, Low/Low, High/Low, Low/High with the left target indicated first) x 5 (repetition) repeated-measures ANOVA on the target asynchronies. The results revealed a significant main effect of target combination on target asynchronies, $F(3,24) = 11.791$, $p < .01$, such that participants completed their movements closest to synchrony when moving both plungers to a high location (M = 53 ms) compared to moving both to a low location (M = 75 ms), the left plunger to a high location and the right plunger to a low location (M = 116 ms), and the left plunger to a low location and the right plunger to a high location (M = 175 ms).

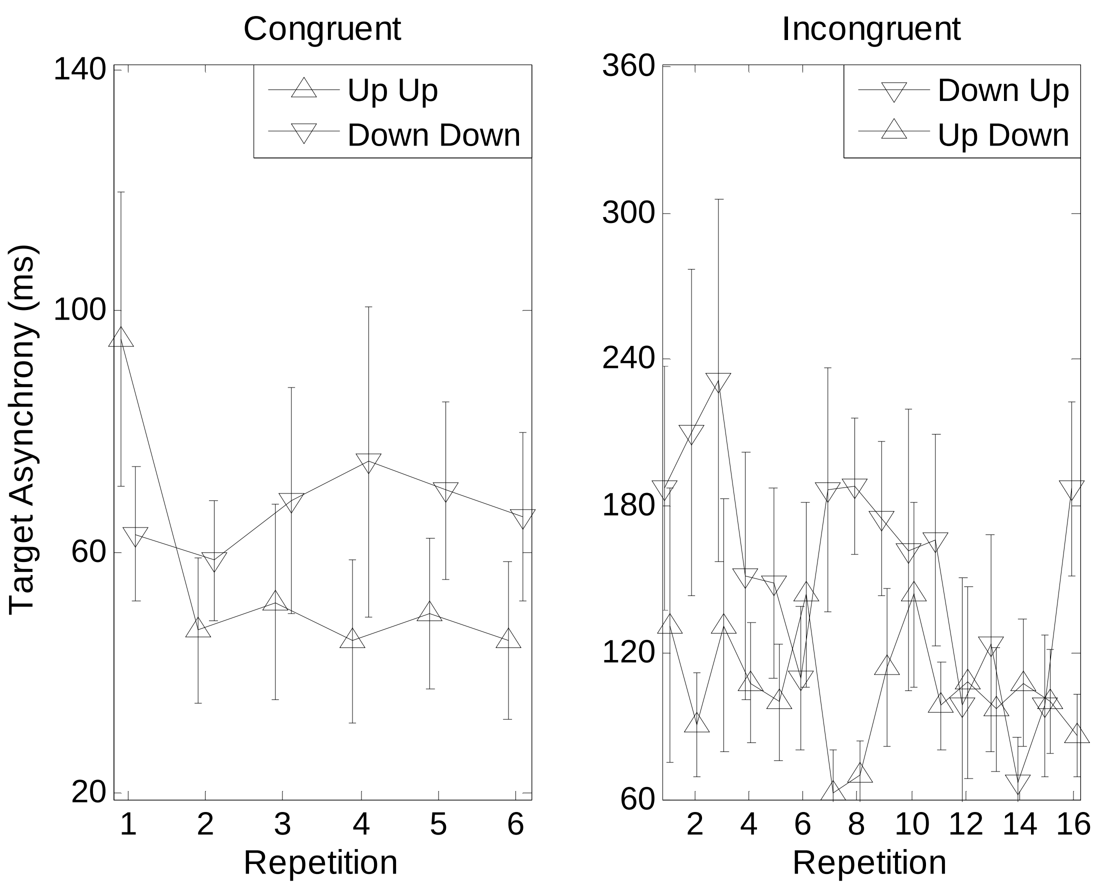

Figure 15. Mean target asynchronies (± 1 SE) for Experiment 3B.

Post-hoc analyses revealed that participants' timing for the congruent conditions was significantly better than for the incongruent conditions. I also performed a 2 (target combination; High/Low or Low/High) x 16 (repetition) repeated-measures ANOVA. This analysis revealed no significant main effects or interactions, $p > .10$.

Movement Times

Figure 16 shows the mean movement times (± 1 SE) for the conditions in Experiment 3B. To determine whether there were differences in movement times for the two hands and between the experimental conditions, I performed a 2 (hand; left or right) x 4 (target combination; High/High, Low/Low, High/Low, Low/High with the left target indicated first) x 6 (repetition) repeated-measures ANOVA. The results of the analysis revealed a significant main effect for hand, $F(1,9) = 29.800$, $p < .01$, such that object transports for the left hand ($M = 1340$ ms) took longer to complete than object transports for the right hand ($M = 1256$ ms). The main effect for target combination also reached significance, $F(1.994,17.945) = 6.943$, $p < .01$, such that object transports took shortest when moving both objects to a high location ($M = 1122$ ms), followed by moving both objects to a low location ($M = 1265$ ms), moving the left plunger to a high location while moving the right plunger to a low location ($M = 1390$ ms), and moving the left plunger to a low location while moving the right plunger to a high location ($M = 1415$ ms). The results revealed no other significant main effects or interactions, $p > .10$.

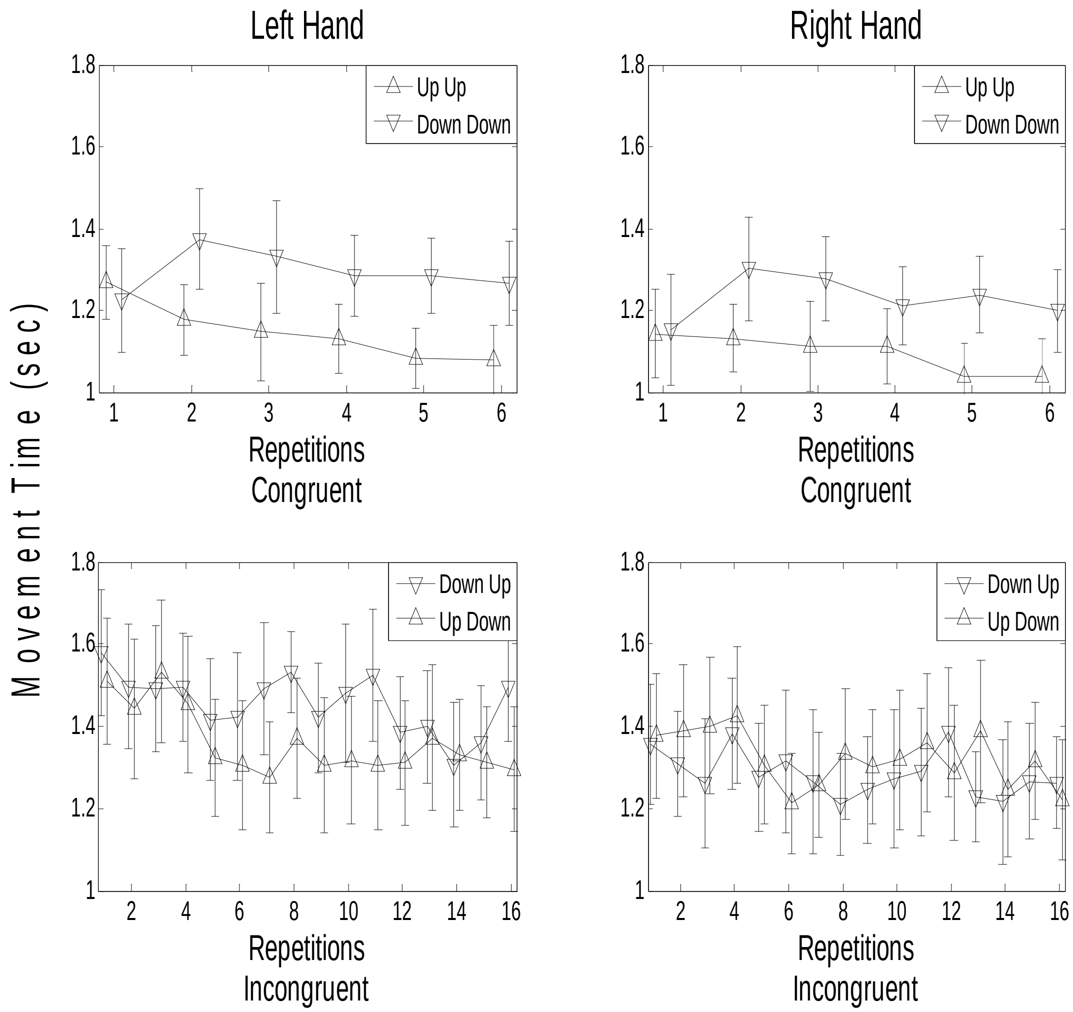

Figure 16. Mean movement times (± 1 SE) for the left and right hand per condition of Experiment 3B.

Discussion of Experiments 3A and 3B

The results of Experiments 3A and 3B indicated that participants did not change their grasp selection appreciably with increased experience when moving two objects to different target locations. Thus, participants continued to perform grasps that were in similar locations for the two hands when moving the objects to different locations even when they performed such transport movements 16 times in a row. When participants moved the two objects to similar locations, they did demonstrate anticipation of the end state of their body by grasping both objects towards the top when moving them to low locations, and grasping them towards the bottom when moving them to high locations. Thus, participants did show the capacity to anticipate the end state of their body, but a tendency to grasp in similar locations with the two hands appeared to override such anticipation for incongruent trials.

The results indicated that participants continued to adopt near symmetric grasps for the two objects in incongruent target conditions with increased experience. If end state comfort planning would have been the primary constraint for bimanual object manipulation, one would have expected participants to start grasping in accord with end state comfort with increased task experience in the incongruent trials. The results indicated that participants did not show such a change in performance.

Experiment 3 addressed the Conceptualization Hypothesis, the notion that participants would initially experience difficulties in grasp planning in the incongruent conditions because they could not conceptualize which grasps to select to end comfortably. With practice, such planning difficulties would have presumably been overcome. Thus, the Conceptualization Hypothesis predicted a shift in the origin of reference frames from predominantly allocentric to more egocentric. In contrast to the Conceptualization Hypothesis, participants did not display a change in grasp selection over repetitions. Thus, the results did not indicate that a shift in the origin of reference frames occurred with increased task experience.

One could interpret the results of Experiments 3A and 3B in several ways. An uninteresting possibility is that participants simply did not care enough about the task to go to the trouble of planning for end state comfort in incongruent conditions. This interpretation is unlikely because participants did display end state comfort planning for congruent conditions.

Another interpretation of the results is that participants continued to have difficulties planning for end state comfort over repetition. Thus, participants may not overcome difficulties to plan for end state comfort despite repeatedly performing the incongruent conditions. Research on stimulus-response compatibility effects suggests that the spatial task requirements influence performance even after extensive practice (e.g. Proctor & Dutta, 1993). Because moving two objects to different locations likely requires multiple spatial codes in parallel, it could be participants continued to have trouble with planning grasps in incongruent conditions. Thus, one could either argue that participants did not perform enough trials in the incongruent conditions to show a change in grasping behavior, or one could argue that a change would not happen regardless of the amount of practice.

A third possible interpretation of the results is that there is a benefit to planning grasps in similar locations for the incongruent conditions. For example, it could be that simultaneously planning two grasps in different locations is perceived as more costly than whatever discomfort might be experienced by grasping in ways that do not support end-state comfort. Alternatively, it could be that grasping in similar locations eases object manipulation. Grasping objects with similar weight distributions in similar locations may make the simultaneous manipulation of the objects less complex. In particular, placing the hands in similar locations relative to the center of mass of the objects could ease the representation of torques and forces because they become similar for the two hands. Thus, increasing the similarity of the representation of object dynamics for the two hands could take precedence over ending in slightly more comfortable ways. Previous research suggests that people are sensitive to object properties such as the center of mass in unimanual tasks (Lederman & Wing, 2003), and that they can shift the reference frame they adopt based on the dynamics of the task (Ahmed, Wolpert, & Flanagan, 2008). Perhaps grasp selection in bimanual tasks is similarly sensitive to the dynamics of object manipulation. This possibility will be explored in Experiment 5.

CHAPTER 5
GRASP SYMMETRY FOR MOVEMENT PLANNING OR MOVEMENT EXECUTION?

There are at least two possible reasons for why people may select grasps to be similar for the two hands in incongruent conditions. These two reasons relate to different aspects of the task. One concerns movement planning; the other concerns movement execution. If simultaneous planning is more costly than the benefit gained from it during movement, then making the planning for the two hands non-overlapping would likely decrease this cost. As a result, it would become more beneficial to plan for end state comfort. Thus, if planning costs dominate movement costs, one could expect to see people adopt end state comfort compliant grasps in the incongruent conditions when the planning costs are decreased by asking people to grasp one object at a time. In contrast, if adopting similar grasps with the two hands is beneficial for the object displacements themselves, one would expect people to still adopt similar grasps when they are asked to grasp one object at a time while moving the objects at the same time. Experiment 4 addressed these two possibilities.

Experiment 4

Method

Participants

Sixteen participants first completed an informed consent form and filled out two questionnaires. One pertained to demographic characteristics and any neurological deficits. The other was the short form of the Edinburgh handedness inventory (Oldfield, 1971). None of the participants reported any neurological deficits and all our participants were right-handed. They ranged in age from 18 to 23 years. All participants were tall enough to comfortably reach the top of the cylinder when it was on the top platform. The Penn State University Institutional Review Board approved the experiment and the rights of all participants were protected.

Procedure

The experimental method for Experiment 4 was identical to Experiment 1 except that participants grasped the plungers either one at a time or simultaneously while always moving them simultaneously. Again, the four conditions in each variation consisted of moving both plungers to the same (up or down) or to different (left up/right down, or left down/right up) target locations. The plungers always started at the same height.

Participants completed two blocks of 20 trials each. In the sequential grasping block, participants grasped the plunger on the left first, followed by the plunger on the right. Then they moved the plungers simultaneously to their respective target locations. To indicate to the participants what the target sequence was and when they should grasp each plunger, participants first heard the target pair through a set of speakers. After a 3 second pause, they then heard the target color for the left hand again, upon which they were instructed to grasp the plunger on the left side. After another 2 second pause, participants then heard the target color for the right hand again, and upon which they grasped the plunger on the right side. After another 1 second pause, participants then heard a tone (25 Hz for 1 second duration) that indicated that they should move the plungers simultaneously from their start locations to their respective target locations.

In the simultaneous grasping block, participants grasped both plungers at the same time and moved them at the same time to their respective target locations. To indicate to the participants what the target sequence was and when they should grasp each plunger, participants first heard the target pair through a set of speakers. After a 3 second pause, participants then heard the target pair again, upon which they were instructed to grasp both plungers. After another 1 second pause, participant heard a tone (25 Hz for 1 second duration) that indicated to move the plungers simultaneously from their start locations to their respective target locations.

In each of the blocks, participants completed a total of 20 trials. Participants completed each congruent condition during trials 1 and 2 of a block of trials, and again during the eleventh and twelfth trial in a block. In trials 3 to 10 of a block, participants performed repetitions of one incongruent condition (i.e. Up/Down or Down/Up), and in trials 13 to 20 of a block they completed repetitions of the other incongruent condition. Half the participants first completed the sequential grasping block; the other half first completed the simultaneous grasping block. The order of the congruent and incongruent conditions within a block was randomized across participants.

Grasp Height Results

Figure 17 shows the magnitude of the grasp height effect (± 1 SE) as a function of repetition number for each of the experimental conditions. The results of the congruent conditions are averaged for the left and right hand. The results for the incongruent conditions are averaged for cases in which participants moved the object on the left up and the object on the right down, and vice versa. The calculation of the strength of the grasp height effect in different conditions was the same as that used in Experiment 1.

To analyze the proportional grasp heights, I performed a 2 (grasp condition; sequential or simultaneous) x 2 (hand; left or right) x 4 (target combination; High/High, Low/Low, High/Low, Low/High with the left target indicated first) x 2 (repetition) repeated-measures ANOVA. The results indicated a main effect of target combination, $F(1.727, 24.183) = 14.671$, $p < .01$, such that participants grasped the plungers at a low location when they moved both plungers to a high target ($M = .497$), they grasped the plungers at a high location when they moved both plungers to

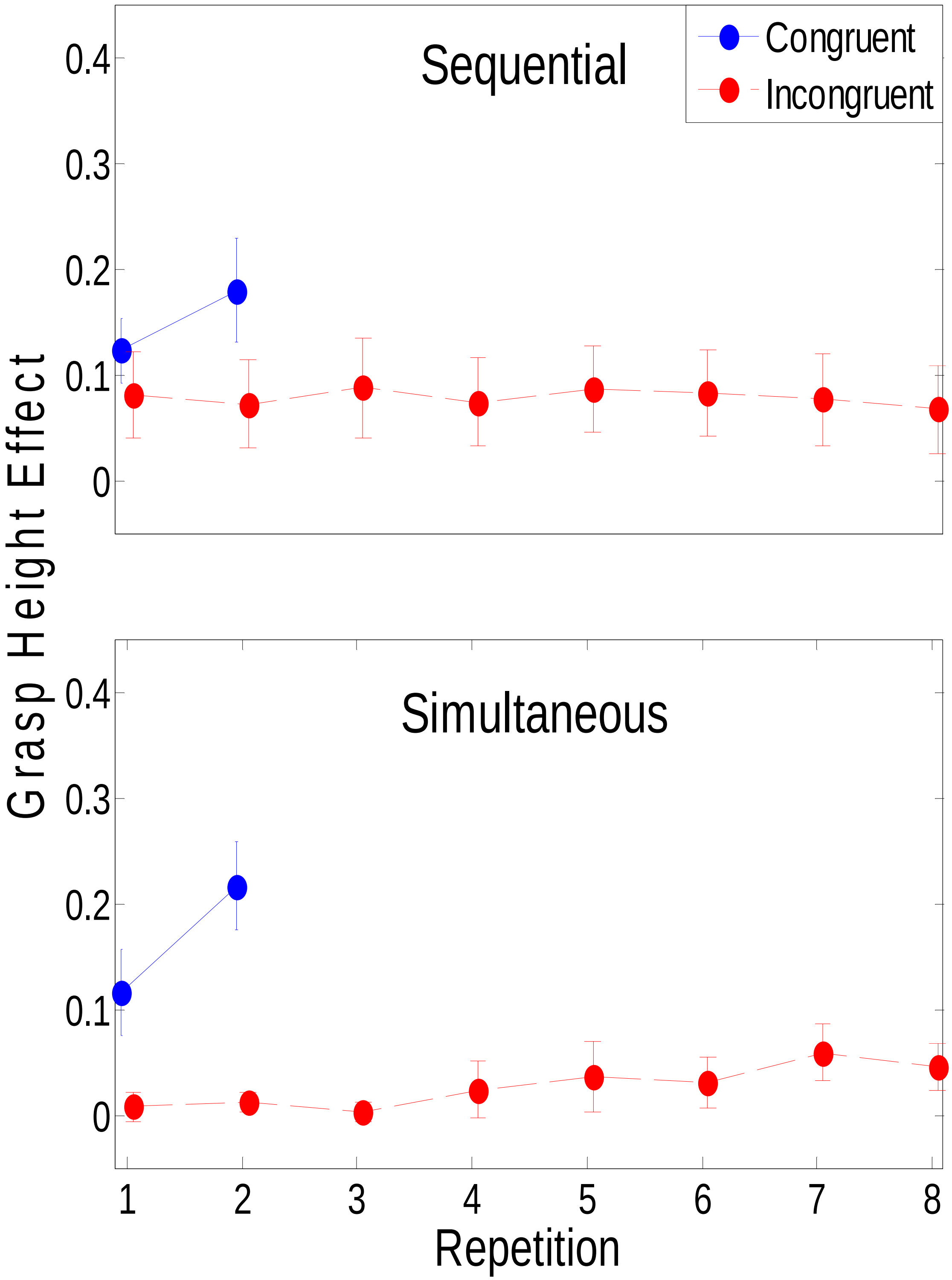

Figure 17. Mean grasp height effect (± 1 SE) for congruent and incongruent conditions of Experiment 4 when grasping sequentially (top panel) or simultaneously (bottom panel).

a low target (M = .655), and they grasped the plungers close to the middle when they moved one plunger to a low location and the other plunger to a high location (M = .550 for High/Low, and M = .568 for Low/High). Post-hoc comparisons indicated significant differences between each of the conditions except between the two incongruent conditions, and between moving both plungers up versus moving the left plunger up and the right plunger down. The results also indicated a significant interaction between hand and target combination, $F(1.267, 17.737) = 4.417$, $p < .05$, such that the grasp height effect for congruent conditions was stronger for the right hand (M = .176) than for the left hand (M = .143). In contrast, the grasp height effect for the incongruent conditions was stronger for the left hand (M = .059) than for the right hand (M = .022). Finally, the results indicated a significant interaction between target pair and repetition, $F(1.672, 23.405) = 4.058$, $p < .05$, such that proportional grasp heights indicated that participants grasped lower when moving the plungers to high targets for the second time (M = .459 versus M = .535). The other conditions had negligible changes in grasp heights. The results revealed no other significant main effect or interactions, $p > .10$. It is important to note that grasping the plungers sequential versus simultaneously did not appear to have a significant influence on the proportional grasp heights that participants adopted.

To further explore the grasp height effect in the incongruent conditions as a function of task experience and grasp condition, I performed a 2 (grasp condition; sequential or simultaneous) x 2 (hand; left or right) x 2 (target combination; High/Low or Low/High) x 8 (repetitions) repeated-measures ANOVA. Again, if participants started to show the grasp height effect with increased experience in incongruent conditions, one would expect to find an effect of repetition number on proportional grasp heights. In addition, if grasping sequentially eased planning, the effect of repetition would have been more pronounced in the sequential grasping conditions than in the simultaneous grasping conditions. The results did not support these predictions. There was no significant effect of either grasping conditions or repetition on proportional grasp height, $p > .10$.

Timing Results

Start Asynchronies

Figure 18 shows the mean start asynchronies (± 1 SE) for the conditions in Experiment 4. To determine whether participants timed the onset of their movements differently for different conditions, I conducted a 2 (grasp timing; sequential or simultaneous) x 4 (target combination; High/High, Low/Low, High/Low, Low/High with the left target indicated first) x 2 (repetition) repeated-measures ANOVA on the start asynchronies. For the incongruent conditions, only the first two repetitions were included for this analysis. The results of the analysis revealed a significant main effect of target combination on start asynchronies, $F(3,42) = 3.298$, $p < .05$, such that participants started their movements closest to synchrony when moving both plungers to a low location ($M = 28$ ms) compared to moving both to a high location ($M = 30$ ms), moving the left plunger to a high location and the right plunger to a low location ($M = 36$ ms), and moving the left plunger to a low location and the right plunger to a high location ($M = 47$ ms). The results also revealed a significant interaction between target combination and repetition, $F(2.326, 32.566) = 3.131$, $p < .05$, such that participants slowed down from the first to the second repetition when moving both plungers up ($M = 25$ ms to $M = 35$ ms for repetition 1 and 2 respectively) and when moving the left plunger up and the right plunger down ($M = 34$ ms to $M = 37$ ms). Participants speeded up when moving both plungers down ($M = 36$ ms to $M = 20$ ms) and when moving the left plunger down and the right plunger up ($M = 52$ ms to $M = 41$ ms). The results revealed no other significant main effects or interactions, $p > .10$.

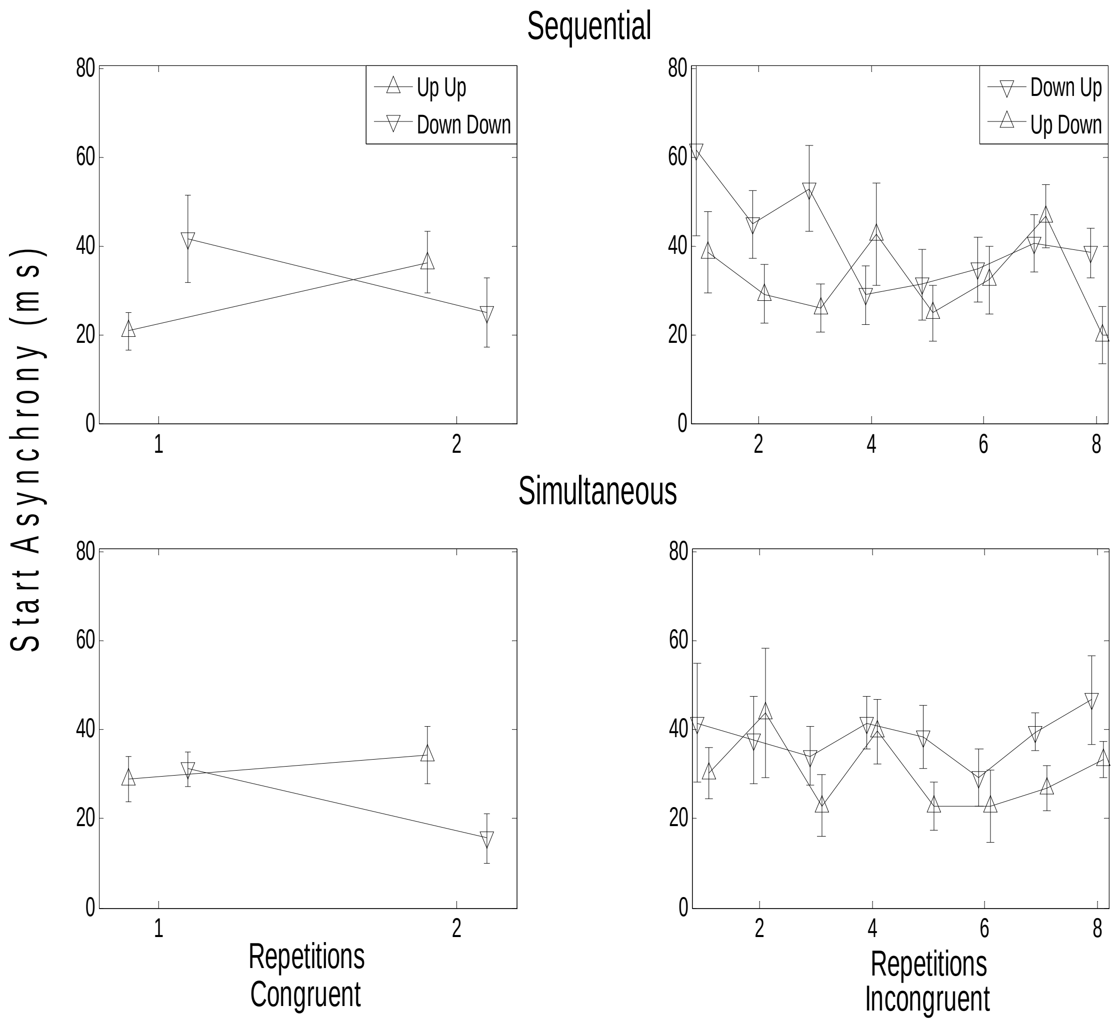

Figure 18. Mean start asynchronies (± 1 SE) for Experiment 4. The upper panels show start asynchronies for sequential conditions, and the lower panels show start asynchronies for simultaneous conditions.

Target Asynchronies

Figure 19 shows the mean target asynchronies (± 1 SE) for the conditions in Experiment 4. I conducted a 2 (grasp timing; sequential or simultaneous) x 4 (target combination; High/High, Low/Low, High/Low, Low/High with the left target indicated first) x 2 (repetition) repeated-measures ANOVA on the target asynchronies to determine if participants timed the completion of transport movements differently in different conditions. For the incongruent conditions, only the first two repetitions were included in this analysis. The results revealed a significant main effect of target combination on target asynchronies, $F(1.810,25.34) = 9.518$, $p < 01$, such that

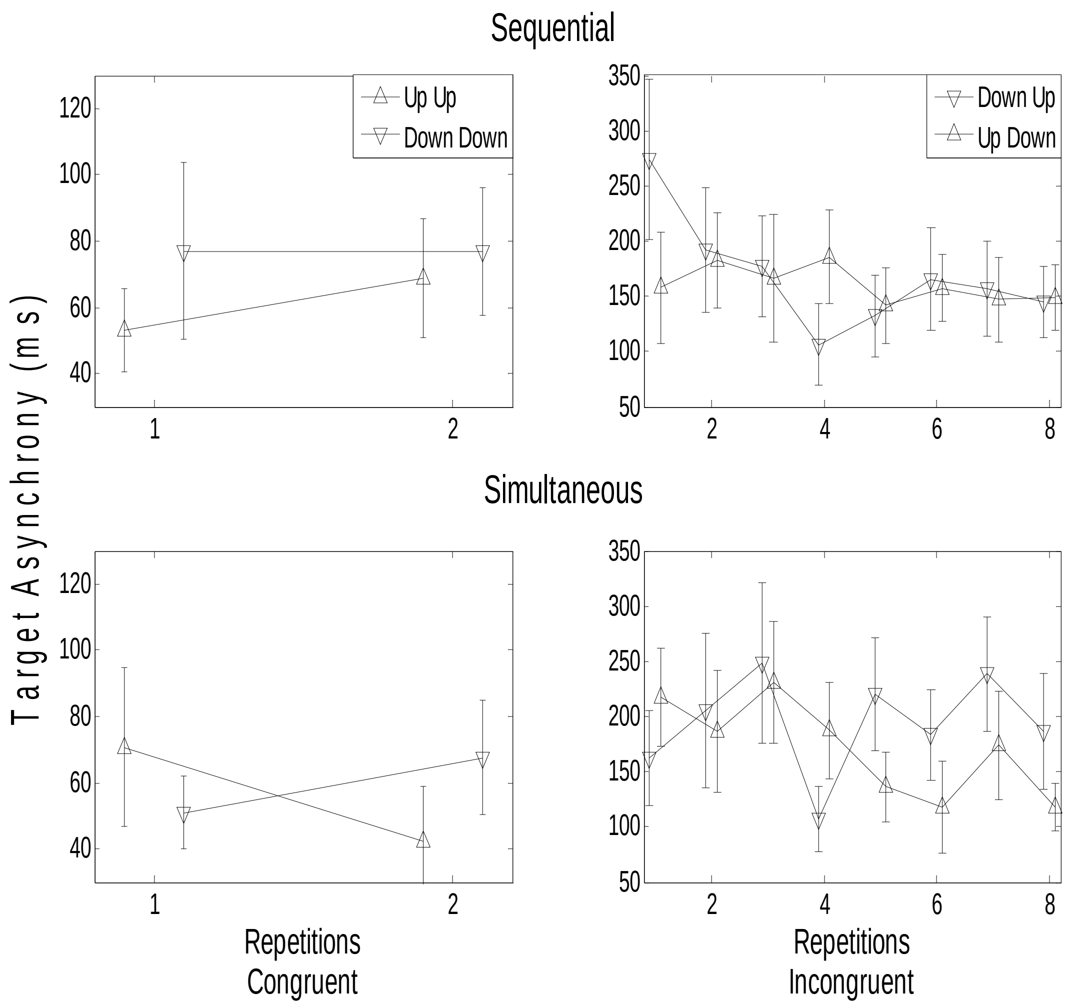

Figure 19. Mean target asynchronies (± 1 SE) or Experiment 4. The upper panels show target asynchronies for sequential conditions, and the lower panels show target asynchronies for the simultaneous conditions.

participants completed their movements closest to synchrony when moving both plungers to a high location (*M* = 59 ms) compared to moving both to a low location (*M* = 68 ms), moving the left plunger to a high location and the right plunger to a low location (*M* = 186 ms), and moving the left plunger to a low location and the right plunger to a high location (*M* = 208 ms). Post-hoc analyses revealed that participants' timing for the congruent conditions was significantly better than for the incongruent conditions. The differences between the two conditions in each of these cases did not reach significance. The results revealed no other significant main effects or interactions, $p > .10$.

Movement Times

Figure 20 shows the mean movement times (± 1 SE) for the conditions in Experiment 4. To determine whether there were differences in movement times for the two hands and between the experimental conditions, I performed a 2 x (grasp timing; sequential or simultaneous) x 2 (hand; left or right) x 4 (target combination; High/High, Low/Low, High/Low, Low/High with the left target indicated first) x 2 (repetition) repeated-measures ANOVA. For the incongruent conditions, only the first two repetitions were included for this analysis. The results of the analysis revealed a significant main effect for hand, $F(1,14) = 12.08$, $p < .01$, such that object transports for the left hand (*M* = 1742 ms) took longer to complete than object transports for the right hand (*M* = 1637 ms). The main effect for target combination also reached significance, $F(2.763,38.678) = 19.687$, $p < .01$, such that object transports took shortest when moving both objects to a high location (*M* = 1406 ms), followed by moving both objects to a low location (*M* = 1436 ms), moving the left plunger to a low location while moving the right plunger to a high location (*M* = 1628 ms), and moving the left plunger to a high location while moving the right plunger to a low location (*M* = 1637 ms). Finally, the results revealed a significant interactive effect of hand and target combination on movement times, $F(1.947, 27.256) = 8.665$, $p < .01$, such that the left hand was faster when moving both plungers up and the right hand was faster when moving both plungers down. In addition, the hand used to move a plunger up in the incongruent conditions was faster than the hand used to move the plunger down. The results did not reveal any other significant main effect or interactions, $p > .10$.

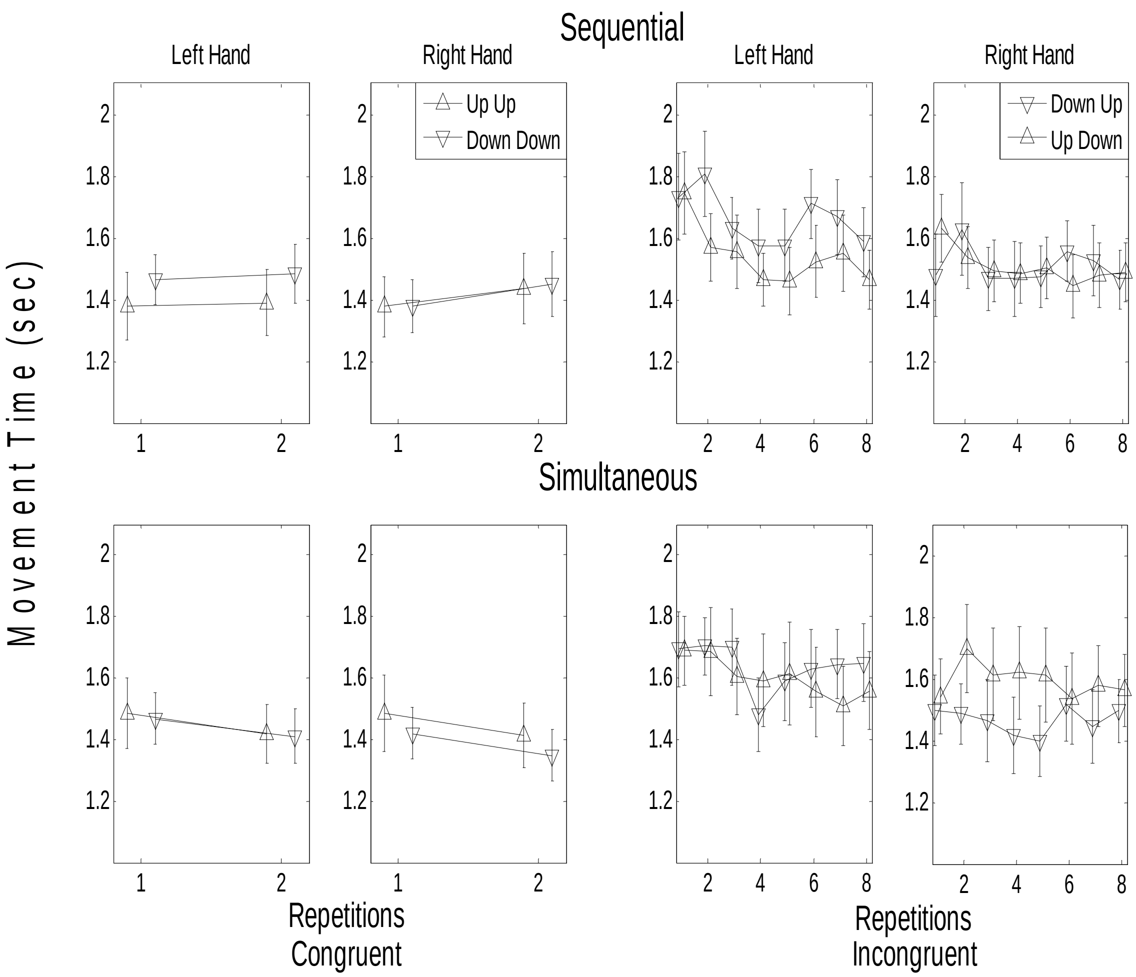

Figure 20. Mean movement times (± 1 SE) for Experiment 4. The upper panels show movement times for sequential conditions, and the lower panels show movement times for the simultaneous conditions.

Discussion of Experiment 4

The results of Experiment 4 indicated a grasp height effect in congruent conditions, such that participants grasped the plungers near the top of the plunger when they moved the plungers to low target locations, and participants grasped the plungers near their base when they moved the plungers to high target locations. In contrast, the magnitude of the grasp height effect was strongly reduced or absent in the incongruent conditions. The results of Experiment 4 replicated the grasp height findings of the previous experiments. Importantly, the results indicated no significant differences for grasping the plungers either one at a time or both at the same time. Thus, the results of Experiment 4 suggest that the reduction in the grasp height effect for incongruent compared to congruent conditions did not result from difficulties with planning two incongruent grasps at the same time. Instead, the results suggest that grasping objects in similar locations may ease movement execution.

The results on the timing of object transports for Experiment 4 indicated that participants moved faster, and started and ended the object transports closer to synchrony, in the congruent conditions than in the incongruent conditions. A possible interpretation of these differences in movement timing for the congruent and incongruent conditions is that the incongruent conditions were more difficult than the congruent conditions. If one accepts this proposition, the current results may indicate that participants relied on different reference frames based on differences in task difficulty. Whereas symmetry as well as the anticipation of the end posture of the body after object transport influenced grasp selection in the congruent conditions, symmetry and not end state comfort planning predominantly influenced grasp selection in the incongruent conditions. Thus, these results suggest that participants relied on different frames of reference – an egocentric frame and an allocentric frame – depending on target congruence.

The results leave open why grasping in similar location in incongruent conditions may ease movement execution. One possible benefit of grasping two objects with similar mass distributions in similar locations is that the manipulation of the objects becomes similar for the two hands. In particular, the more similar the position of the hands on the two objects, the more similar the torques acting on the hands during object transport. Thus, grasping for object symmetry may simplify the representation of the dynamics that operate on the hands during object manipulation. Previous research on bimanual object lifting suggests that people have a tendency to generate similar grip forces when they simultaneously lift objects of different weights with their two hands (Serrien & Wiesendanger, 2001a, 2001b). This finding is in line with the assertion that people may prefer similar dynamics for the two hands during object manipulation. For unimanual grasping, it has in addition been shown that people modify their grasp location on an object when the location of the center of mass is predictable (Lukos, Ansuini, & Santello, 2007). A question is whether similar modification of grasp locations could be observed for bimanual grasping.

If the hypothesis holds that one aspect of selecting grasps is to provide similar dynamics for the two hands, then one would expect to start seeing differences in grasp selection for incongruent conditions when people are asked to simultaneously move two objects with different mass distributions. Experiment 5 addressed this possibility.

Experiment 5

Method

Participants

Sixteen participants first completed an informed consent form and filled out two questionnaires. One pertained to demographic characteristics and any neurological deficits. The other was the short form of the Edinburgh handedness inventory (Oldfield, 1971). None of the participants reported any neurological deficits and all our participants were right-handed. They ranged in age from 17 to 24 years. All participants were tall enough to comfortably reach the top of the cylinder when it was on the top platform. The Penn State University Institutional Review Board approved the experiment and the rights of all participants were protected.

Procedure

The experimental method for Experiment 5 was identical to Experiment 4, except that one of the plungers was heavier than the other in all trials. To achieve this difference in weight, I added a cylindrical extension to the top of each plunger. This extension was a PVC pipe that was 23 cm in length and 3.3 cm in diameter. The PVC pipe was connected to the top of the plunger shaft with silver electrical tape. The PVC pipe itself was also wrapped with electrical tape to make it look more homogeneous. The PVC pipe weighted 128 gram. The PVC pipe contained either no additional weight or an additional 400 gram of nickels. The center of mass of the plunger without a weight was located at approximately 30.0 % of the plunger shaft. Adding the weight moved the center of mass up along the plunger to approximately 74.4% of the plunger shaft. The heavier plunger always stood on one side for all trials for a given participant. The side of the heavier plunger was counterbalanced between participants.

Participants completed two blocks of 24 trials each. As in Experiment 4, participants completed one sequential and one simultaneous grasping block. The order of these blocks was counterbalanced between participants. The method of presentation of the target sequence in a trial was identical to Experiment 4. Participants completed each congruent condition during trials 1 and 2 of a block of trials, and again during the thirteenth and fourteenth trial in a block. In trials 3 to 12 of a block participants performed repetitions of one incongruent condition (i.e. Up/Down or Down/Up), and in trials 15 to 24 of a block they completed repetitions of the other incongruent condition. The order of the congruent and incongruent conditions within a block was randomized across participants.

Grasp Height Results

Figure 21 shows the magnitude of the grasp height effect (± 1 SE) as a function of repetition number for each of the experimental conditions. The results of the congruent conditions are averaged for the left and right hand. The results for the incongruent conditions are averaged for cases in which participants moved the object on the left up and the object on the right down, and vice versa. The calculation of the strength of the grasp height effect in different conditions was the same as that used in Experiment 1.

To analyze the proportional grasp heights, I performed a 2 (grasp condition; sequential or simultaneous) x 4 (target combination; High/High, Low/Low, High/Low, Low/High with the left target indicated first) x 2 (hand; left or right) x 6 (repetition) repeated-measures ANOVA. The results indicated a main effect of target combination, $F(1.971, 29.566) = 39.321$, $p < .01$, such that participants grasped the plungers at a relatively low location when they moved both plungers to a high target ($M = .580$), they grasped the plungers at a high location when they moved both plungers to a low target ($M = .844$), and they grasped the plungers on average close to the middle when they moved one plunger to a low location and the other plunger to a high location ($M = .722$ for High/Low, and $M = .723$ for Low/High). For the incongruent conditions these values are based on averages collapsed over the left and right hand. These averages were qualified by a significant two-way interaction between target combination and hand, $F(1.121, 16.814) = 13.591$, $p < .01$, and a three-way interaction between target combination, hand, and repetition on the adopted grasp heights, $F(2.622, 39.332) = 4.439$, $p < .05$.

Post-hoc analyses of the data revealed that participants tended to grasp lower when they moved the plunger to a high location, and they tended to grasp higher when they moved the plunger to a low location. This effect was present in all congruent trials and grew stronger over

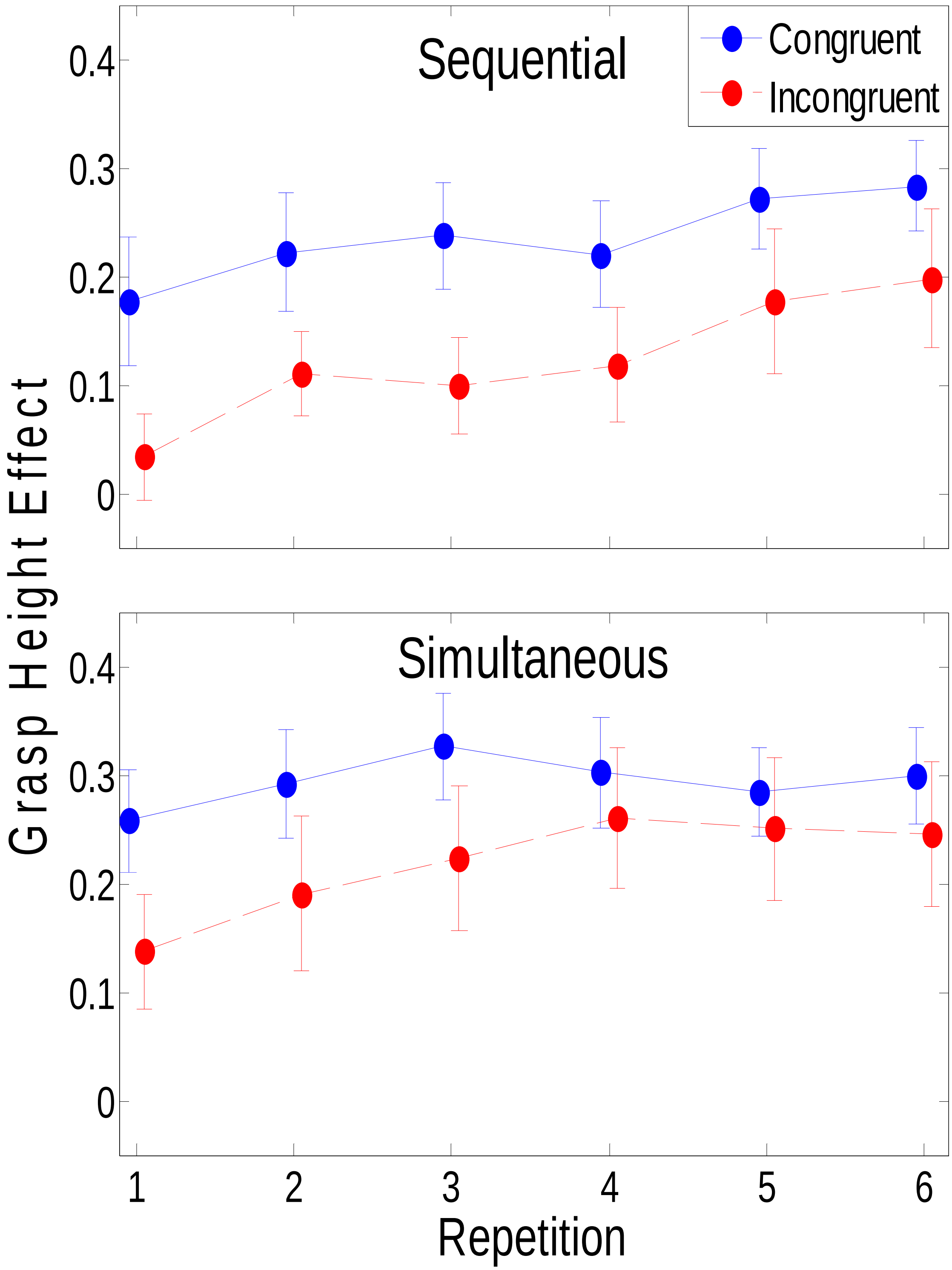

Figure 21. Mean grasp height effect (± 1 SE) for congruent and incongruent conditions of Experiment 5 when grasping sequentially (top panel) or simultaneously (bottom panel).

repetitions in the incongruent trials. On average, participants showed a difference in adopted grasp heights of about 15% between the hands by the second repetition. By the last repetition, this difference in proportional grasp height averaged about 22%. In the congruent trials, participants on average showed a grasp height effect of about 21% for the first repetition, and a grasp height effect of about 30% by the last repetition. Thus, although the grasp height effect was stronger for the congruent trials, participants showed a substantial grasp height effect in the incongruent trials. This is the first time this observation was made in the series of experiments reported in this dissertation.

Timing Results

Start Asynchronies

Figure 22 shows the mean start asynchronies (± 1 SE) for the conditions in Experiment 5. To determine whether participants timed the onset of their movements differently for different conditions, I conducted a 2 (grasp timing; sequential or simultaneous) x 4 (target combination; High/High, Low/Low, High/Low, Low/High with the left target indicated first) x 6 (repetition) repeated-measures ANOVA on the start asynchronies. The results of the analysis revealed a significant main effect of target combination on start asynchronies, $F(3,39) = 9.933$, $p < .01$, such that participants started their movements closest to synchrony when moving both plungers to a low location ($M = 30$ ms) compared to moving both plungers to a high location ($M = 32$ ms), moving the left plunger to a high location and the right plunger to a low location ($M = 37$ ms), and moving the left plunger to a low location and the right plunger to a high location ($M = 48$

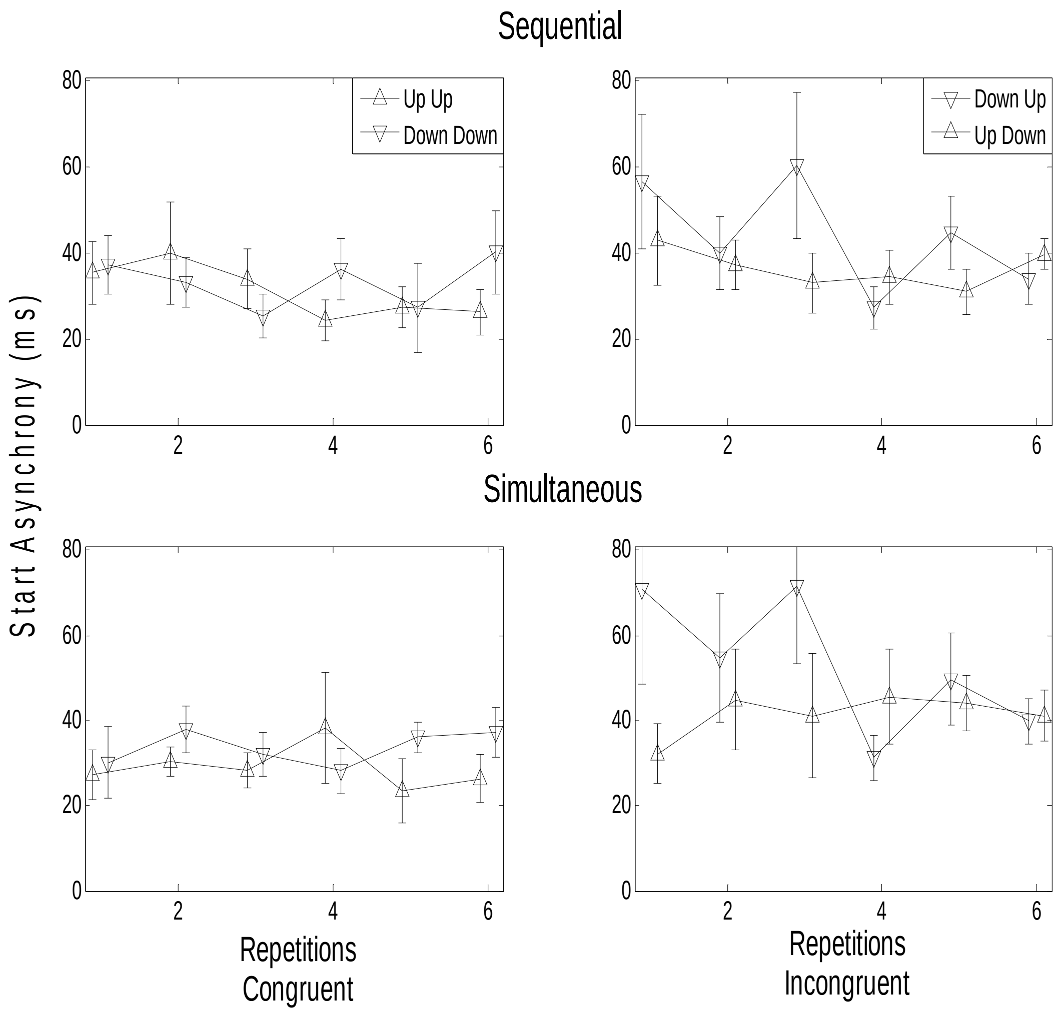

Figure 22. Mean start asynchronies (± 1 SE) for Experiment 5. The upper panels show start asynchronies for sequential conditions, and the lower panels show start asynchronies for simultaneous conditions.

ms). The results also showed a significant interaction between target combination and repetition, $F(15, 195) = 2.094$, $p < .05$, such that the asynchrony in onset of the object displacements stayed relatively constant in most conditions, but tended to decrease over repetitions when moving the left plunger down and the right plunger up. The results showed no other significant main effects or interactions, $p > .10$.

Target Asynchronies

Figure 23 shows the mean target asynchronies (± 1 SE) for the conditions in Experiment 5. I conducted a 2 (grasp timing; sequential or simultaneous) x 4 (target combination; High/High, Low/Low, High/Low, Low/High with the left target indicated first) x 6 (repetition) repeated-measures ANOVA on the target asynchronies to determine if participants timed the completion of transport movements differently in different conditions. This analysis revealed a significant main effect of target combination on target asynchronies, $F(1.934,29.014) = 15.865$, $p < 01$, such that participants completed their movements closest to synchrony when moving both plungers to a high location (M = 71 ms) compared to moving both to a low location (M = 101 ms), moving the left plunger to a high location and the right plunger to a low location (M = 177 ms), and moving the left plunger to a low location and the right plunger to a high location (M = 187 ms).

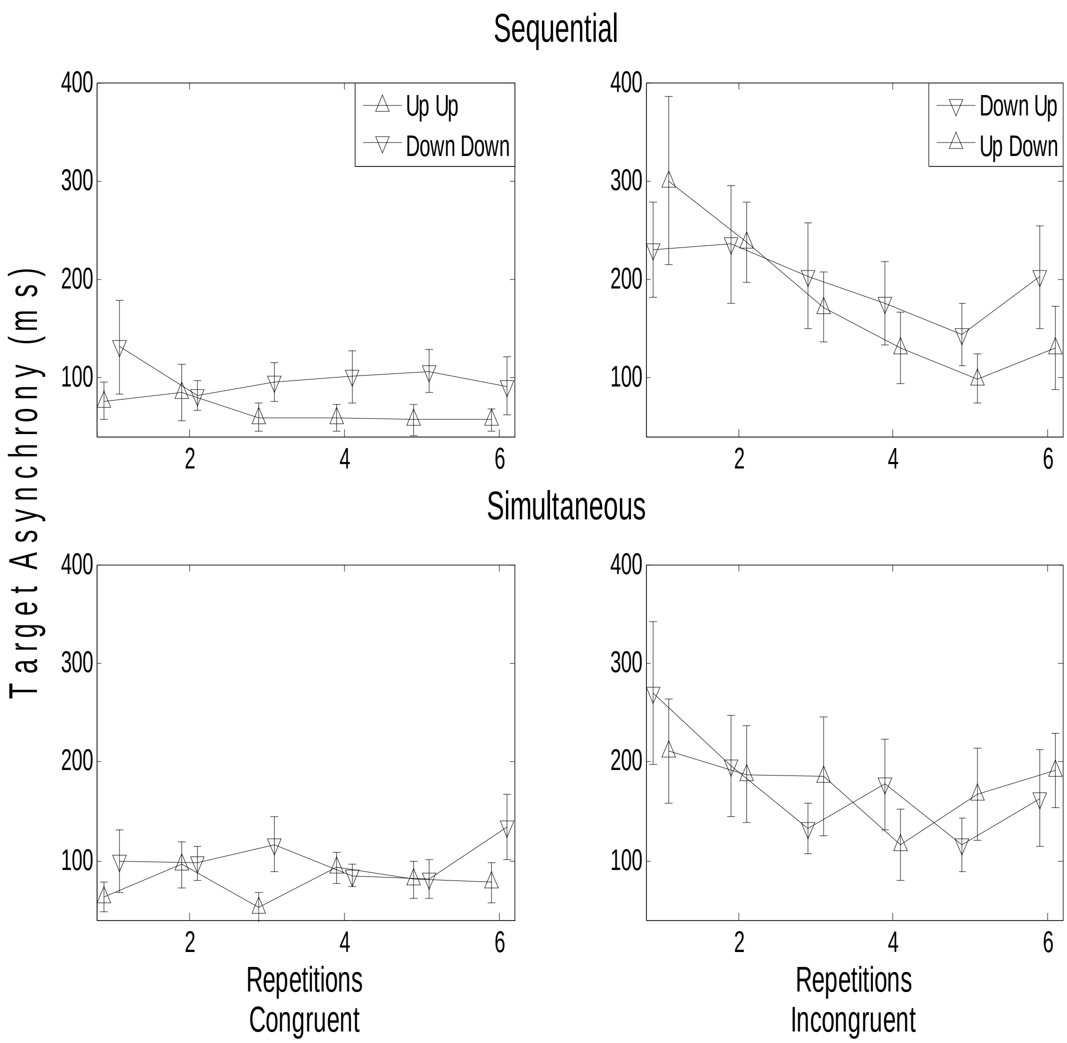

Figure 23. Mean target asynchronies (± 1 SE) for Experiment 5. The upper panels show target asynchronies for sequential conditions, and the lower panels show target asynchronies for simultaneous conditions.

Post-hoc analyses revealed that participants' timing for the congruent conditions was significantly better than for the incongruent conditions. The differences between the two conditions in each of these cases did not reach significance. The results also indicated a main effect of repetition on target asynchronies, $F(3.123, 46.844) = 4.100$, $p < .05$, such that participants tended to time the ending of the object transports to be more synchronous over repetitions. The results revealed no other significant main effects or interactions, $p > .10$.

Movement Times

Figure 24 shows the mean movement times (± 1 SE) for the conditions in Experiment 5. To determine whether there were differences in movement times for the two hands for the different experimental conditions, I performed a 2 x (grasp timing; sequential or simultaneous) x 2 (hand; left or right) x 4 (target combination; High/High, Low/Low, High/Low, Low/High with the left target indicated first) x 6 (repetition) repeated-measures ANOVA. The results of the analysis revealed a significant main effect for hand on movement times, $F(1,8) = 10.045$, $p < .05$, such that object transports for the left hand (M = 1420 ms) took longer to complete than object transports for the right hand (M = 1308 ms). The main effect for target combination on movement times also reached significance, $F(3, 24) = 15.056$, $p < .01$, such that object transports took shortest when moving both objects to a high location (M = 1237 ms), followed by moving both objects to a low location (M = 1354 ms), moving the left plunger to a low location while moving the right plunger to a high location (M = 1361 ms), and moving the left plunger to a high location while moving the right plunger to a low location (M = 1504 ms). The results revealed a significant repetition on movement times, $F(2.016, 16.127) = 16.127$, $p < .01$, such that movement times decreased with an increasing number of repetitions. Finally, the results indicated a significant interactive effect of hand and repetition on movement times, F(2.069,

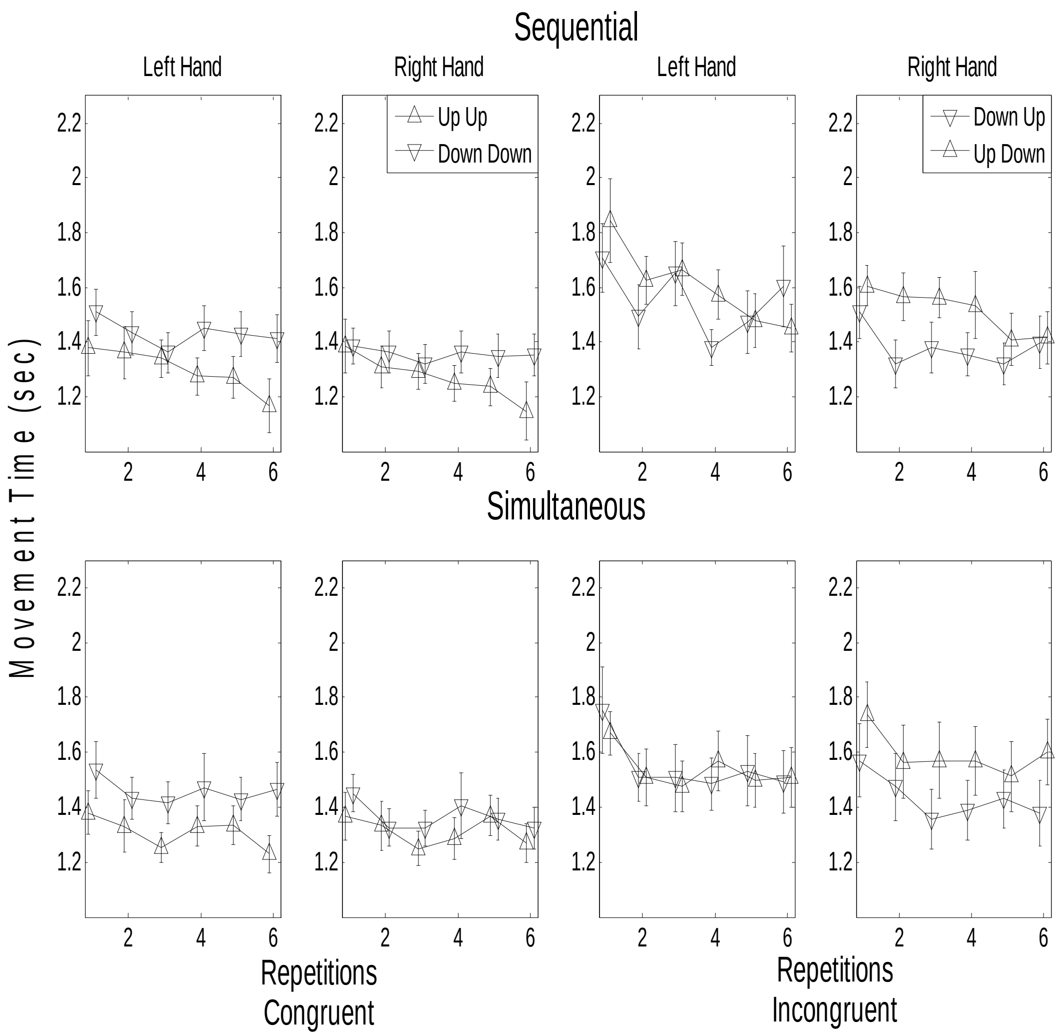

Figure 24. Mean movement times (± 1 SE) for Experiment 5. The upper panels show movement times for sequential conditions, and the lower panels show movement times for the simultaneous conditions.

16.549) = 4.190, $p < .05$, such that movement times for the left hand decreased more strongly than movement times for the right hand with increasing number of repetitions. The results did not reveal any other significant main effect or interactions, $p > .10$.

Discussion of Experiment 5

The main finding of Experiment 5 was that participants displayed a grasp height effect in all conditions of the experiment, including when they were asked to move the two plungers at the same time to opposite locations. This finding contrasted with the findings of the previous experiments in this dissertation. In these previous experiments, participants tended to grasp the plungers in similar locations with the two hands when they transported them to different locations. The main difference with previous experiments was that the plungers differed in their weight distribution in Experiment 5, such that participants always moved one lighter and one heavier plunger at the same time. The rationale for manipulating the weight distribution was that in the earlier studies participants may have preferred to grasp in similar locations with their two hands to ease the representation of object dynamics during object transport. Said another way, because the weight distribution of the two plungers was always approximately identical in the previous experiments, grasping the plungers in similar locations implied that the hands experienced similar dynamics during object manipulation. This benefit of similarity in the dynamics for the two hands may explain why participants did not display a grasp height effect in incongruent conditions in the earlier studies. The results of Experiment 5 indicated that removing this benefit resulted in a tendency for participants to display a grasp height effect in incongruent conditions.

The results are consistent with the notion that people employ a flexible hierarchy of constraints when they manipulate objects with their two hands. In this hierarchy, people may care more about easing the representation of object dynamics when doing so is relatively easy. By contrast, people may care more about their body posture after object transport when planning for similarity in object dynamics for the two hands is more difficult.

The notion of flexibility in the constraints that people rely on resonates with earlier work by Attneave and Reid (1968), who demonstrated that people could voluntarily shift between a retinal reference frame and a reference frame tied to the major axis of the head when asked to rate the perceived slant of visually presented lines. Similarly, participants in Experiment 5 may have elected to shift between reference frames. In particular, the results of Experiment 5 are consistent with the notion that eliminating a benefit of an object-centered reference frame (i.e. symmetry in dynamics for the two hands) resulted in a switch from an object-centered reference frame to a reference frame related to the body's end state.

CHAPTER 6
GENERAL DISCUSSION

This section first provides a short summary of the main results of the experiments in this dissertation. Then it discusses the implications of the findings for several issues in cognition and action, as well as directions for future research.

The results of Experiment 1 indicated that bimanual grasp selection is sensitive to the locations to which objects are moved. Participants showed a preference for adopting grasps at similar locations along the object shafts. When both objects needed to be moved to similar target heights, participants displayed a grasp height effect by grasping low for high targets and high for low targets. This grasp height effect was not observed when participants simultaneously moved both objects to different target heights.

The results of Experiment 1 were consistent with the hypothesis that participants would adopt different reference frames depending on task requirements. In congruent conditions, participants planned their grasps with respect to the end state of their body after object transport. In incongruent conditions, participants did not rely on this reference frame. Instead, they grasped the objects in similar locations with their two hands.

The results of Experiment 1 leave open why participants preferred to adopt similar grasps when moving two objects simultaneously to different target heights. Possible reasons are planning difficulties, a preference for body symmetry during grasping, a preference for visual symmetry, or a preference for similar dynamics for the two hands.

To distinguish among these different forms of symmetry, I manipulated the start and target heights in Experiment 2. The results of Experiments 2 indicated that participants preferred grasps to be symmetrical for the two hands with respect to the manipulated objects, not with respect to the initial state or end state of the body. This outcome suggests that participants used an allocentric reference frame that was tied to the objects they moved. The results of Experiment 2 did not address whether participants displayed this form of symmetry because of difficulties in planning, or because of a preference for similarity in object dynamics for the two hands.

Experiments 3 and 4 suggested that planning difficulties were unlikely to cause participants to grasp objects in similar locations in incongruent target conditions. When participants repeated the same incongruent condition 16 times in a row, they continued to adopt grasps that were similar for the two hands. Regardless of whether participants grasped the objects one object at a time or both at the same time while moving them simultaneously, they continued to grasp the objects in similar locations along the object shafts, as if this was a satisfactory mode of performance.

The results of Experiment 5 were consistent with this interpretation. Presenting participants with two objects that had different weight distributions removed the benefit of similarity of the dynamics for the hands. In this context, participants started to show a grasp height effect over repetitions in incongruent conditions. They did so regardless of whether they grasped the objects one at a time or both at the same time. These results suggest that participants were sensitive to the dynamics of object manipulation and that breaking the similarity in dynamics for the two hands pushed participants away from grasping in similar locations along the object shafts.

The present experiments have implications for the planning of bimanual object manipulation actions, as well as for action planning in general. I will first relate the presented findings to previous findings on bimanual object manipulation, and then discuss broader implications of the results for human action planning.

Bimanual Object Manipulation, Constraint Hierarchies, and Reference Frames

As stated in the introduction, previous studies provided a mixed picture in terms of the ordering of constraints for the planning of bimanual object manipulations. Some studies indicated that people adhered to end-state comfort (Fischman et al., 2005; Weigelt et al., 2006; Janssen et al., 2008), whereas others indicated that movement symmetry was a more important constraint for bimanual grasp selection (Hughes & Franz, 2008). The results of this dissertation suggest that the weighing of different constraints in the hierarchy may vary based on relatively small task variations. For example, the results of Experiment 1, 3, and 4 suggest that participants cared about both symmetry and end state comfort when they selected their grasps for objects in congruent conditions, such that they grasped low for high targets and grasped high for low targets and grasped in similar locations with the two hands. In these experiments, participants apparently prioritized symmetry for grasps over end state comfort when they needed to displace the objects to different target heights. In contrast, the results of Experiment 5 suggested that participants cared both about symmetry and end state comfort when they selected their grasps for objects in congruent conditions, but they cared more about end state comfort in incongruent conditions. Thus, the results in this dissertation are consistent with the notion that the weighing of different constraints for bimanual grasp selection was subject to change.

In addition to changes in the constraint hierarchy based on task variations, the weighing of constraints for object manipulation changed as a function of experience within a given task. In particular, the results of Experiment 5 suggested that participants may have initially selected grasps based on symmetry between the hands, but switched to adopting a grasp height effect when such symmetry did not result in similar dynamics for the two hands. Thus, the constraints that participants mainly cared about were not static, but changed with experience.

At a more abstract level, the dominant reference frame that participants adopted appeared to depend on task characteristics and on the level of experience with the task. Whereas the results of Experiment 2 indicated that bimanual grasp selection for objects with similar mass distributions relied primarily on an object-centered reference frame, the results of Experiment 5 were not consistent with the use of such a reference frame. Instead, participants in Experiment 5 started to adopt grasps that were consistent with the use of a reference frame tied to the end-state of their body after object transport. Such a shift in reference frames based on task characteristics and experience is consistent with previous research in other domains of performance (e.g. Attneave & Reid, 1968; Lee et al., 2008; Tolman, 1948). Overall, then, the results of this dissertation suggest that bimanual grasp selection may arise from a combination of different reference frames that are weighted differently based on the task and based on experience with the task. A similar argument for differential involvement of reference frames has been made in the context of other spatial tasks (Adam, Hommel, & Umiltà, 2003; de Kleine & Verwey, 2008; Deroost, Zeeuws, & Soetens, 2006; Heuer & Sangals, 1998; Liu et al., 2007). To the best of my knowledge, however, the present results provide the first demonstration that multiple reference frames are involved in bimanual object manipulation.

Implications for Hypotheses about Bimanual Grasp Selection

I will now evaluate the presented findings in relation to the main hypotheses presented in the introduction. Overall, the results provide strong support for the Bimanual End State Comfort hypothesis and the Bimanual Symmetry hypothesis, and only very weak support for the Conceptualization hypothesis.

With respect to the Bimanual End State Comfort hypothesis, the results indicate that participants adopted grasps that were consistent with end state comfort in the congruent conditions in each experiment. In addition, participants adopted end state comfort compatible grasps in the incongruent conditions in Experiment 5. With respect to the Bimanual Symmetry hypothesis, the results indicate that participants grasped the objects in similar locations along the object with their two hands in all conditions, except the incongruent conditions of Experiment 5. With respect to the Conceptualization hypothesis, the results of Experiment 5 suggest that participants managed to conceptualize adopting different grasps with their two hands after a relatively small number of repetitions. Thus, it is unlikely that the absence of a grasp height effect in the incongruent conditions of Experiment 1, 3, and 4 originated entirely from difficulties with conceptualizing the necessary or possible grasps for the two hands.

Anticipation and Interference in Action Planning

One tack towards understanding human action planning is to investigate how behavior in the present changes as a function of what is expected for the future. Another tack is to determine the conditions under which performance in a task suffers. The rationale behind the latter approach is that the conditions under which interference arises can inform researchers about the underlying action planning processes. I will discuss these two approaches in relation to the presented findings.

The central assumption in the study of anticipatory behavior is that what people anticipate provides insight into what they plan for. A challenge for this approach is to understand how observed behavior maps onto underlying planning process. On the one hand, finding that people change their behavior in a consistent manner based on what is to come provides evidence that people show a level of sensitivity to forthcoming task requirements. For example, when people walk up to a table to pick up an object and displace it to a target location, they modulate their strides in consistent ways when doing so that provides a benefit for transporting the object (van der Wel & Rosenbaum, 2007). Such a result suggests that the planning of strides may be influenced by longer-range task demands. However, an absence of consistent changes in behavior based on the forthcoming task requirements need not imply that people fail to anticipate forthcoming task requirements. In fact, it could imply that people have a very clear awareness of their capabilities. For example, in a task in which participants produced sequences of manual lifting movements between series of targets, people did not gradually increase the height of their movements before they needed to move over an obstacle (van der Wel, Fleckenstein, Jax, & Rosenbaum, 2007). This finding could imply the absence of anticipatory planning, but it could equally well suggest that people anticipate that they are capable of clearing the obstacle without increasing the height of their movements beforehand. Thus, finding that people change their behavior based on future task demands is informative, but finding no change in behavior is not. This issue is important for the interpretation of the findings presented in this dissertation, as discussed next.

Except for Experiment 5, the experiments in this dissertation indicated that participants did not systematically change their adopted grasps based on the combination of target heights in the incongruent conditions. One could take this finding to indicate interference in grasp selection in incongruent conditions. However, the absence of a change in the selected grasps based on the height of the target locations under these conditions need not imply that participants did not anticipate aspects of the task. Another possible interpretation is that participants anticipated that grasping in similar locations on the two objects would ease object transport. In particular, such anticipation may have occurred because grasping objects with similar mass distributions in similar locations may have eased the representation of the dynamics operating on the two hands during object transport. Such sensitivity of grasp selection to object dynamics has been reported for unimanual tasks (Lederman & Wing, 2003). These two interpretations are not distinguishable based on the results of Experiments 1, 3, and 4, but the results of Experiment 5 favor the latter interpretation. Because participants displayed a grasp height effect in the incongruent conditions after a small number of repetitions in Experiment 5, it is unclear why participants did not do so in the preceding experiments. The most parsimonious explanation is that the difference in results was due to the difference in the mass distribution of the objects because this was the only difference between Experiment 5 and preceding experiments.

The results of Experiments 3, 4, and 5 did indicate interference at the level of movement timing for incongruent compared to congruent conditions. Although participants were told to move at a comfortable pace, they took more time to complete the object transports in the incongruent conditions than in the congruent conditions. In addition, participants completed the object transports more asynchronously in the incongruent conditions than in the congruent conditions. These findings may be taken to suggest that transporting two objects to different locations is a more demanding task than transporting them to similar locations. This interpretation is consistent with previous research on bimanual coordination showing interference at the level of initiation along with attendant changes in reaction and movement times for bimanual reaching and aiming movements (e.g. Diedrichsen, Grafton, Albert, Hazeltine, & Ivry, 2006; Franz, Eliassen, Ivry, & Gazzaniga, 1996; Kelso, Southard, & Goodman, 1979; Spijkers, Heuer, Kleinsorge, & van der Loo, 1997; Weigelt, 2007) as well as for bimanual object manipulation (Kunde & Weigelt, 2005). Previous research has also indicated bimanual interference at the level of movement trajectories for simultaneous movements with different spatial requirements (e.g. Franz et al., 1991; Kelso, Putnam, & Goodman, 1983; Sherwood, 1990; Sherwood, 2004; Sherwood, 2006; Sherwood, 2007; Spijkers & Heuer, 1995).

Weber's Law and Bimanual Grasping

As already indicated, one possible interpretation of the presented findings is that participants were sensitive to the dynamics of object manipulation, so they selected grasp locations that would result in similar dynamics for the two hands. The finding that participants exhibited a grasp height effect in incongruent conditions suggested that the end state of the body became a dominant factor in action planning only if similar grasp locations did not result in similar dynamics for the two hands.

An alternative account of the presented findings centers on discriminability. According to this account, participants did not adopt a grasp height effect in incongruent conditions when the object weights were similar because the differences in the resulting end postures of the body for different grasps were difficult to discriminate. In other words, differences in body posture at the end of the object transports due to changes in grasp heights at the start locations may not have been noticeably different. In contrast, asymmetries in grasps at the start locations of the plungers may have been quite noticeable because they occurred near the middle of the range of motion. In addition, departures from symmetry at the start locations may have been more salient based on visual information. Thus, it may have been that differences in grasp heights at the start locations were more noticeable than were the effects of such differences at the target locations, and as a result participants grasped in similar locations. In Experiment 5, adding weight to one of the plungers may have made the effect of adopting different grasps at the start locations on the body posture at the target locations more noticeable, resulting in a change in grasp selection.

This alternative interpretation of the results is consistent with Weber's law. According to this law, people's sensitivity to changes in a given physical continuum is relative rather than absolute when measured in physical units (Marks & Algom, 1998). A central assumption within this interpretation is the idea that perception of differences in body posture near the center of the range of motion should be more sensitive than perception of differences in body posture near the extremes of the range of motion. However, this assumption may be problematic for two reasons. First, it should be noted that the applicability of Weber's law to visually guided actions is an ongoing debate (Ganel, Chajut, & Algom, 2008; Ganel, Chajut, Tanzer, & Algom, 2008; Smeets & Brenner, 2008). Second, previous research on just noticeable differences for body postures suggests that people are more sensitive to postural differences near the extremes of the range of motion than near the middle of the range of motion (Choi, Meeuwsen, & Arnhold, 1995; Meeuwsen, Tesi, & Goggin, 1992).

A possible way to reconcile these findings with the assumption could be that the perceived visual differences for grasps at the start locations may override the perceived kinesthetic differences at the target locations. Adding a weight to one of the plungers may have caused the perception of kinesthetic differences to become more salient than the perception of visual differences. This possibility is consistent with the notion that kinesthetic information is normally not primary for processing the location of the hand in space (e.g. Helms Tillery, Flanders, & Soechting, 1991). It is important to note that the dynamics of object manipulation per se are not important within this alternative explanation.

Shifts in Reference Frames and Skill Acquisition

The presented results suggest that a shift in the dominant reference frame may occur as a function of task characteristics as well as of experience. The results of Experiments 1, 3, and 4 indicate that people may rely on a different reference frame when they move two objects to different locations as compared to when they move them to similar locations. The results of Experiment 5 indicated that people may switch readily to the use of a different dominant reference frame depending on the task characteristics. Similarly, Lee et al. (2008) observed a shift from an allocentric reference frame to an egocentric reference frame. An open question is how such switches in reference frames with increased task experience relate to theories of skill learning. A question for future research is whether switches in reference frames arise in a discrete or gradual manner. Another question is how such switches map onto, for example, the different stages of skill acquisition postulated by Fitts and Posner (1967), and onto the power law of learning (Newell & Rosenbloom, 1981), according to which the rate of improvement on a task diminishes with increased levels of experience. Research relating skill acquisition to more general cognitive and motor abilities suggests that performance for novice learners is better predicted by measures such as verbal, math, and spatial abilities than by psychomotor measures. Performance in experts correlates better with psychomotor abilities instead (e.g. Ackerman, 2007; Ackerman & Cianciolo, 2000). A possible reason why performance in novices may be better predicted by measures such as spatial abilities could be that discovering the appropriate reference frame for tasks relies on such abilities. Once the appropriate reference frame is discovered for a task, performance would be better predicted by perceptual-motor processes because the planning process per se is similar between people, but the execution speed and accuracy may differ.

Attention and Bimanual Grasping

Another factor that likely influences the presented results is that object transports to similar versus different target locations differ in attention requirements. In particular, transporting two objects to different locations requires the division of attention to more distant spatial locations than transporting two objects to similar locations. Such differences in attention cannot account for the presented results, however, because this account does not explain why participants showed a grasp height effect in incongruent conditions in Experiment 5 but not in the other experiments. Future studies could investigate the role of attention requirements for bimanual grasp selection.

Symbolic versus Direct Cuing

In the presented experiments, I used symbolic cuing of the targets, such that the target locations were named with respect to their colors. The participants then derived the spatial locations of the targets based on those colors. A priori, it is possible that this translation process increased the difficulty of the task, in particular for incongruent conditions. It is possible that without having to convert symbolic cues into spatial locations, participants would show a grasp height effect in incongruent conditions more rapidly. A reason for this possibility is that interference in reaction times and movement times for incongruent target locations in bimanual aiming studies is much weaker or even absent when the target locations are cued directly (Albert, Weigelt, Hazeltine, & Ivry, 2007; Diedrichsen et al., 2001; Hazeltine, Diedrichsen, Kennerley, & Ivry, 2003; Obhi & Goodale, 2005). Thus, if inference is part of the reason why participants in the presented studies did not show a grasp height effect for incongruent conditions, they may show a grasp height effect in such conditions when the targets are cued directly. It should be noted, however, that the observation that participants did display a grasp height effect for incongruent conditions in Experiment 5 makes it unlikely that interference due to the employed cuing method caused participants not to display a grasp height effect in Experiments 1, 3, and 4.

Posture-Based Motion Planning and Reference Frames

The reported findings provide insight into the problem of posture selection. The specification of postures constitutes the core mechanism from which movements arise in some theories of motor control. For example, the posture-based motion planning theory (Rosenbaum, Meulenbroek, Vaughan, & Jansen, 2001; Rosenbaum, Loukopoulos, Meulenbroek, Vaughan, & Engelbrecht, 1995) contends that people plan movements with respect to body postures such that the planning of movements initially entails the selection of appropriate end postures, after which movement emerges as a result of the specification of such a new end posture. The importance of end postures for movement planning has been supported by neurophysiological studies in which 500 millisecond trains of stimulation applied to different areas of motor cortex and premotor cortex of the macaque monkey reliably evoked particular body postures in the monkey (e.g. Graziano, Aflalo, & Cooke, 2005).

The present findings suggest that posture selection may rely on different reference frames depending on characteristics of the task, as well as on the level of experience someone has with the task. For the posture-based motion planning theory (Rosenbaum et al., 2001), the present findings suggest that the same basic algorithm may be applied for posture selection, but that the reference frame based in which these postures are selected and stored may change depending on task context.

Assessing Judged Relative Costs of Breaking Symmetry versus End State Comfort

The presented results suggest that people may weigh different constraints differently depending on task characteristics. For bimanual grasp selection, it appears that both end state comfort and bimanual symmetry form constraints that people consider. A remaining question is how people weigh these two constraints against one another. A quantification of this weighing could help the development of a formal model of bimanual grasp selection.

Recently, Rosenbaum and Gaydos (2008) developed a method for estimating psychophysical cost functions for human actions, the Judged Relative Cost (JRC) method. This method relies on a two-choice forced choice paradigm. Participants choose one of two tasks that they think is easier to perform. Central to the method is the pairing of different tasks against one another. The pairing occurs in such a way that the tasks vary systematically along one or more task dimensions. Recording the tasks that participants elect to perform establishes a probability function for each of the task dimensions. The shape of the probability function provides a quantification of how sensitive participants are to different task dimensions.

The JRC-method could be applied to bimanual grasps, such that participants choose between different target pairs as well as between different grasp locations along the plungers. Through systematic variations of the tasks that participants choose from, relative cost functions for violating end state comfort as well as breaking bimanual symmetry could be established. Further manipulations with, for example, the weights of the objects could reveal how the cost function for a given constraint changes as a function of other task characteristics. Such an approach could lead to a quantification of the constraints for bimanual grasp selection over a range of settings. This in turn could spur the development of a quantitative model for bimanual grasping.

Modeling Bimanual Object Manipulation

An issue for future consideration is whether models of grasp selection should rely on a strict hierarchical organization or if they should rely on a more self-organizing form of control similar to many complex systems of animal behavior (e.g. Bonabeau, Dorigo, & Theraulaz, 1999; Gordon, 2007). The results presented in this dissertation are consistent with the notion that grasp selection does not rely on an immutable hierarchy of constraints. If this were the case, it would be difficult to explain why people would care more about symmetry for the two hands in some conditions and more about end-state comfort in other conditions. Instead, the presented findings can be accounted for more readily with a model along the lines of a Pandemonium model (Selfridge, 1959) or a connectionist network model (e.g. McClelland & Rumelhart, 1986; Thagard, 2005). The structure of such a model of the constraint hierarchy could comprise a set of nodes corresponding to different constraints. The weights associated with different nodes, and their connections, could change as a function of the task and as a function of experience (Prince & Smolensky, 1997). Developing such a model could yield further testable predictions concerning the fluidity of constraint hierarchies for action planning and task variations for which changes in the hierarchy may be expected.

Similar to different nodes that correspond to different constraints, a connectionist network model could incorporate different reference frames that have different levels of activation depending on context. A possible way of conceptualizing the relationship between constraints and reference frames in such a network could be that reference frames comprise a collection of nodes of constraints that relate either to egocentric or allocentric task factors. In some contexts, the total activity of nodes related to egocentric constraints may dominate the total activity of nodes related to allocentric constraints, or vice versa. A model with such a structure would allow for different reference frames to influence behavior simultaneously. The possibility that multiple reference frames may be active in parallel during action planning is consistent with a growing body of literature.

REFERENCES

Ackerman, P.L. (2007). New developments in understanding skilled performance. *Current Directions in Psychological Science*, *16*(5), 235-239.

Ackerman, P.L., & Cianciolo, A.T. (2000). Cognitive, perceptual speed, and psychomotor determinants of individual differences during skill acquisition. *Journal of Experimental Psychology: Applied*, *6*, 259-290.

Adalbjornsson, C.F., Fischman, M.G., & Rudisill, M.E. (2008). The end-state comfort effect in young children. *Research Quarterly for Exercise and Sport*, *79*, 36-41.

Adam, J.J., Hommel, B., & Umiltà, C. (2003). Preparing for perception and action (I): The role of grouping in the response-cuing paradigm. *Cognitive Psychology*, *46*, 302–358.

Ahmed, A.A., Wolpert, D.M., & Flanagan, J.R. (2008). Flexible representations of dynamics are used in object manipulation. *Current Biology*, *18*, 763-768.

Albert, N.B., Weigelt, M., Hazeltine, E., & Ivry, R.B. (2007). Target selection during bimanual reaching to direct cues is unaffected by the perceptual similarity of the targets. *Journal of Experimental Psychology: Human Perception and Performance*, *33*(5), 1107-1116.

Attneave, F., & Reid, K.W. (1968). Voluntary control of frame of reference and slope equivalence under head rotation. *Journal of Experimental Psychology*, *78*(1), 153-159.

Austin, J.T., & Vancouver, J.B. (1996). Goal constructs in psychology: Structure, process, and content. *Psychological Bulletin*, *120*(3), 338-375.

Batista, A.P., Buneo, C.A., Snyder, L.H., & Andersen, R.A. (1999). Reach plans in eye-centered coordinates. *Science*, *285*, 257-260.

Bernstein, N. (1967). The coordination and regulation of movements. London: Pergamon.

Bekkering, H., Wohlschläger, A., & Gattis, M. (2000). Imitation of gestures in children is goal-directed. *Quarterly Journal of Experimental Psychology. Human Experimental Psychology*, *53*, 153-164.

Beurze, S.M., van Pelt, S., & Medendorp, W.P. (2006). Behavioral reference frames for planning human reaching movements. *Journal of Neurophysiology*, *96*, 352-362.

Blakemore, S.J., Goodbody, S.J., & Wolpert, D.M. (1998). Predicting the consequences of our own actions: the role of sensorimotor context estimation. *The Journal of Neuroscience, 18*(8), 7511-7518.

Bonabeau, E., Dorigo, M., & Theraulaz, G. (1999). *Swarm intelligence: from natural to artificial systems.* New York, NY: Oxford University Press.

Bullock, D., Grossberg, S., & Guenther, F. (1993). A self-organizing neural model of motor equivalent reaching and tool use by a multi-joint arm. *Journal of Cognitive Neuroscience, 5*, 408-435.

Carson, R.G., & Kelso, J.A.S. (2004). Governing coordination: Behavioural principles and neural correlates. *Experimental Brain Research*, *154,* 267-274.

Choi, S.O., Meeuwsen, H.J., & Arnhold, R.W. (1995). On the psychophysics of arm-positioning movements. *Perceptual Motor Skills, 80*, 1163-1169.

Cohen, R.G., & Rosenbaum, D.A. (2004). Where objects are grasped reveals how grasps are planned: Generation and recall of grasps. Experimental Brain Research, 157, 486-495.

Colby, C. L., & Goldberg, M. E. (1999). Space and attention in parietal cortex. Annual Review of Neuroscience, 22, 319–349.

Collucia, E., Mammarella, I.C., De Beni, R., Ittyerah., M., & Cornoldi, C. (2007). Remembering object position in the absence of vision: Egocentric, allocentric, and egocentric decentered frames of reference. *Perception, 36*, 850-864.

De Kleine, E., & Verwey, W.B. (in press). Representations underlying skill in the discrete sequence production task: effect of hand used and hand position. *Psychological Research.*

Deroost, N., Zeeuws, I., & Soetens, E. (2006). Effector-dependent and response location learning of probabilistic sequences in serial reaction time tasks. *Experimental Brain Research, 171*, 469–480.

Diedrichsen, J., Grafton, S., Albert, N., Hazeltine, E., & Ivry, R.B. (2006). Goal-selection and movement-related conflict during bimanual reaching movements. *Cerebral Cortex*, *16*, 1729-1738.

Diedrichsen, J., Hazeltine, E., Kennerley, S., Ivry, R.B. (2001). Moving to directly cued locations abolishes spatial interference during bimanual actions. *Psychological Science, 12*, 493-498.

Feldman, A.G. (1986). Once more on the equilibrium-point hypothesis (λ model) for motor control. *Journal of Motor Behavior*, *18*, 17-54.

Feldman, J. (2000). Bias toward regular form in mental shape space. *Journal of Experimental Psychology: Human Perception and Performance*, *26*(1), 152-165.

Fischman, M.G., Stodden, D.F., & Lehman, D.M. (2003). The end-state comfort effect in bimanual grip selection. *Research Quarterly for Exercise and Sport*, *74*(1), 17-24.

Fitts, P.M., & Posner, M.I. (1967). *Learning and skilled performance in human performance.* Belmont, CA: Brock-Cole.

Flanagan, J.R., & Rao, A.K. (1995). Trajectory adaptation to a nonlinear visuomotor transformation: Evidence of motion planning in visually perceived space. *Journal of Neurophysiology*, *74*, 2174-2178.

Flash, T. & Hogan, N. (1985). The coordination of arm movements: An experimentally confirmed mathematical model. *Journal of Neuroscience, 5*, 1688-1703.

Franz, E.A., Eliassen, J.C., Ivry, R.B., & Gazzaniga, M.S. (1996). Dissociation of spatial and temporal coupling in the bimanual movements of callosotomy patients. *Psychological Science*, *7,* 306–310.

Franz, E.A., Zelaznik, H.N., & McCabe, G. (1991). Topological constraints in a bimanual task. *Acta Psychologica*, *77*, 137-151.

Franz, E.A., Zelaznik, H.N., Swinnen, S. & Walter, C. (2001). Spatial conceptual influences on the coordination of bimanual actions: When a dual task becomes a single task. *Journal of Motor Behavior*, 33(1), 103-112.

Ganel, T., Chajut, E., & Algom, D. (2008). Visual coding for action violates fundamental psychophysical principles. *Current Biology*, *18*(14), 599-601.

Ganel, T., Chajut, E., Tanzer, M., & Algom, D. (2008). When does grasping escape Weber's law? *Current Biology*, *18*(23), 1090-1091.

Giurfa, M., Eichmann, B., & Menzel, R. (1996). Symmetry perception in an insect. *Nature*, *382*, 458-461.

Gordon, D.M. (2007). Control without hierarchy. *Nature*, *446*, 143.

Graziano, M.S.A. (2001). Is reaching eye-centered, body-centered, hand-centered, or a combination? *Reviews in the Neurosciences*, *12*, 175-185.

Graziano, M.S.A., Aflalo, T.M., & Cooke, D.F. (2005). Arm movements evoked by electrical stimulation in the motor cortex of monkeys. *Journal of Neurophysiology*, *94*, 4209-4223.

Harris, C. M. & Wolpert, D. M. (1998). Signal-dependent noise determines motor planning. *Nature*, *394*, 780-784.

Hazeltine, E., Diedrichsen, J., Kennerley, S.W., & Ivry, R.B. (2003). Bimanual cross-talk during reaching movements is primarily related to response selection, not the specification of motor parameters. *Psychological Research*, *67*(1), 56-70.

Helms Tillery, S.I., Flanders, M., & Soechting, J. (1991). A coordinate system for the synthesis of visual and kinesthetic information. *The Journal of Neuroscience*, *11*(3), 770-778.

Heuer, H., & Klein, W. (2006). The influence of movement cues on intermanual interactions. *Psychological Research*, *70*, 229-244.

Heuer, H., & Sangals, J. (1998). Task-dependent mixtures of coordinate systems in visuomotor transformations. *Experimental Brain Research*, *119*, 224–236.

Hommel, B, Müsseler, J., Ascherleben, G., & Prinz, W. (2002). The theory of event coding (TEC): a framework for perception and action planning. *Behavioral and Brain Sciences*, *24*, 849–878.

Hughes, C.M.L., & Franz, E.A. (2008). Goal-related planning constraints in bimanual grasping and placing of objects. *Experimental Brain Research*, *188*, 541-550.

Ivry, R.B., Diedrichsen, J., Spencer, R.M.C., Hazeltine, E., & Semjen, A. (2004). A cognitive neuroscience perspective on bimanual coordination and interference. In Swinnen S.P., & Duysens, J. (Eds.). Interlimb Coordination. Kluwer Academic; Norwell, MA., 259–295.

Janssen, L., Beuting, M., Meulenbroek, R., & Steenbergen, B. (2008). Combined effects of planning and execution constraints on bimanual task performance. *Experimental Brain Research*.

Jeannerod, M. (1981). Intersegmental coordination during reaching at natural objects. In J. Long & A. Baddeley (Eds.), *Attention and performance IX* (pp. 153-169). Hillsdale, N.J.: Erlbaum.

Jeannerod, M. (1984). The timing of natural prehension movement. *Journal of Motor Behavior*, *26*(3), 235-254.

Kelso, J.A.S., Putnam, C.A., & Goodman, D. (1983). On the space-time structure of human interlimb co-ordination. *Quarterly Journal of Experimental Psychology*, *35A,* 347–375.

Kelso, J.A.S., Southard, D.L., & Goodman, D. (1979). On the co-ordination of two-handed movements. *Journal of Experimental Psychology: Human Perception and Performance, 5*, 229-238.

Keulen, R.F., Adam,J.J., Fischer, M.H., Kuipers, H.,& Jolles, J. (2002). Selective reaching: Evidence for multiple frames of reference. *Journal of Experimental Psychology: Human Perception and Performance*, *28*(3), 515-526.

Kunde, W. & Weigelt, M. (2005). Goal-congruency in bimanual object manipulation. *Journal of Experimental Psychology: Human Perception and Performance*, *31*(1), 145–156.

Lam, M., McFee, K., Chua, R., & Weeks, D.J. (2006). Macroscopic aspects of gross motor control: A test of the end-state comfort effect. *Research Quarterly for Exercise and Sport, 77*, 396-400.

Lederman, S.J., & Wing, A.M. (2003). Perceptual judgment, grasp selection, and object symmetry. *Experimental Brain Research, 152*, 156-165.

Lee, T.D., Ishikura, T., Kegel, S., Gonzalez, D., & Passmore S. (2008). Head-putter coordination patterns in expert and less skilled golfers. Journal of Motor Behavior, *40*(4), 267-72.

Liu, T., Lungu, O.V., Waecher, T., Willingham, D.T, & Ashe, J. (2007). Frames of reference during implicit and explicit learning. *Experimental Brain Research*, *180*, 273-280.

Marks, L.E., & Algom, D. (1998). Psychophysical scaling. In M.H. Birnbaum (Ed.). *Measurement, Judgment and Decision Making* (pp. 81–178), San Diego, CA: Academic Press.

McClelland, J.L., Rumelhart, D.E. & PDP Research Group (1986). *Parallel Distributed Processing*, Cambridge, MA: MIT Press.

Mechsner, F., Kerzel, D., Knoblich, G. & Prinz, W. (2001). Perceptual basis of bimanual coordination. *Nature*, *414*, 69–73.

Mechsner, F., & Knoblich, G. (2004). Do muscle matter in bimanual coordination? *Journal of Experimental Psychology: Human Perception and Performance*, *30*, 490-503.

Meeuwsen, H.J., Tesi, J.M, & Goggin, N.L. (1992). Psychophysics of arm movements and human aging. *Research Quarterly for Exercise and Sport*, *63*, 19-24.

Neely, K.A., Tessmer, A., Binsted, G., & Heath, M. (2007). Goal-directed reaching: movement strategies influence the weighing of allocentric and egocentric visual cues. *Experimental Brain Research*, *186*, 375-384.

Newell, A.M. & Rosenbloom, P.S. (1981). Mechanisms of skill acquisition and the law of practice. In J.R. Anderson (Ed.), Cognitive skills and their acquisition (pp. 1-55). Hillsdale, NJ: Erlbaum.

Obhi, S.S., & Goodale, M.A. (2005). Bimanual interference in rapid discrete movements is task specific and occurs at multiple levels of processing. *Journal of Neurophysiology*, *94*(3), 1861-1868.

Obhi, S.S., & Haggard, P. (2004). The relative effects of external spatial and motoric factors on the bimanual coordination of discrete movements. *Experimental Brain Research*, *154,* 399-402.

Oldfield, R.C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia*, *9*, 97-113.

Oliveira, F.T.P, & Ivry, R.B. (2008). The representation of action: Insights from bimanual coordination. *Current Directions in Psychological Science*, *17*(2), 130-135.

Pashler, H. (1990). Coordinate frame for symmetry detection and object recognition. *Journal of Experimental Psychology: Human Perception and Performance*, *16*(1), 150-163.

Patchay, S., Haggard, P., & Castiello, U. (2006). An object-centered reference frame for control of grasping: effects of grasping a distractor object on visuomotor control. *Experimental Brain Research, 170*, 532-542.

Prince, A., & Smolensky, P. (1997). Optimality: From neural networks to universal grammar. *Science*, *275*, 1604-1610.

Proctor, R.W., & Dutta, A. (1993). Do the same stimulus-response relations influence choice reactions initially and after practice? *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *19*(4), 922-930.

Ramachandran, V.S., & Hirstein, J. (1999). The science of art. A neurological theory of aesthetic experience. *Journal of Consciousness Studies*, *6*, 115-151.

Rhodes, G. (2006). The evolutionary psychology of facial beauty. *Annual Reviews of Psychology*, *57*, 199-226.

Riek, S., & Woolley, D. (2005). Hierarchical organisation of neuro-anatomical constraints in interlimb coordination. *Human Movement Science*, *24*, 798-814.

Röder, B., Kusmierek, A., Spence, C., & Schicke, T. (2007). Developmental vision determines the reference frame for the multisensory control of action. *Proceedings of the National Acadamy of Sciences*, *104*(11), 4753-4758.

Rogosky, B., & Rosenbaum, D.A. (2000). Frames of reference for human perceptual-motor coordination: Space-based versus joint-based adaptation. *Journal of Motor Behavior*, *32*(3), 297-304.

Rosenbaum, D.A., & Chaiken, S.R. (2001). Frames of reference in perceptual-motor learning: Evidence from a blind manual positioning task. *Psychological Research*, *65*, 119-127.

Rosenbaum, D.A., Dawson, A.M., & Challis, J.H. (2006). Haptic tracking permits bimanual independence. *Journal of Experimental Psychology: Human Perception and Performance*, *32*(5), 1266-1275.

Rosenbaum, D.A., & Gaydos, M.J. (2008). A method for obtaining psychophysical estimates of movement costs. *Journal of Motor Behavior*, *40*(1), 11–17.

Rosenbaum, D.A., Halloran, E.S, & Cohen, R.G. (2006). Precision requirements affect grasp choices. *Psychonomic Bulletin & Review*, *13*, 918-922.

Rosenbaum, D.A., & Jorgensen, M.J. (1992). Planning macroscopic aspects of manual control. *Human Movement Science*, *11*, 61-69.

Rosenbaum, D.A., Loukopoulos, L.D., Meulenbroek, R.G. J., Vaughan, J., & Engelbrecht, S.E. (1995). Planning reaches by evaluating stored postures. *Psychological Review*, 102, 28-67.

Rosenbaum, D.A., Marchak, F., Barnes, H.J., Vaughan, J., Slotta, J., & Jorgensen, M.J. (1990). Constraints for action selection: Overhand versus underhand grips. In M. Jeannerod (Ed.), *Attention and Performance XIII-Motor representation and control* (pp. 321-342). Hillsdale, NJ: Erlbaum.

Rosenbaum, D.A., Meulenbroek, R.G.J., Vaughan, J., & Jansen, C. (2001). Posture-based motion planning: Applications to grasping. *Psychological Review*, *108*, 709-734.

Salter, J.E., Wishart, L.R., Lee, T.D., & Simon, D. (2004). Perceptual and motor contributions to bimanual coordination. *Neuroscience Letters*, *363*, 102-107.

Sasaki, Y., Vanduffel, W., Knutsen, T., Tyler, C., & Tootell, R. (2005). Symmetry activates extrastriate visual cortex in human and nonhuman primates. *Proceedings of the National Academy of Sciences*, *102*(8), 3159-3163.

Selfridge, O.G. (1959). Pandemonium: A Paradigm for Learning. In Blake, D.V. and Uttley, A.M. (Eds.), *Proceedings of the Symposium on Mechanization of Thought Processes.* H.M. Stationary Office, London.

Serrien, D.J., & Wiesendanger, M. (2001a). A higher-order mechanism overrules the automatic grip-load force constraint during bimanual asymmetric movement. *Behavioural Brain Research*, *118*, 153-160.

Serrien, D.J., & Wiesendanger, M. (2001b). Bimanual organization of manipulative forces: Evidence from erroneous feedforward programming of precision grip. *European Journal of Neuroscience*, *13*, 1825-1832.

Sherwood, D.E. (2007). Separate movement planning and spatial assimilation effects in sequential bimanual aiming movements. *Perceptual Motor Skills*, *105*(2), 501-513.

Sherwood, D.E. (2006). Intermovement interval and spatial assimilation effects in sequential bimanual and unimanual movements. *Human Movement Science*, *25*(2), 145-164.

Sherwood, D.E. (2004). Movement time modulates spatial assimilation effects in rapid bimanual movements. *Research Quarterly for Exercise and Sport*, *75*(2), 203-208.

Sherwood, D.E. (1990). Practice and assimilation effects in a multilimb aiming task. *Journal of Motor Behavior*, *22,* 267–291.

Short, M.W., & Cauraugh, J.H. (1997). Planning macroscopic aspects of manual control: End-state comfort and point-of-change effects. *Acta Psychologica, 96*, 133-147.

Simon, H. (1955). A behavioral model of rational choice. *Quarterly Journal of Economics*, *69*, 99-118.

Smeets, J.B.J., & Brenner, E. (2008). Grasping Weber's law. *Current Biology, 18*(23), 1089-1090.

Spijkers W. & Heuer, H. (1995). Structural constraints on the performance of symmetrical bimanual movements with different amplitudes. *Quarterly Journal of Experimental Psychology A, 48*, 716-740.

Spijkers, W., Heuer, H., Kleinsorge, T., & van der Loo, H. (1997). Preparation of bimanual movements with same and different amplitudes: Specification interference as revealed by reaction time. *Acta Psychologica, 96,* 207–227.

Swinnen, S.P., & Wenderoth, N. (2004). Two hands, one brain: The cognitive neuroscience of bimanual coordination. *Trends in cognitive sciences, 8,* 18–25.

Thagard, P., (2005). *Mind: Introduction to Cognitive Science*, second edition, Cambridge, MA: MIT Press.

Tolman, E.C. (1948). Cognitive maps in rats and men. *Psychological Review*, *55*(4), 189-208.

Tversky, A. (1972). Elimination by aspects: A theory of choice. *Psychological Review*, *79*, 281-299.

Uno, Y., Kawato, M., & Suzuki, R. (1989). Formation and control of optimal trajectory in human multijoint arm movement: Minimum torque-change model. *Biological Cybernetics*, *61*, 89-101.

van der Wel, R.P.R.D., Fleckenstein, R.M., Jax, S.A., & Rosenbaum, D.A. (2007). Hand path priming in manual obstacle avoidance: Evidence for abstract spatio-temporal forms in human motor control. *Journal of Experimental Psychology: Human Perception and Performance*, *33*(5), 1117-1126.

van der Wel, R.P.R.D., & Rosenbaum, D.A. (2007). Coordination of locomotion and prehension. *Experimental Brain Research*, *176*, 281-287.

Weigelt, M. (2007). Re-examining structural constraints on the initiation of bimanual movements: The role of starting locations, movement amplitudes, and target locations. *Human Movement Science*, *26*, 212-225.

Weigelt, M., Kunde, W., & Prinz, W. (2006). End-state comfort in bimanual object manipulation. *Experimental Psychology*, *53*(2), 143-148.

Weigelt, M. Cohen, R.G., & Rosenbaum, D.A. (2007). Returning home: Locations rather than movements are recalled in human object manipulation. *Experimental Brain Research*, *149*, 191-198.

Weiss, D.J., Wark, J. & Rosenbaum, D.A. (2007) Monkey see, monkey plan, monkey do: The end-state comfort effect in cotton-top tamarins (*Saguinus oedipus)*. *Psychological Science*, *18*(12), 1063-1068.

Witt, J.K., Ashe, J., & Willingham, D.T. (2008). An egocentric frame of reference in implicit motor sequence learning. *Psychological Research*, *72*, 542-552.

APPENDIX
INSTRUCTIONS

Instructions for Experiment 1

In the experiment, you will be asked to move two plungers from a start location to an end location. You will move the plungers either one at a time, or both at the same time. You will always move the plunger on the left with your left hand and the plunger on the right with your right hand. In each trial, I will tell you the two targets for that trial, indicating the left target first and the right target last. As you see, the targets on the top are Black and the targets on the bottom are White. I will indicate the targets you will move to through those colors. In a trial, I will for example say “White White.” I will also say either “Sequentially” to indicate that you move the left plunger first, followed by the right plunger, or “Simultaneously” to indicate that both plungers should be moved at the same time. After I tell you the target sequence and the timing, I would like you to repeat this back to me. You can then go ahead and move each plunger to its respective target.

Each plunger should be grasped with a power grip, similar to how you would grasp a tennis racquet. Once you grasp a hold of a plunger, make sure to not let the plunger slide through your hand during the movement. You can move at whatever pace feels comfortable. We will repeat this basic task eight times.

Instructions for Experiment 2

In the experiment, you will be asked to move two plungers simultaneously from a start location to an end location. You will always move the plunger on the left with your left hand and the plunger on the right with your right hand, grasping them at the same time, and putting them down at the same time. In each trial, I will tell you the two targets for that trial, indicating the left target first and the right target last. As you see, the targets on the top are Black and the targets on the bottom are White. I will indicate the targets that you will move to through those colors. In a trial, I will for example say “White White.” I would like you to repeat this back to me, and you can then go ahead and move both plungers to their white targets at the same time.

Each plunger should be grasped with a power grip, similar to how you would grasp a tennis racquet. Once you grasp a hold of a plunger, make sure to not let the plunger slide through your hand during the movement. You can move at whatever pace feels comfortable. We will repeat the task about 30 times.

Instructions for Experiment 3

In the experiment, you will be asked to move two unused plungers from a start location to an end location. You will always move the plunger on the left with your left hand and the plunger on the right with your right hand, grasping them at the same time, and putting them down at the same time. In each trial, I will tell you the two targets for that trial, indicating the left target first and the right target last. As you see, the targets on the top are Black and the targets on the bottom are White. I will indicate the targets you will move to through those colors. In a trial, I will for example say “White White.” I would like you to repeat this back to me, and you can then go ahead and move both plungers to their white targets at the same time.

Each plunger should be grasped with a power grip, similar to how you would grasp a tennis racquet. Once you grasp a hold of a plunger, make sure to not let the plunger slide through your hand during the movement. You can move at whatever pace feels comfortable. Remember however that is important that you time the movements to start and end at the same time.

Your performance will be taped with a webcam that we will use for later analysis in the lab. Your face will not be visible in the recording and the recording is for lab use only. In addition, a motion tracking camera will track the movements of two IREDs that we will attach to your hand.

We will complete two blocks of 15 trials each. You can take a short break between any of the trial blocks. Do you have any questions before we begin?

Instructions for Experiment 4 and 5

In the experiment, you will be asked to move two unused modified plungers from a start location to an end location. You will always move the plunger on the left with your left hand and the plunger on the right with your right hand. In each trial, you will hear the two targets for that trial through a set of speakers, indicating the left target first and the right target last. As you see, the targets on the top are Black and the targets on the bottom are White. I will indicate the targets you will move to through those colors. In a trial, you will for example hear “White Black”, indicating that you will move the plunger on the left to its white target and the plunger on the right to its black target.

Depending on the block of conditions, grasping the plungers should either happen one at a time, or both at the same time. When you need to grasp them one at a time, you will hear for example the following sequence: “Black White, pause, Black, pause, White, pause, beep” to indicate that you will move the plunger on the left to black, and the one on the right to white. You will grasp the plunger on the left once you hear black being repeated, and the plunger on the right once you hear white being repeated. After that, you will hear a beep to indicate that you could go ahead and move the two objects at the same time to their targets. When you need to grasp both plungers at the same time, you will for example hear “Black White, pause, Black White, pause, beep”.

Each plunger should be grasped with a power grip, similar to how you would grasp a tennis racquet. You may grasp anywhere along the wooden shaft. Once you grasp a hold of a plunger, make sure to not let the plunger slide through your hand during the movement. You can move at whatever pace feels comfortable. Remember however that is important that you time the movements to end at the same time.

Your performance will be taped with a webcam that we will use for later analysis in the lab. Your face will not be visible in the recording and the recording is for lab use only. We will complete two blocks of X trials (X = 15 in Experiment 4, X = 24 in Experiment 5) each. You can take a short break between any of the trial blocks. Do you have any questions before we begin?

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Awards

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CMU Junior Scientist Travel Award to Carnegie Symposium on Cognition	2006
Children Youth and Family Consortium Level 2 Award	2006
Penn State Psychology Department Travel Award	2005
Children Youth and Family Consortium Level 1 Award	2005
Penn State University Graduate Fellowship	2004-2008
VSB Fonds Award for Study Abroad	2004-2006
Stichting Wetenschappelijk Onderzoek Limburg Award for Study Abroad	2002-2003

Publications

van der Wel, R.P.R.D., Rosenbaum, D.A., & Sternad, D. (under revision). Filling or killing time: Strategies for rate control in human motor control. *Experimental Brain Research.*

van der Wel, R.P.R.D., Eder , J.R., Mitchell, A.M., Walsh, M., & Rosenbaum, D.A. (2009). Trajectories emerging from discrete versus continuous processing models in phonological competitor tasks: A commentary on Spivey, Grosjean, and Knoblich (2005). *Journal of Experimental Psychology: Human Perception and Performance*.

Rosenbaum, D.A., Cohen, R.G., Dawson, A.M., Jax, S.A., Meulenbroek, R.G., van der Wel, R., & Vaughan, J. (2008). The posture-based motion planning framework: new findings related to object manipulation, moving around obstacles, moving in three spatial dimensions, and haptic tracking. In D. Sternad (Ed.), *Progress in Motor Control- A Multidisciplinary Perspective*. Springer.

van der Wel, R.P.R.D., Fleckenstein, R.M., Jax, S.A., & Rosenbaum, D.A. (2007). Hand path priming in manual obstacle avoidance: Evidence for abstract spatio-temporal forms in human motor control. *Journal of Experimental Psychology: Human Perception and Performance*, *33*(5), 1117-1126.

van der Wel, R.P.R.D., & Rosenbaum, D.A. (2007). Coordination of locomotion and prehension. *Experimental Brain Research*, *176*, 281-287.

Rosenbaum, D.A., Cohen, R.G., Jax, S., Weiss, D. & van der Wel, R.G.J. (2007). The problem of serial order in behavior: Lashley's Legacy. *Human Movement Science*, *26*, 525–554.

Reviewing

Ad hoc reviewer for Experimental Brain Research, Journal of Motor Behavior, Journal of Experimental Psychology: Human Perception and Performance, Psychological Research, Psychological Science.