The Influence of Task Demands on Manual Asymmetries for Reaching Movements to Tools

by

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Abstract

In this dissertation, three experiments were conducted that examined the influence of task demands on manual asymmetries for the performance of reaching movements to tools. In all three experiments, the difference between the hands (in terms of preference for Experiment 1 and performance for Experiments 2 and 3) was studied in response to varying task demands for grasping movements to tools.

In the first experiment, 82 right-handed and 60 left-handed university students performed reaching movements to tools and dowels at five positions within working space. Differences in the reaching patterns of the left and right hands to the tools and dowels were examined, as well as the effect of task demands (lift, use) and type of object (tool, dowel) on the reaching patterns. Dowels were used in order to examine if participants would treat a neutral object as if it were a tool in terms of their reaching patterns in working space. Results confirmed and extended prior research on the influence of task demands on reaching patterns within working space. Overall, there were more similarities in the general reaching patterns of left- and right-handed participants than differences. However key differences between the handedness groups emerged in the treatment of the dowel and the frequency of switches (reaching to lift the object with the non-preferred hand and transferring it to the preferred hand to use). Results also showed that tools enjoy a privileged association with the preferred hand, and that the intent of the movement has a very real goal on movement planning.

The first experiment examined patterns of hand use across working space in response to differing task demands. In the next experiments performance differences between the hands in terms of movement planning and initiation were examined through the use of reaction time and movement time. In these experiments, reaction time represented the time from the presentation of a go signal to when the participant first lifted their hand, and movement time was the time

between lifting the hand to lifting a tool off a sensor. Movement time represented the time to pick up the tool, and did not include the time to use the tool to perform a particular task and complete the reaching movement. In the second experiment, reaction time and movement time to tools placed at the midline position were examined under varying degrees of advance information using a precue paradigm. Three precue conditions were used which presented advance information on the hand to use to perform the movement (left or right) and/or the task (lift, use, or pantomime) to be performed: (1) both hand and task were cued in advance (Both precue); (2) task only was cued in advance (Task precue); and (3) neither hand nor task were cued in advance (No precue). Twenty-four right-handed university students performed reaching movements to tools under the three different precue conditions. The results of Experiment 2 showed that reaction time was sensitive to the amount of advance information presented in the precue. For reaction time manual asymmetries were observed in one condition only – a right hand advantage was present in the No precue condition. In contrast manual asymmetries in favor of the right hand were clearly observed with the movement time results. Experiment 2 was the first experiment reported in the literature to systematically examine reaction time for reaching and grasping movements to tools.

In order to further explore these results, in Experiment 3 a fourth precue condition (in which the hand to be used was cued in advance; the Hand precue) was added to the precue paradigm used in Experiment 2. An additional variable called replacement time, which represented the time spent interacting with the tool, was also examined. Forty-two right-handed university students participated in Experiment 3. The results of Experiment 3 largely replicated the findings of Experiment 2, and indicated that both the amount and type of precue information had an effect on reaction time. The addition of the Hand precue condition suggested that having advance knowledge of the hand to be used to perform the task was of greater importance for movement planning than was advance knowledge of the task to be performed. Regarding the movement time results, Experiment 3 was one of the first experiments to show the influence of task demands on the magnitude of manual asymmetries. The lack of differences between the hands for the replacement time results also suggested that the initial execution of the movement (represented by movement time) was most sensitive to manual asymmetries.

Overall, these experiments provided further insight into manual asymmetries for the performance of reaching movements, and illustrated how simple manipulations of task demands led to differences between the hands in measures of both preference and performance when interacting with tools.

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Dedication

To Pasquale, Joanne, Mario, Julia and Roberto. I love you all so much!

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Chapter 1: General Introduction

What did you do this morning? A fairly typical morning would likely involve one or more of these activities: brushing your teeth, combing your hair, eating cereal, buttering toast, and using a key to lock the door as you leave home for the day. Common to all these activities is that they involve using a tool-a toothbrush, comb, spoon, knife, and key. Most people can perform these tasks, and countless other similar ones, without much effort and indeed, on what can seem to be an automatic level. Although we may perform these tasks with little notice, this belies the high degree of skill and knowledge behind them. Working with tools requires a precise interaction between the individual and the tool itself in order to properly manipulate it. For the experiments in this dissertation, the task demands involved when interacting with tools are of interest in that they allow for an examination of the reaching patterns and performance differences between right and left hand use, or manual asymmetries.

The first experiment explored the manual asymmetries of reaching patterns of left- and right-handed participants as they performed different tasks with tools and dowels in working space. Also of interest was whether tools were unique, or if participants would spontaneously treat dowels as tools, as reflected by their reaching patterns. The results both confirmed and extended previous research on the influence of task demands on reaching patterns.

Preferred hand reaches were at a maximum within ipsilateral space for both handedness groups, and within contralateral space, both groups showed an increased frequency of preferred hand reaches as the task demands increased. Key differences between the handedness groups emerged in their treatment of the dowel and in the frequency of switches. Left-handers made significantly fewer preferred hand reaches to the dowel than did right-handers, and performed on average more switches than did right-handers.

The second and third experiments investigated whether task demands affected manual asymmetries, as measured by the initiation (reaction time) and execution (movement time) of reaching movements to tools in healthy young adult participants. Experiment 2 was the first experiment reported in the literature to systematically examine reaction time for reaching and grasping tools.

The results of Experiment 2 showed that reaction time was sensitive to the amount of advance information presented before the initiation of the movement, with reaction time decreasing as the amount of advanced information increased (from the No to the Task to the Both precue condition). For reaction time manual asymmetries were observed in only one condition: a right-hand advantage for reaction time occurred during the No precue condition, in which no advance information was presented. Unlike the reaching patterns observed in working space in Experiment 1, there were no differences between the hands in terms of reaction time as the task demands were varied. In contrast, manual asymmetries were clearly observed with the movement time results. Overall there was a right hand advantage for movement time, such that movement time was shorter for movements performed with the right hand than the left hand. There was also a significant effect of task, such that movement time for the lift task was significantly shorter than for the pantomime and use tasks.

Experiment 3 built on these findings with the addition of a fourth precue condition, the Hand precue, in which the hand to be used was known in advance. The results of Experiment 3 largely replicated the findings of Experiment 2. The addition of the Hand precue highlighted that both the type and amount of advance information contained in the precue was of importance. The addition of the Hand precue condition showed that knowing the choice of hand in advance led to a significantly faster reaction time than knowing the choice of task in advance. These and other findings suggested that having advance knowledge of the hand to be used to perform the task was of greater importance for movement planning than was advance knowledge of the task to be performed. Regarding the movement time results, the right hand advantage for movement time was found to increase with the task demands. Thus Experiment 3 was one of the first experiments to show the influence of task demands on the magnitude of manual asymmetries. By examining replacement time, the time spent interacting with the tool and completing the movement, Experiment 3 also showed that the initial phase of movement execution was most sensitive to manual asymmetries.

The goal of these experiments was to use relatively simple manipulations of task demands to further understand manual asymmetries observed when performing reaching movements to interact with tools. In all three experiments, the difference between the hands (in terms of preference for Experiment 1 and performance in Experiments 2 and 3) was studied in response to varying task demands.

1.1 Handedness and Cerebral Dominance

Why is handedness interesting and the subject of so much research? One reason is because handedness is related to cerebral organization, and thus is a visible behaviour that can be used to infer brain function and organization. If the right hand is more skilled at a particular task then it is inferred that the left hemisphere is dominant for that task, or for some component of the task.

In right-handed people, the left hemisphere has long been known to be dominant for various aspects of language function since the discoveries of Broca in 1861 and Wernicke in 1874 (Goble & Brown, 2008). In 1905 Liepmann hypothesized that the hemisphere contralateral to the preferred arm (i.e. the left hemisphere for right-handed people) also had a privileged role for the motor control of voluntary movements. Limb apraxia represents impairment in the ability to produce learned, skilled movements that is not attributable to primary motor or sensory loss, and is often caused by stroke, and has long been associated with left hemisphere damage. Liepmann examined 83 right-handed patients with either a right hemiplegia (indicating left hemisphere damage) or left hemiplegia (indicating right hemisphere damage) on tests of pantomime, imitation, and tool use. About 50% of the patients with a right hemiplegia had apraxic deficits, while none of the patients with a left hemiplegia exhibited such deficits. Thus Liepmann found that apraxia was exclusively associated with left hemisphere damage, with no apparent apraxic deficits occurring in patients with right hemisphere damage. Furthermore, damage to the left hemisphere resulted in an inability to make skilled movements with both hands, whereas only the left hand was affected when the right hemisphere was damaged. This led Liepmann to conclude that the left hemisphere of right-handed people played a dominant role in the production of skilled movements (Heilman & Rothi, 1997).

Although there is much research to support Liepmann's early study on the role of the left hemisphere in apraxia, more recent evidence shows that patients with right hemisphere damage can exhibit apraxic deficits as well. One example is a study by Roy, Black, Blair, and Dimeck (1998) that examined the gestural performance of 63 stroke patients with left or right hemisphere damage. It was found that 54% of patients with left hemisphere damage and 30% with right hemisphere damage could be classified as apraxic. The more sensitive gesture analysis scoring system used in this study is one possible reason for the detection of apraxia in the right hemisphere damaged patients. Consequently it is possible for patients with either left or right hemisphere lesions to exhibit apraxia. Thus although the left hemisphere is superior for the control of skilled voluntary movements, the right hemisphere also plays a role.

More recent studies have shown potential anatomical correlates for handedness. One study using magnetic resonance morphology showed that the depth of the central sulcus was related to handedness: in right-handers the left central sulcus was deeper than the right, and the opposite pattern was shown for left-handers (Amunts et al., 1996). Furthermore, this macroscopic asymmetry was accompanied by microscopic differences in neutrophil volume, with a greater volume in the hemisphere contralateral to the preferred hand. The authors posit that handedness is associated with more profuse horizontal connections (reflected by the greater neutrophil volume), and the increased intrasulcal surface of the precentral gyrus which may provide a potential substrate for the more complex movements performed by the preferred hand (Amunts et al., 1996). Another study that used magnetoencephalography found a significant increase in the volume of the primary motor cortex opposite to the preferred hand (Volkmann, Schnitzler, Witte, & Freund, 1998). The results of these studies demonstrate a biological correlate for handedness in the motor cortex.

Another study examined the effects of handedness and gender on the depth of the central sulcus in the region of cortical hand representation (Amunts, Jancke, Mohlberg, Steinmetz & Zilles, 2000). Male consistent right-handers were found to have a significantly deeper left central sulcus than right central sulcus. The difference in depth of the central sulcus between the hemispheres was found to decrease significantly from consistent male right-handers, to inconsistent male right-handers, to consistent male left-handers. For left-handers, 62% of the consistent left-handers had a deeper right central sulcus than left central sulcus; however for the group as a whole this effect was not significant. Interestingly, females did not show this interhemispheric asymmetry for the central sulcus (Amunts et al., 2000). This study suggests that gender differences may also affect the cortical organization of hand movements.

In right-handers, the left hemisphere is typically dominant for language and motor control functions. The majority of left-handers also have left hemisphere dominance for language. Thus left-handers cannot be thought of as simply "reversed" right-handers; if this was the case one would expect left-handers to be right hemisphere dominant for language. In terms of motor control there is some evidence that the right hemisphere is dominant for hand movements, as evidenced by apraxia in left-handed people after right hemisphere strokes. However the left hemisphere is also believed to play a role in the motor control of left-handers (Peters, 1996).

The left hemisphere has long been recognized as being dominant for the motor control of skilled voluntary movements in most right- and left-handed individuals; however right hemisphere superiority has also been shown for certain motor functions. Manual asymmetries, by nature of the fact that they are observable behaviours, can therefore provide insight into the organization and functioning of the brain. In this thesis, manual asymmetries will be explored through the simple manipulation of task demands for reaching movements to tools.

1.2 Preference and Performance Measures of Manual Asymmetries

The term manual asymmetries refers to differences between the left and right hands. These differences can be exhibited through the use of measures of preference and performance. With regards to hand use, preference refers to the individual's choice to use one hand over the other to perform a particular task. For example, a person may choose to use their right hand to use a spoon to stir sugar in a cup of coffee, or the left hand may be chosen to lift a book off the floor. When examining preference measures, it is the choice of hand that is used to do a specific task that is the variable of interest. In Experiment 1, a preference-based measure was used to examine the effects of task demands on manual asymmetries.

With regards to hand use, performance measures refer to which hand performs a particular task with more skill (for example, faster or more accurately). One example of a simple performance measure is the finger-tapping task. With this task, a counter is used to record the number of finger taps completed within a specified time frame, such as 10 seconds. The number of taps made by the left index finger compared to the number of taps made by the right index finger would be the variable of interest. If more finger taps were made by the right hand, then the right hand would be said to have a performance advantage over the left hand for this particular task. In Experiments 2 and 3, performance measures were used to examine the effects of task demands on manual asymmetries.

1.3 Determining Hand Preference With Questionnaires

Determining handedness often appears to be a deceptively simple matter: ask which hand is used for writing, and you have your answer; however, the hand used for writing is just one aspect of handedness. People often use one hand or the other to perform different tasks, whereas a few people use one hand (their preferred hand) almost exclusively. Thus both the direction (left or right) and the degree (or strength) of handedness are important aspects that define hand use. Self-report questionnaires are one tool that has been used to examine both the direction and degree of hand preference (see M. P. Bryden, 1977 and M.P. Bryden, Bulman-Fleming, & MacDonald, 1996 for a review of the use of questionnaires to measure hand preference).

Because they are quick and relatively easy to administer, questionnaires have proven to be one of the most popular methods of assessing the strength of hand preference (Bishop, Ross, Daniels, & Bright, 1996). Annett (1970) developed one of the earliest questionnaires used to assess hand preference. Annett believed that a simple dichotomy distinguishing left- and right-hand use on the basis of which hand is used for writing was insufficient. Instead, handedness could be considered a continuum, with people exhibiting different degrees of hand preference, from exclusively right-handed to exclusively left-handed. This could be measured through the use of a questionnaire that examined different tasks. Annett developed a 12-item questionnaire to assess this continuum of hand preference. The questionnaire asks participants to consider which hand is typically used to perform 12 different tasks (e.g. throw a ball to hit a target, write a letter legibly, etc.) Annett (1970) gave this questionnaire to over 2000 young adult participants, and an association analysis was performed to classify different subgroups of hand preference.

The results of the association analysis showed a large variety of patterns of responses, with 23 different patterns of hand preference distinguished. However it is not necessary to fully distinguish all such patterns, instead this finding highlights that it may be more accurate to describe handedness as a continuum, rather than two discrete categories of left and right. A second main result of this analysis was that similar patterns existed for participants classified as left- and right-handed. The main difference between the handedness groups was that there were many more right-handed participants who reported exclusive right hand use for all 12 tasks (72%) than there were left-handers who reported exclusive left hand use for all 12 tasks (3%) (Annett, 1970).

The Annett (1970) handedness questionnaire determined the strength of hand preference by examining the number of tasks that the participant reported doing with their preferred hand.[1] Other questionnaires have also been developed to assess hand preference. For example, Oldfield developed the Edinburgh Handedness Inventory (Oldfield, 1971), which asks participants to indicate the hand they would use to do 10 activities, such as writing, throwing, and using a broom. The instructions for the Edinburgh Handedness Inventory state that participants can put a check both left and right hand use if they are "indifferent" as to which hand is used to perform a particular task. Participants may also place two check marks for either the right or left hand in order to indicate that they "would never try to use the other hand" for a particular task. Thus the Edinburgh Handedness Inventory does assess the degree of handedness also.

The Waterloo Handedness Questionnaire assesses the degree of hand preference by having the participant respond whether he or she tends to use the left hand or right hand "always," "usually," or "equally" to perform 20 different tasks. Based on the responses, a measure of both the direction and degree of hand preference can be determined (Steenhuis and M. P. Bryden, 1989). For these experiments, the Waterloo Handedness Questionnaire (Appendix 1) was used to determine the hand preference of participants. The Waterloo Handedness Questionnaire was chosen because it assesses both the direction (left or right) and the degree (or strength) of hand preference. With 20 items, the Waterloo Handedness Questionnaire is not overly long but is detailed enough to provide a comprehensive assessment of handedness. Additionally, as described in Section 1.3, the Waterloo Handedness Questionnaire includes items relating to both skilled and unskilled activities. Furthermore the items included in the questionnaire are relatively familiar activities making it relevant to participants and directly applicable.

1.4 Skilled versus Unskilled Tasks

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[1] Throughout this dissertation, the term "preferred hand" will refer to the use of the dominant hand. The term "non-preferred hand" will refer to the use of the non-dominant hand. For right-handers, the right hand is the preferred

Steenhuis and M. P. Bryden (1989) gave a 60-item version of the Waterloo Handedness Questionnaire to almost 700 young adult participants. A factor analysis was performed to determine the underlying factors associated with the different tasks. Four main factors emerged:

(1) manipulating or using an object - these were skilled tasks that were highly lateralized (e.g. writing, throwing a dart, and using tweezers), such that most participants reported they "always use" a specific hand to perform these tasks;

(2) picking up objects (ranging in size from a pin to a book), with hand preference less lateralized such that few participants reported exclusively using a particular hand to perform these tasks;

(3) 2 items, using a bat and axe, with strongly lateralized responses;

(4) 3 items relating to picking up and carrying a heavy object or a suitcase, with less lateralized responses and many participants reporting using either hand.

These four factors were replicated by a second study in which a shorter, 33-item Waterloo Handedness Questionnaire was given to a second sample of 252 young adults. In this new analysis, the authors hoped to find a clear dissociation between the manipulation or use of an object (factor 1) and picking up an object (factor 2). Marker questions, designed to specifically address the common property thought to underlie each factor were also added. For example, which hand was used to manipulate tools was the marker question for factor 1. The results of the second factor analysis replicated the four factors. Additionally, the marker questions loaded onto the factors they were considered to represent. The underlying dimension of the first factor could therefore be considered the manipulation of tools. The underlying dimension of the second factor was picking up objects (Steenhuis & M. P. Bryden, 1989).

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hand and the left hand is the non-preferred hand, and vice versa for left-handers.

Based on these results, Steenhuis and M. P. Bryden proposed that the skill required to perform a task may be an important factor in assessing hand preference. The manipulation of tools (the first factor) represents a relatively complex sequence of actions. These tasks can be thought of as requiring more skill than simply picking up an object, a relatively unskilled task (the second factor). The tasks that loaded onto the first factor were strongly lateralized, with participants reporting exclusive use of one hand. In contrast the tasks that loaded onto the second factor were less lateralized, with participants reporting greater use of either hand. In this self-report measure, participants indicated a greater tendency to use their preferred hand when the task required more skill; and participants were more likely to report the use of either hand when the skill demands of a task were lower.

1.5 Performance-Based Measures of Hand Preference

Although useful, the inherent subjectivity of questionnaires is problematic, as is any self-report measure. Question meanings are open to interpretation, and participants must recall from memory which hand they tend to use to perform each task. To circumvent these problems, a variety of performance-based measures of hand preference have been developed. Performance-based measures of hand preference differ from questionnaires in that instead of having to recall the hand that is typically used, participants are asked to actually perform a particular task, and the hand that was used is observed and recorded by the experimenter.

An example of a performance-based measure of hand preference is a card-sorting task developed by Bishop, Ross, Daniels, and Bright (1996), called the Quantification of Hand Preference task. With this study, cards were placed at seven positions within working space. Right-handed participants had to reach for a card and then place it within a box at the midline position. The hand used to pick up each card was recorded. The frequency of right hand use at each position in working space differentiated the participants into groups on the basis of the degree of hand preference: predominant right-handers (who stated that they preferred to use their left hand for certain tasks) were distinguished from exclusive right-handers (who stated that they used their right hand for all tasks). Exclusive right-handers used their preferred right hand to pick up the card more often than did the predominant right-handers. This study demonstrated that the spatial location of the card in working space influenced hand selection. This study also showed that handedness subgroups (based on the degree of hand preference) could be distinguished based on their performance on a behavioural task.

Doyen and Carlier (2001) performed a validation study of Bishop's original card-reaching task. They used a modified version of the Quantification of Hand Preference task that had two cards placed at each of the seven positions. The order participants were asked to pick up the cards was random, but the same order was repeated for each participant. The repetition of the task allowed for the calculation of homogeneity and test-retest reliability of the Quantification of Hand Preference task. The results of the Doyen and Carlier (2001) experiment demonstrated that the Quantification of Hand Preference task exhibited acceptable homogeneity and test-retest reliability. This indicated that participants were consistent in their responses for this task. Doyen and Carlier (2001) were able to replicate the original findings and distinguish between subgroups of right-handed participants as defined by Bishop et al., (1996). However the Doyen and Carlier (2001) study was not able to replicate the two subgroups of left-handers defined by Bishop et al. (1996), and instead posited that because left-handers are a very heterogeneous group, manual asymmetries elicited by simple, everyday tasks were not adequate to distinguish subgroups. Left-handers will be further discussed in Section 1.5.

In a follow-up study to their original card-reaching task, Calvert and Bishop (1998) varied the skill demands of the reaching task used in the Quantification of Hand Preference task. In addition to the original task, two other tasks were included: (1) a pointing task, which required participants to point to the location of an alphabetic letter (simpler motor requirements), and (2) a placing task, which required participants to pick up a marble and place it within a small receptacle (more complex motor requirements). These tasks were included to examine the interaction between location in working space and skill demands.[2] The results showed that participants tended to use their preferred right hand for all three tasks when performed within ipsilateral space. In contralateral space the frequency of right hand use differed depending on the task. The right hand was used more often to perform the more skill-demanding reach and place task than it was for the simpler point task. These findings highlighted the interaction between task difficulty and location in working space.

Gabbard, Tapia, and Helbig (2003) achieved similar results with another variation of the performance-based reaching task. In this experiment, participants were blindfolded and required to grasp a small cube at one position in working space and release it a different position. The positions were cued with multiple auditory tones in order to increase task difficulty. In the first condition of the task, the first auditory tone indicated the pick up position and the second tone indicated the release position. The order of the tones was reversed in the second condition. Similar results were found in both conditions: an average of 96% of participants used their preferred right hand to reach for the cube in right hemispace and release it in left hemispace, while 60% used their right hand to reach for the cube in left hemispace and release it in right

[2] Within working space, the terms "ipsilateral" and "contralateral" will be defined in relation to the preferred hand. Therefore for right-handers, ipsilateral space refers to the right side of working space, and contralateral space refers to the left side of working space. For left-handers, ipsilateral and contralateral space refers to the left and right side of space, respectively.

hemispace. This percentage is greater than the average of 30% preferred hand use in contralateral space previously reported for a simpler version of the task (Gabbard, Iteya, and Rabb, 1997). Thus the majority of participants persisted in using their preferred hand within contralateral space when the complexity of the task became more demanding.

P. J. Brdyen, Pryde, and Roy (2000) used another performance-based measure of hand preference to examine reaching patterns in working space. Participants were asked to perform five tasks within working space with a dowel: point, pick up, toss, sweep, and position. For both left- and right-handed participants, the choice of task was found to be non-significant. These findings were in contrast to the earlier work of Steenhuis and M. P. Bryden (1989) and Calvert and Bishop (1998). One possibility was that the tasks were not distinct enough to elicit significant differences between the hands in terms of the frequency of preferred hand use.

Stins, Kadar, and Costal (2001) used a novel performance-based method to examine hand preference across working space. In this experiment participants had to reach to small glasses located at seven positions across working space. Accuracy demands were varied in that the glasses were either empty or filled to the brim with liquid. Participants were required to lift the glass a few centimeters and put it back down on the same spot, and were instructed not to spill any liquid in the filled glass condition. The authors were interested in examining the position in working space at which participants transitioned from predominantly using their preferred hand to using their non-preferred hand. This was termed the transition point. The results showed that for both left- and right-handed participants the transition point occurred further into contralateral space for participants reporting stronger hand preference (as determined by the Annett (1970) hand preference questionnaire). Participants were also somewhat more likely to use their preferred hand when the accuracy demands were high (glass was full) than when accuracy demands were low (glass was empty). Overall this experiment demonstrated that the size of workspace for the preferred hand (as represented by the transition point) was associated with the degree of preference for the preferred hand (as reported on a handedness questionnaire).

The findings of Stins, Kadar, and Costall (2001) regarding the transition point support earlier work by P. J. Bryden, Singh, Steenhuis, and Clarkson (1994). P. J. Bryden, et al., (1994) used a long pegboard and asked left- and right-handed participants to move small wooden pegs from one end of the pegboard to the other by "leap-frogging" the pegs in order. Participants were allowed to change from using one hand to the other as they wished. Left-handers moved farther into contralateral space with their preferred hand before switching to use their non-preferred hand. Although not statistically significant, a similar pattern of results was observed for right-handers. As well, performance on the pegboard task had a strong positive correlation to scores on the Waterloo Handedness Questionnaire. The P. J. Bryden et al., (1994) and Stins et al., (2001) studies demonstrated that the transition point (where hand use switches from the preferred to non-preferred hand) was related to the strength of hand preference.

1.5.1 Using Tools with Performance-Based Measures of Hand Preference

In the performance-based measures of hand preference experiments described in the previous section, the tasks involved lifting or moving small objects such as cards, marbles or small blocks. Although fine motor skill was required to grasp these small objects, the tasks themselves (picking up the object) would be classified as having low skill demands according to the factor analysis of Steenhuis and M. P. Bryden (1989). The factors could be classified by their task demands, with a low skill demand factor underlying the tasks that involved picking up objects and a higher skill demand factor underlying the tasks that involved the manipulation of tools.

In terms of task complexity, there is evidence to suggest that tasks can be classified as "skilled" or "unskilled." A defining feature of skilled tasks is that they place greater demands on spatial precision (e.g., a small target) and require a relatively complex sequence of movements, (such as manipulating a tool), whereas unskilled tasks do not involve such large demands on spatial precision or a complex sequence of actions (such as lifting a tool). On questionnaires of hand preference, participants tend to show a strong preference for using one hand to perform skilled tasks, whereas they are more likely to report using either hand to perform unskilled tasks (Steenhuis & M.P. Bryden, 1989). Thus using tasks that involve the manipulation of tools should be a good method of further examining task demands within the context of performance-based measures of hand preference.

Steenhuis and M. P. Bryden (1999) used a reaching task with varying task demands as a performance-based measure of hand preference. In the first condition, participants simply had to reach for and pick up tools that were placed directly in front of them (at the midline position) in working space. In the second condition, participants had to reach for and demonstrate how to use the tool (i.e. pantomime). The midline position can be considered a neutral position in terms of spatial location because it was the same distance from either hand. It was found that the frequency of preferred hand reaches increased when the intent was to use the tool compared to simply picking up the tool. The increased skill demands of the use task compared to the simpler pick-up task led to an increase in the frequency of preferred hand reaches. For example, just picking up a tool is a relatively easy task. Using the tool (e.g. a hammer) is a more skillful task, because it requires the proper interaction with an object (e.g. a nail), which requires performing an accurate movement in the appropriate spatial plane. As this study showed, participants were more likely to use their preferred hand to perform a task as the skill demands increased, even at the neutral midline position.

More recently, P. J. Bryden, Roy, and Mamolo (2003) used a similar performance-based measure of hand preference to examine the effects of skill demands on preferential reaching. In this study, different tools (pencil, toothbrush, hammer, paintbrush, and spoon) were placed at 45° intervals in an array in front of the participant. Participants were asked to either pick up the tool (Pick Up task), or pick up and pretend to use the tool (Use task). The results showed that the frequency of preferred hand use was higher for the Use task than the Pick Up task, supporting the findings of Steenhuis and M. P. Bryden (1999) and Calvert and Bishop (1998), suggesting that the skill level of a task is an important factor in hand preference. Tool position also affected the results: preferred hand use was higher for all tasks within the side of working space ipsilateral to the preferred hand. Within the side of working space contralateral to the preferred hand, preferred hand use was less frequent but the effects of the skill demands of the task could be seen: the preferred hand was used more often to perform the Use task than the Pick Up task. This was in spite of the fact that it was less biomechanically efficient to use the preferred hand in contralateral space, because doing so required reaching across the body midline. That preferred hand use was so high in contralateral space in spite of this biomechanical inefficiency indicated the strength of hand preference in these right-handed participants.

In summary, right-handed individuals tended to use their preferred hand almost exclusively when reaching to tools in ipsilateral space. Right-handed participants were also willing to use their preferred hand to reach into contralateral space, although this depended on the skill demands of the task being performed. As the skill demands of the task increased, right-handers were more likely to use their preferred hand to perform the reaching movement.

1.6 Left-Handers

Much of the research described in the previous section was conducted solely with right-handed participants; fewer experiments have examined both handedness groups. It is important to study left-handed participants also, because it is likely that they will not exhibit identical patterns to right-handed participants. Left-handedness, for example, has been reported as occurring more often in males than females. A recent meta-analysis of 144 studies on handedness, which included over 1.7 million participants in total, did indeed support this, with a male to female odds ratio of 1.23 (95% confidence interval of 1.19 – 1.27) (Papadatou-Pastou, Martin, Munafo, & Jones, 2008). Although it is not known why more males than females are left-handed, this is one finding that demonstrates that left-handers are not necessarily the same as right-handers.

Also of relevance is that right-handedness seems to increase with age. Young children tend to be more ambiguous with respect to hand preference. For example, younger children (5-6 years) tend to be less strongly lateralized than older children (10-12 years) (Leconte & Fagard, 2006). Children aged 10-12 were more likely to reach across their body midline for objects in contralateral space than were children aged 5-6, who were more likely to use their non-preferred hand (Leconte & Fagard, 2006). Other studies have demonstrated that the proportion of left-handers is lower in older age groups, for example, only 1-3% in adults over the age of 55 (Bryden, M. P., Bulman-Fleming, & MacDonald, 1996). Thus left-handedness in the population seems to decrease with increasing age.

There are different theories explaining left-handedness, which are still currently debated. The right-shift theory states that there is a normal distribution for handedness which is by chance shifted to the right. It does not determine handedness but increases the probability of right-handedness by displacing the random distribution to the right (Annett, 2000). This theory also asserts that hand preference lies on a continuum, rather than in discrete subtypes. Other theories regard left-handedness as being due to some form of pathology. One version of this theory is that there is a subgroup of left-handers who became left-handers because the motor control system for the right hand was damaged in some way during early development or did not develop properly (Bishop, 1984). In a stronger version of the pathology theories, Coren and Halpern (1991) claimed that left-handers have a shorter life expectancy than right-handers, and that this was due to dangers that left-handers are exposed to because of their unconventional hand use. Because left-handers make up only 10% of the population, they must deal with an environment largely designed by and for right-handed people. The Right-Sided World Hypothesis (Porac & Coren, 1981) refers to this covert yet pervasive pressure in favor of right-handedness that is evident in the environment. Most tools, machines, musical instruments, furniture, and sports equipment are designed in a manner to facilitate use for right-handers. Left-handers thus either have to learn to perform many tasks with their non-preferred right hand, or adapt to the discomfort and awkwardness of using an object with their left hand that is designed for the right hand. Right-handers, in contrast, are rarely, if ever, expected to perform tasks with their non-preferred left hand.

This potential for left-handers to be influenced by environmental factors may arise from the absence in left-handers of a genetic predisposition to hand preference seen in right-handers, the so-called right-shift factor (Bryden, Roy, McManus & Bulman-Fleming, 1997). Hand preference in left-handers then may be determined much more by chance. The influence of environmental factors such as living in a world designed for right-handers and overt societal pressure may have also played a role in modifying the handedness behaviour of left-handers. Not long ago, students in the Western world were discouraged from writing with their left hand by parents and teachers (Peters, 1996). Through this influence, left-handers would have naturally acquired more experience using their non-preferred hand.

Previous research has provided some support for this observation that left-handers have acquired greater experience with using their non-preferred hand. Gabbard, Iteya, and Rabb (1997) used a performance-based measure of hand preference to examine patterns of preferential reaching with left- and right-handed participants. Participants were required to reach for and pick up a small cube that was placed at one of nine positions in working space. After picking up the cube, participants placed it in a box at the midline position. In general, it was found that left-handers did not use their preferred hand as frequently in contralateral space and at the midline as did right-handed participants. That is, left-handers were more likely to use their non-preferred hand to perform the task within contralateral space, and this tendency increased with the distance of the position from the midline.

The Steenhuis and M. P. Bryden (1999) study described in Section 1.4.1 found that left-handed participants used their non-preferred hand more often to both pick up objects and to use objects than did right-handed participants. Right-handed participants often used their non-preferred hand to pick up objects, and only infrequently used their non-preferred hand when they had to actually use objects. These results showed that left- and right-handed participants do indeed differ in their patterns of hand preference. These findings also provide some support for the observation that left-handers tend to acquire greater experience with using their non-preferred hand in everyday life, and therefore were more likely to use the non-preferred hand than were right-handers. Additionally, in the Calvert and Bishop (1998) Quantification of Hand Preference study described in Section 1.4, it was found that although the performance of the handedness groups was similar, left-handers differed from right-handers in that they were more likely to use their non-preferred hand to perform the unskilled motor task.

There is research to indicate that there are subgroups of left-handers. Consistent left-handers regularly use their left hand for most activities, and inconsistent left-handers prefer to use their left hand for fine motor skills such as writing and use the right hand for other motor activities involving strength or ballistic movements. One study by Gilbert and Wisocki (1992) found that among adults aged 20-30 years old, 4.4% of males and 4.1% of females write with the left hand and throw with the right hand (inconsistent left-handers), whereas 8.7% of males and 6.5% of females both write and throw with the left-hand (consistent left-handers). Although with writing there may be cultural or social pressures to use the right hand it is unlikely that the same pressures apply to throwing a ball.

As the results of these studies demonstrated there were differences between left- and right-handers in terms of their reaching patterns in working space. Left-handers were more likely to use their non-preferred hand in contralateral space than were right-handed participants. Left-handers were also more willing than right-handers to use their non-preferred hand when performing tasks with low skill demands. Overall these findings demonstrated a greater use of the non-preferred hand by left-handed participants.

1.7 Summary

Several key findings regarding hand preference and performance were evident from the research outlined above. First, questionnaires for hand preference, such as the Waterloo Handedness Questionnaire, can be used to distinguish both the direction (either left- or right-handed) and the degree (strongly versus weakly lateralized) of hand preference. Second, a performance-based measure of hand preference can also be used to categorize participants on the direction and degree of hand preferenece by observing their reaching patterns (Bishop et al., 1996). Unlike a questionnaire, in which the participant has to recall their past reaching behaviour, performance-based measures of hand preference can be considered more objective because participants simply have to act, and their choice of hand can be observed. Third, hand preference was influenced by the position of the object within working space (Calvert & Bishop, 1998; Gabbard et al., 2003). In ipsilateral space the preferred hand was predominantly chosen, whereas some non-preferred hand use occurred in contralateral space. Fourth, the demands of the task also influenced hand preference. Skilled and unskilled tasks loaded onto different factors during a factor analysis using the original version of the Waterloo Handedness Questionnaire (Steenhuis & M. P. Bryden, 1989). Also, with performance-based measures of hand preference more preferred hand reaches were made for skilled than unskilled tasks (Calvert & Bishop, 1998; Stins et al., 2001; P. J. Bryden et al., 2003). Fifth, left-handed participants exhibited some differences in terms of their reaching patterns compared to right-handed participants (Gabbard et al., 1997; Calvert & Bishop, 1998; Steenhuis and M. P. Bryden, 1999).

Experiment 1 was designed to replicate and extend these main findings within the hand preference and performance literature. Experiment 1 further explored the effect of task demands, object position, and type of object on preferred hand reaches in left- and right-handed participants.

Chapter 2: Experiment 1 - The Tool and Dowel Experiment

In this experiment, the reaching patterns of left- and right-handed participants were explored as they interacted with tools and dowels.

2.1 Background Reaching Experiment

A previous experiment conducted as part of my Masters research (Mamolo, Roy, Rohr, & P.J. Bryden, 2006) formed the background for Experiment 1. The purpose of this earlier experiment (Mamolo et al, 2006) was to examine the effects of task demands and tool position on hand preference. To afford a gradation of task demands three tasks were examined: (1) Lift (reach to and lift the tool); (2) Pantomime (reach to, lift and pretend to use the tool); and (3) Use (reach to, lift and use the tool on the objects provided). The participant reached to and interacted with the tool at the cued position for each trial. This is different from other studies, such as the Quantification of Hand Preference tasks by Bishop et al. (1996) and Calvert & Bishop (1998) in which participants reached to an object within an array, and then brought it back to a position at the body midline. It was believed that reaching to and interacting with the tool at the cued position in hemispace would give a purer representation of the position effect of task demands on hand use in working space.

The tools were placed at five positions in front of the participant (90° and 45° to the left and right, and at the midline) in order to examine the effect of tool position in working space on hand preference. Small plastic tools were used, and the associated object for each tool was placed at one of the positions in working space. Unlike previous experiments that involved reaching to tools, in this experiment one of the tasks was to use the tool on its associated object. For example, a nail in a block of wood was provided for the hammer. The Use task was included in order to further increase the skill demands. The 22 right-handed and 15 left-handed participants were told the task and position for each trial, and were free to use either hand. The frequency of preferred hand reaches was the dependent variable.

The results of this experiment (Mamolo et al. 2006) showed that for both handedness groups, the frequency of preferred hand reaches increased with the skill demands of the task in contralateral space and at the midline position. Pantomiming the use of the tool lead to a higher frequency of preferred hand reaches than did simply Lifting the tool, as others have found (Bryden et al. 2003; Steenhuis & Bryden, 1999). Moreover, the effect of increasing task demands was seen in a further increase in the frequency of preferred hand reaches when the tool was actually used (Use condition). The effect of task demands on preferred hand reaching was also modified by the position of the tool in working space. Participants used their preferred hand exclusively to reach for and perform all three tasks at the positions in ipsilateral space. Although the task effect was seen at the midline position, this effect was most prominent in contralateral space. The fewest number of preferred hand reaches was seen for the Lift task, while it was only for the more complex Pantomime and Use tasks that participants chose to use their preferred hand for a majority of the time in contralateral space. This is in spite of the biomechanical inefficiency associated with this strategy, because participants must reach across their bodies to perform the task. This attests to the strength of preference for the preferred hand in these participants and concurred with previous findings using similar performance-based measures of hand preference, such as the Quantification of Hand Preference tasks by Calvert and Bishop (1998) and the blindfolded reaching tasks by Gabbard, Tapia, and Helbig (2003).

Similar to what was found by Steenhuis and M. P. Bryden (1999) and by Calvert and Bishop (1998) an analysis directly comparing the handedness groups found that left-handers were more likely to use their non-preferred hand than were right-handers in contralateral space. Right-handers largely persisted in using their preferred hand to reach across their body midline to perform the tasks. A significant difference in terms of the frequency of preferred hand reaches occurred between the handedness groups for the Use task at the near contralateral position and for the Lift and Pantomime tasks at the far contralateral position. The difference between the groups was perhaps most apparent for the Lift task at the far contralateral position: right-handers made approximately 35% of reaches with their preferred hand, compared to less than 1% for left-handers. As this finding indicated, left-handers almost exclusively used their non-preferred hand to perform the simplest task within the most extreme reaches of their contralateral space. Similar to the results of Gabbard, Iteya, and Rabb (1997), this illustrated that left-handed participants were quite willing to use their non-preferred right hand to perform tasks within contralateral space. From a biomechanical perspective this makes sense, as it is less efficient to reach across the body midline with the preferred hand to perform a task in contralateral space. It seems possible that these differences between left- and right-handers within regions of contralateral space reflect adaptations by left-handers to living in an environment designed for right-handers. The greater experience left-handers likely have using their non-preferred hand than right-handers may be manifested by their much greater use of the non-preferred hand within contralateral space than right-handers.

For both the left- and right-handed participant groups, the correlation between the Waterloo Handedness Questionnaire scores (a self-report measure of the degree of hand preference) and the total frequency of preferred hand reaches at the midline and contralateral positions was non-significant. This is in contrast to previous findings (P. J. Bryden, Pryde, & Roy, 2000). Possibilities for this result include the limited variability in this sample: five participants exclusively used their right hand to perform all tasks at all positions, as well as the small sample size of this study (N = 22 for right-handers, N = 15 for left-handers).

In another analysis the cross-over point (the position at which fewer than 50% of the reaches for all tasks were made with the preferred hand) was examined. It was found that the cross-over point was significantly correlated with the Waterloo Handedness Questionnaire scores for the right-handed participants only. This finding indicates that the higher an individual's score on the Waterloo Handedness Questionnaire (indicating a stronger degree of preference for the right hand), the further into contralateral space the cross-over point occurred. In other words, for right-handed participants, the further into left hemispace participants persisted in reaching with their right hand. This is similar to the finding of Stins, Kadar, and Costall (2001), who also found that the degree of handedness was related to the point at which participants switched from using one hand to the other. In contrast, the cross-over point was not significantly correlated with the Waterloo Handedness Questionnaire scores for left-handed participants. Given the distribution of reaches in working space for the left-handers this lack of a correlation most likely indicated that the degree of handedness in these left-handers as assessed through questionnaires was not directly related to their willingness to perform reaching movements with their preferred hand (Mamolo, Roy, Rohr, & P.J. Bryden, 2006). However, the small sample size (N = 15) might also explain the lack of a significant correlation.

2.2 Experiment Objectives

There were three main objectives for Experiment 1:

1. The first objective was to replicate and extend the findings from the previous performance-based measure of hand preference experiment from my Masters research (Mamolo

et al. 2006). In order to do this the sample size was greatly increased from 15 to 60 left-handed participants and from 22 to 82 right-handed participants

2. The second objective was to examine switching behaviour. While the previous experiment was being conducted, it was noted that during the Use task, some of the participants would pick up the tool with one hand (the non-preferred hand), and then switch the tool to the other hand (the preferred hand) to actually use the tool. The Use task could be considered as having two movement components: first reaching to and lifting the tool, and second, pantomiming the use of the tool. To examine this behaviour in more detail, the experimenter recorded which hand was used for both of the component movements of the Use task in Experiment 1. To simplify the procedure, only the Lift and Use tasks were conducted for this experiment. This allowed for a direct comparison between the Lift task, and the lift component of the Use task.

3. The third objective of this experiment was to examine the effect of using different objects on the frequency of preferred hand reaches. One question arising from the previous research on tool use and hand preference regards whether tools are unique. Tools have certain affordances; that is, a particular action is associated with a particular tool (Tucker & Ellis, 1998). For example, the shape, weight, and gripping surface of a hammer serve to limit the number of possible actions for its use. The features of the organism interacting with the tool also serve to limit the range of possibilities (for example, the form of the human hand). Thus the action of hammering is afforded by the characteristics of the hammer itself, as well as the organism interacting with it (Gibson, 1979). Because tools are usually used with the preferred hand, it is possible that greater preferred hand use will be seen for tools than for other objects, such as dowels. In contrast to tools, dowels (small wooden cylinders) can be considered neutral objects

and thus do not have specific affordances that associate them with a particular action. Thus one question of interest was whether a dowel can gain such an association by having the participant use it as if it was a particular tool. That is, would the use of the preferred hand increase for picking up a dowel if it were to be used as a tool? This question was explored in Experiment 1, which used both tools and small wooden dowels in a performance-based measure of hand preference experiment.

2.3 Methodology

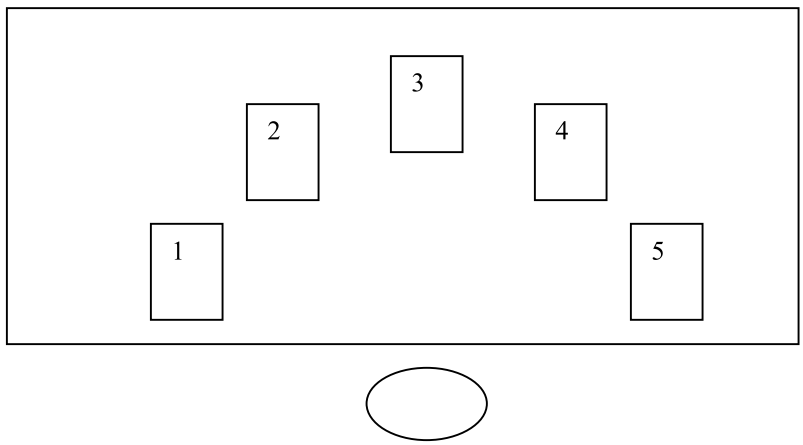
2.3.1 Participants

Participants were 60 left-handed and 82 right-handed undergraduate students at the University of Waterloo. The average age was 18.7 years. Fifty-six right-handed participants were female and 26 were male, while 38 left-handed participants were female and 22 were male. Handedness was determined through the use of the current version of the Waterloo Handedness Questionnaire (Appendix 1). A positive score indicated the participant was right-handed, whereas a negative score indicated the participant was left-handed. The experiment received ethical clearance from the Office of Research Ethics at the University of Waterloo.

2.3.2 Apparatus

Tools and dowels were placed at five positions in working space in front of the participant (Diagram 1). The positions were 45° and 90° to the left of the participant, 45° and 90° to the right of the participant, and one at the midline position. The tools used were a hammer, paintbrush, pencil, spoon, and toothbrush. A small toy hammer was used, in order to be of similar weight and size to the other tools and dowels. The dowels were small wooden cylinders of approximately the same size and weight as the tools. The objects were placed at an equal distance from the starting position at the midline in front of the participant.

Diagram 1: Schematic drawing of the object and participant positions



2.3.3 Procedure

Each participant performed four blocks of ten trials each. Tools were used for two blocks of trials and dowels were used for two blocks of trials. The position of the objects was rearranged after every block of trials. The tasks were also intermixed within a block of trials. The experimenter asked the participants to reach to, and perform one of two tasks with the object at a particular position:

1. Lift. For this task the participant was asked to simply lift the object.
2. Use. This task was composed of two components: picking up the object (PUO), and then pantomiming the use of the tool (or in the case of the dowel, participants were told to show how to use it as if it were a particular tool). The experimenter recorded

which hand lifted the object (PUO), and which hand used the object. This was done to examine the frequencies of switches in hand use (from lifting to using the object). Note that the participant was never told to think of the Use task as two separate components. Rather the experimenter simply observed the natural response of the participant regarding their choice of hand while performing the Use task, and would note which hand was used for the lift action and the use action. It is for analysis purposes that the Use task is separated into two components.

For trials in which the dowel was the test object, participants were told to use the dowel as if it was a particular tool for the Use task. The experimenter recorded which hand was used for each task, including both components of the Use task. In this experiment, the terms contralateral and ipsilateral space are used in reference to the preferred hand for each handedness group being discussed. The dependent variable was the frequency of preferred hand use.

2.4 Results

For all post-hoc analyses, the Bonferroni adjustment was applied for multiple comparisons. A value of $p < 0.05$ was used as the level of significance after applying the Bonferroni adjustment. All non-significant findings are listed in Appendix 2.

2.4.1 Right-Handed Participants

A repeated measures analysis of variance was performed on the frequency of preferred hand use for each task (3: Lift, PUO, Use) with each object (2: dowel, tool) at each position (5: far contralateral, near contralateral, midline, near ipsilateral, far ipsilateral). However, there was little variance at the two positions in ipsilateral space (the near and far right positions, standard error of 0.012 and 0.011, respectively), with almost all reaches performed by the participants with their preferred right hand at these positions (Figure 1). Mauchley's test of sphericity also indicated that for position, $p < 0.05$, therefore equality of variances could not be assumed. Because there was little variance at the two positions in ipsilateral space, a second analysis was performed excluding the ipsilateral positions. The results of the first analysis are shown in Appendix 3.

The second repeated measures analysis of variance involved: task (3: Lift, PUO, Use) by object (2: dowel, tool) by position (3: far contralateral, near contralateral, midline)[3]. Mauchley's test of sphericity showed that position was no longer significant ($p = 0.30$) therefore homogeneity of variances can be assumed. All main effects and interactions were significant. First, there were significantly more preferred hand reaches to tools (mean = 1.34, SE = 0.04) than dowels (mean = 1.17, SE = 0.04), as shown by the significant main effect of object {$F(1, 81) = 31.48$, $p < 0.001$, $\eta^2 = 0.28$}. The main effect of task {$F(2, 162) = 146.41$, $p < 0.001$, $\eta^2 = 0.64$} showed that the frequency of preferred hand reaches increased from Lift (mean = 0.89, SE = 0.04) to PUO (mean = 1.19, SE = 0.05) to Use (mean = 1.69, SE = 0.05). Post-hoc analyses revealed that all the tasks were significantly different from each other. The significant main effect of position {$F(2, 162) = 289.75$, $p < 0.001$, $\eta^2 = 0.78$} indicated that the frequency of preferred hand use increased from contralateral space to the Midline positions. Post-hoc analyses showed that the Midline (mean = 1.84, SE = 0.03) and the positions in contralateral (left) hemispace (Far Left mean = 0.77, SE = 0.05; Near Left mean = 1.15, SE = 0.05) were all significantly different from each other.

The three-way interaction of object by task by position was significant {$F(4,324) = 2.88$, $p < 0.05$, $\eta^2 = 0.03$; see Figure 2}. To better understand the 3-way interaction, it was

[3] The results of the second analysis using 3 positions were similar to the pattern of results found for the first analysis that included all 5 positions (listed in Appendix 3).

decomposed to examine the task by position interaction for each object. For dowels, the task by position interaction was significant {$F(4, 324) = 45.66$, $p < 0.001$, $\eta^2 = 0.36$; see Figure 3}. Furthermore, post-hoc analyses showed that the task effect was significant at each position. At the Far Left {$F(2, 162) = 117.06$, $p < 0.001$, $\eta^2 = 0.58$} and Near Left {$F(2, 162) = 94.78$, $p < 0.001$, $\eta^2 = 0.50$) positions, each task was significantly different from each other, with the frequency of preferred hand reaches increasing from Lift to PUO to Use. At the Midline position {$F(2, 162) = 3.40$, $p < 0.05$, $\eta^2 = 0.19$}, only the Lift and Use tasks were significantly different.

The task by position interaction was also significant for tools {$F(4, 324,) = 35.71$, $p < 0.001$, $\eta^2 = 0.33$; see Figure 4}. Post-hoc analyses were used to examine the task effect at each position. For the Far Left {$F(2, 162) = 79.74$, $p < 0.001$, $\eta^2 = 0.42$} and Near Left {$F(2, 162) = 49.47$, $p < 0.001$, $\eta^2 = 0.37$} positions, each task was significantly different from the others in terms of preferred hand reaches, increasing from Lift to PUO to Use. This is similar to the findings for the dowel at these positions. The task effect was not significant for the tool at the Midline position {$F(2, 162) = 0.085$, $p = 0.27$}. All three tasks were performed with a high frequency of preferred hand use at the Midline.

Finally, differences in preferred hand use between the tool and dowel were examined by performing a series of paired t-tests. Each t-test compared tool and dowel use for a particular task at a particular position. The results (see Table 1 below) revealed that for the Lift and PUO tasks, there was a significantly greater frequency of preferred hand use when reaching to the tool than the dowel for both the Far and Near Left positions. At the Midline there was no difference between the tool and the dowel for these tasks. For the Use task, at the Far Left position only there was a significantly greater frequency of preferred hand use for the tool than the dowel. For the Near Left and Midline positions there was no difference between the tool and dowel in terms of preferred hand use.

Table 1: Paired t-tests between the tool and dowel for each task by position

Pair	t	Significance (Bonferroni correction for multiple comparisons applied)
Far Left, Lift	3.49	< 0.05
Near Left, Lift	5.49	<0.001
Midline, Lift	.897	>0.05
Far Left, PUO	3.10	<0.05
Near Left, PUO	5.29	<0.001
Midline, PUO	1.51	>0.05
Far Left, Use	4.89	<0.001
Near Left, Use	1.73	>0.05
Midline, Use	1.93	>0.05

2.4.1.1 The Relationship Between Hand Preference and Performance in Right-Handers

One question of interest was whether there was a relationship between the degree of hand preference and the frequency of preferred hand reaches. This question was answered by examining the correlation between the Waterloo Handedness Questionnaire and the total frequency of preferred hand reaches at the contralateral and midline positions. The ipsilateral positions were not included since preferred hand use was at a maximum at these positions. This correlation was indeed significant ($r = 0.65$, $p < 0.001$), indicating that the greater the degree of hand preference, the higher the frequency of preferred hand reaches. When the Waterloo Handedness Questionnaire was correlated with the frequency of preferred hand reaches at the contralateral positions only, the findings were similar ($r = 0.58$, $p < 0.001$).

This relationship was examined in a second way through the use of the cross-over point. The cross-over point was the position in hemispace at which less than 50% of reaches were made with the preferred hand. For right-handers, the Far Left position was the cross-over point for 40.2% of participants, the Near Left position for 26.8% of participants, and the midline for 2.4% of participants. Another 30.5% of participants had no cross-over point, indicating that these participants used their preferred hand for the majority of reaches at all positions. The cross-over point was then correlated with the Waterloo Handedness Questionnaire score, a measure of the strength of hand preference. This correlation was found to be significant ($r = 0.44$, $p < 0.001$), indicating that the stronger the preference for the right hand, the more likely the participant was to reach into contralateral space to use their preferred hand to perform the tasks.

The second objective of this experiment was to examine the transfer of the object from one hand to the other in more detail (switches). This behaviour was examined by calculating the difference between the PUO and Use tasks. If no switches occurred, then the frequency of preferred hand reaches for the PUO task and for the Use task would be the same, indicating that the participant picked up the object with their preferred hand and also used it with their preferred hand. Since there were significantly more preferred hand reaches for the Use task than the PUO task (as indicated by the significant main effect of task), some participants must have picked up the object with their non-preferred hand and then transferred it to their preferred hand to use it. Analysis of the number of switches performed by each participant (see Figure 5) revealed that almost one third of right-handed participants (n = 27, or 32.9%) did not perform any switches at all. These participants always performed the PUO and Use task with the same hand. The mean number of switches made by the right-handed participants was 3.0, with a range from 0 to 9 switches.

In order to determine if the degree of hand preference was associated with this measure, a correlation was performed between the frequency of switches and the Waterloo Handedness Questionnaire scores. This correlation was found to be non-significant ($r = 0.07$, $p > 0.05$). Since so many participants did not perform any switches, the same relationship was examined only for the participants who performed at least one switch. This correlation was also found to be non-significant ($r = 0.16$, $p > 0.05$). Finally the switch ratio (the frequency of preferred hand reaches divided by the total frequency of preferred hand use) was calculated to correct for individual differences for all participants. When the switch ratio was correlated with the Waterloo Handedness Questionnaire score, this relationship was also found to be non-significant ($r = -0.18$, $p = 0.83$). Next, the correlation between the cross-over point and frequency of switches was examined, and this was found to be significant ($r = 0.294$, $p < 0.001$). This would suggest that participants who made few switches (and therefore used their preferred hand for both lifting and using the objects) also reached farther into contralateral space with their preferred hand, or did not have a cross-over point at all.

2.4.2 Left-Handed Participants

The same procedure for data analysis used for the right-handers was used for the left-handed participants. An analysis of variance was performed on the frequency of preferred hand reaches for each task (3: Lift, PUO, Use) by object (2: dowel, tool) by position (5: Far Contralateral, Near Contralateral, Midline, Near Ipsilateral, Far Ipsilateral). Again as with the right-handers, there was little variance at the two positions in ipsilateral space (the Near and Far Left positions, standard error of 0.022 and 0.012, respectively), with almost all reaches performed by the participants with their preferred left hand at these positions (Figure 6). Mauchley's test of sphericity also indicated that for position, $p < 0.01$, therefore equality of variances could not be assumed. The results of this analysis are listed in Appendix 3.[4] The two ipsilateral positions were therefore excluded from the second analysis: a task (3: Lift, PUO, Use) by object (2: dowel, tool) by position (3: Far Contralateral, Near Contralateral, Midline) analysis of variance. Mauchley's test of sphericity showed that position was no longer significant (p = 0.51) therefore homogeneity of variances can be assumed.

For the main effect of object $\{F(1, 59) = 51.27, p < 0.001, \eta^2 = 0.47\}$, preferred hand use was significantly greater for the tools (mean = 1.29, SE = 0.05) than the dowels (mean = 1.02, SE = 0.04). The main effect of task was significant $\{F(2, 118) = 164.99, p < 0.001, \eta^2 = 0.74\}$. Post-hoc comparisons revealed that all tasks were significantly different from each other, and preferred hand use increased from the Lift (mean = 0.82, SE = 0.05) to the PUO (mean = 0.99, SE = 0.05) to the Use task (mean = 1.66, SE = 0.66). The main effect of position $\{F(2, 118) = 172.01, p < 0.001, \eta^2 = 0.75\}$ showed an increased frequency of preferred hand use from the contralateral to midline positions. Post-hoc analyses showed that the frequency of preferred hand reaches decreased from the Midline (mean = 1.77, SE = 0.05) and across contralateral space (Near Right mean = 0.95, SE = 0.07; Far Right mean = 0.74, SE = 0.04)

The three-way interaction of object by task by position was not significant (Appendix 3). The interaction of object by task $\{F(2, 118) = 4.74, p < 0.05$, effect size = $0.07\}$ (shown in Figure 7) was significant. To examine this interaction, post-hoc analyses were performed by

[4] The results of the second analysis that used 3 positions showed a similar pattern of results to the analysis that included all 5 positions (listed in Appendix 3).

looking at the effect of object for each task. For the Lift task, this effect was significant {$F(1, 59) = 35.97$, $p < 0.001$, $\eta^2 = 0.34$}, as it was for the PUO task {$F(1, 59) = 30.24$, $p < 0.001$, $\eta^2 = 0.32$}, and the Use task {$F(1, 59) = 9.14$, $p < 0.05$, $\eta^2 = 0.18$}. For each task, more preferred hand reaches were performed with the tool than with the dowel. Although the object effect was significant for all three tasks, the difference between the frequency of preferred hand reaches for the tool and dowel was greater for the Lift and PUO tasks than for the Use task (difference equal to 0.93, 1.02, and 0.43, for the Lift, PUO and Use tasks respectively).

The object by position interaction {$F(2, 118) = 6.92$, $p < 0.05$, $\eta^2 = 0.11$} (shown in Figure 8), was also significant. Post-hoc analyses examining the object effect for each position revealed that this effect was significant for all three positions, that is, at the Midline {$F(1, 59) = 6.96$, $p < 0.05$, $\eta^2 = 0.11$}, Near Right {$F(1, 59) = 24.94$, $p < 0.001$, $\eta^2 = 0.30$} and Far Right {$F(1, 59) = 37.62$, $p < 0.001$, $\eta^2 = 0.39$} positions. As can be seen from Figure 8, although the difference between the objects was significant for each position this difference was greater for the contralateral positions than for the Midline position (tool-dowel difference equaled 0.32 for the Midline, 1.08 for the Near Right, and 0.98 for the Far Right positions).

The significant interaction of task by position {$F(4, 236) = 61.25$, $p < 0.001$, $\eta^2 = 0.51$} is shown in Figure 9. Post-hoc analyses were performed by looking at the task effect for each position. For the Near Right position, the task effect was significant {$F(2, 118) = 76.64$, $p < 0.001$, $\eta^2 = 0.57$}, with all three tasks different from one another. This was also the case for the Far Right position {$F(2, 118) = 184.91$, $p < 0.001$, $\eta^2 = 0.76$}. For the Midline the task effect was significant {$F(2, 118) = 10.65$, $p < 0.001$, $\eta^2 = 0.15$}, however, only the Lift task was significantly different from the PUO and Use tasks, which did not differ from each other.

2.4.2.2 The Relationship Between Hand Preference and Performance in Left-Handers

As with right-handed participants, the relationship between the degree of hand preference and the frequency of preferred hand reaches was examined by determining the correlation between the Waterloo Handedness Questionnaire and the total frequency of preferred hand reaches at the contralateral and midline positions. This was found to be significant ($r = 0.54$, $p < 0.001$), indicating that a stronger degree of hand preference was associated with a higher frequency of preferred hand reaches. Similar results were found when the frequency of preferred hand reaches at only the contralateral positions was correlated with the Waterloo Handedness Questionnaire score ($r = 0.40$, $p < 0.01$).

The cross-over point was calculated for left-handed participants. The cross-over point was the position in hemispace at which less than 50% of reaches were made with the preferred hand. For left-handers, 26.7% had no cross-over point (indicating that these participants used their preferred hand for the majority of reaches at all positions), for 26.7% of participants the cross-over point was the Far Right position, for 41.7% of participants it was the Near Right position, and for 5.0% of participants it was the Midline position. The cross-over point was correlated with the Waterloo Handedness Questionnaire score, a measure of the strength of hand preference. This correlation was found to be significant ($r = 0.27$, $p < 0.05$), indicating that the stronger the preference for the left hand, the more likely the participant was to reach into contralateral space to use their preferred hand to perform the tasks.

Switching behaviour was also examined for left-handed participants. An examination of the significant main effect of task indicated that the frequency of preferred hand reaches for the PUO task did not equal that of the Use task, therefore some switches must have occurred. The frequency of switches was determined by calculating the difference between the frequency of preferred hand reaches for the Use and PUO tasks for each participant; this is shown in Figure 10. The mean number of switches made by left-handed participants was 5.0, with a range from 0 to 11 switches. Only one left-handed participant did not perform any switches. A correlation was performed between the frequency of switches and the Waterloo Handedness Questionnaire scores. This correlation was found to be non-significant ($r = 0.01$, $p > 0.05$). The switch ratio (the frequency of preferred hand reaches divided by the total frequency of preferred hand use) was calculated to correct for individual differences. When the switch ratio was correlated with the Waterloo Handedness Questionnaire score, the relationship was also found to be non-significant ($r = -0.002$, $p > 0.05$). Finally, the correlation between the frequency of switches and the cross-over point was also examined. This too was found to be non-significant ($r = 0.05$, $p > 0.05$).

2.4.3 Comparison of Left- and Right-Handed Participants

The final analysis was performed in order to determine if there were any significant differences between the handedness groups in terms of patterns of preferred hand use. The same procedure for data analysis used for the handedness groups separately was used here except that handedness group was included as a factor. Thus, a group (2: left, right) by task (3: Lift, PUO, Use) by object (2: dowel, tool) by position (3: far contralateral, near contralateral, midline) repeated-measures analysis of variance was performed, with group as a between-subjects factor. Only the midline and contralateral positions were examined, since both right- and left-handed participants performed almost all of their reaches into ipsilateral space with the preferred hand. Since the main objective of this analysis was to allow for direct comparisons between the handedness groups, only the effects that involved handedness group as a variable will be discussed. The non-significant interactions that involved group are listed in Appendix 3, as are the significant interactions that did not involve handedness group as a variable. These interactions will not be discussed further, as they were already described in the results section for the individual handedness groups.

There were two significant interactions involving group. The first was the 3-way interaction of task by position by handedness group. {$F(4, 560) = 4.88$, $p < 0.001$, $\eta^2 = 0.03$ see Figure 11}. The task by position interaction was examined for each handedness group. The task by position interaction was significant for right-handers {$F(4, 324) = 61.63$, $p < 0.001$, $\eta^2 = 0.65$} and for left-handers also{$F(4, 324) = 61.25$, $p < 0.01$, $\eta^2 = 0.70$}. For both handedness groups, all three tasks were significantly different from each other at the Near and Far Contralateral positions. The source of the three-way interaction emerged from differences between the handedness groups at the Midline position. For right-handers, significantly more preferred hand reaches were made for the Use task than the Lift task, and the PUO task did not differ from either the Lift or Use tasks. For left-handers, at the Midline position the frequency of preferred hand use was equal for the PUO and Use tasks, which were significantly greater than for the Lift task.

The second significant interaction involving handedness group was the significant interaction of group by object {$F(1, 140) = 4.209$, $p < 0.05$, $\eta^2 = 0.03$}. As shown in Figure 12, this interaction indicated that right-handers used their preferred hand more frequently than did left-handers when reaching to the dowel. However there was no difference between the handedness groups when reaching to the tool.

2.5 Discussion

The first objective of this experiment was to replicate and extend my earlier Masters research on hand preference and tool use across working space (Mamolo et al., 2006). These findings largely confirmed my earlier work with left- and right-handed participants. First, preferred hand use increased as the skill demands of the task increased, from the Lift to PUO to Use task. Although the Lift and PUO tasks were the same action (picking up the object), preferred hand use differed as the goal of the movement changed from simply lifting the object, to lifting the object with the intent to use it. This highlights the task-specific nature of manual asymmetries as well as the importance of the intention of the action. This finding also lends support to the end-point comfort hypothesis proposed by Rosenbaum (Rosenbaum et al., 1990), in which an individual may initially grasp an object in an awkward manner, in order to achieve maximum grip comfort for the final position of the object at the end of the movement. A classic example of this is the initial grasp used to reach for an inverted glass. Typically people will use a rather awkward hand position (with the thumb pointing down) to initially reach for and grasp the inverted glass, and then rotate the wrist to place the glass in the usual, upright position at the end of the movement (maximizing the comfort of the final hand and wrist position). In this scenario the end goal of the movement affects the initial planning. Further evidence of the relationship between action planning and task demands can be found in the literature examining the kinematics of reaching movements. In one experiment by Marteniuk, MacKenzie, Jeannerod, Athenes and Dugas (1987), the time spent in the deceleration phase of the reaching movement was longer when the participant was asked to place the object in a precise position than when the participant was told to toss the object. The greater spatial precision required for the placing movement as opposed to the tossing movement was manifested in the greater amount of time spent homing in on the target in the deceleration phase of the placing movement. The finding of a significant difference between the Lift and PUO tasks in Experiment 1 highlighted that the ultimate goal or intent of a movement has a very real effect on movement planning. This finding also supports a task-specific view of movement planning and control, in which movements are planned and organized to meet the specific goals of an individual acting within a particular environment. This will be addressed in greater detail in Section 3.2.

Returning now to the findings of Experiment 1 that supported my Masters work, the frequency of preferred hand reaches also increased from the PUO to Use task. The significant difference between the PUO and Use tasks indicated that for this reaching movement, there were a number of times when the participants lifted the object with one hand, and then transferred it to their other hand to use it. Given that the frequency of preferred hand reaches was greater for the Use task than for the PUO task, participants were likely picking up the object with their non-preferred hand and transferring it to their preferred hand to use the object. This will be discussed in further detail below, in the section describing switching the object from one hand to the other.

Preferred hand use increased from contralateral to ipsilateral space, where it reached a maximum. Preferred hand use also increased within contralateral space, from the Far Contralateral to the Near Contralateral positions. These results also replicated the findings from my Masters research (Mamolo et al., 2006), as well as other previous research (Calvert & Bishop, 1998; Gabbard, Tapia, & Helbig, 2003).

Contradictory findings have been observed in previous research examining the relationship between the degree of hand preference and the frequency of preferred hand reaches. This relationship can be examined by correlating the Waterloo Handedness Questionnaire scores with the total frequency of preferred hand reaches for the Midline and contralateral positions. In Mamolo et al. (2006) a significant relationship was not observed, whereas in P. J. Bryden, Pryde, and Roy (2000) there was a significant correlation between the variables. The results of Experiment 1 showed a significant correlation between Waterloo Handedness Questionnaire scores and the frequency of preferred hand reaches for both left- and right-handed participants. This relationship suggests that as the degree of hand preference increased (i.e. the more strongly left- or right-handed an individual) the greater the frequency of preferred hand reaches. This confirmed the findings of Bryden, Pryde, and Roy (2000) and suggests that the lack of a correlation found with Mamolo et al. (2006) was due to the small sample sizes (22 right-handers and 15 left-handers) used in that experiment. Another possible explanation is that the use of different tasks in the experiments may have lead to the different findings. The Mamolo et al. (2006) experiment included a use task (in which participants actually had to use the tool on its associated object), which was not included in the present experiment. The significant correlation between the Waterloo Handedness Questionnaire and the frequency of preferred hand reaches for left- and right-handed participants provides support for the idea that the degree of hand preference, as assessed by the Waterloo Handedness Questionnaire, was reflected by the actual behaviour of participants. This provides justification for the use of the Waterloo Handedness Questionnaire as a simple and quick method to approximate hand preference in situations where direct observation with a performance measure of hand preference is impractical.

The relationship between strength of hand preference and reaching behaviour was further examined through the use of the cross-over point, a measure of the position in hemispace at which participants made less than 50% of reaches with their preferred hand. For both left- and right-handed participants, the correlation between the Waterloo Handedness Questionnaire score and the cross-over point was significant. This indicated that participants with a stronger preference for their preferred hand (as measured by the Waterloo Handedness Questionnaire) persisted in reaching farther into contralateral space with their preferred hand to perform the tasks. This was similar to the finding of Stins, Kadar, and Costall (2001), who also found a relationship between the strength of hand preference and the position in hemispace at which participants started using their non-preferred hand to lift a glass. The relationship was stronger for right-handers than for left-handers in this experiment and in the Stins et al. (2001) study. Stins et al. (2001) suggest that this may be due to the less consistent patterns of hand preference that tend to be exhibited by left-handed participants.

During my masters research (Mamolo et al., 2006) participants were asked to react as quickly and naturally as possible. Switching behaviour was an unexpected response by some of the participants to the trial demands that was observed by the experimenter. Although the occurrence of switches was noted during this experiment, it was not directly studied. Therefore the second goal of Experiment 1 was to explicitly examine switching behaviour by quantifing and examining in detail the frequency of switches. Switching occurred when the participant picked up the object in one hand (usually the non-preferred hand) and transferred it to their preferred hand to use it. Switching was of interest because it represented a strategy to deal with the location and task demands of a trial. The PUO task was added to this experiment in order to explicitly examine this behaviour. The frequency of switches was measured by the difference between the PUO and Use tasks.

It was possible that the degree of hand preference, as determined by the Waterloo Handedness Questionnaire, was related to the frequency of switches. However, this was not found to be the case. For both left- and right-handed participants, the correlation between the Waterloo Handedness Questionnaire and the frequency of switches as well as the switch ratio (the frequency of preferred hand reaches divided by the total frequency of preferred hand use) were found to be non-significant for both left- and right-handers. However, when the frequency of switches was correlated with the cross-over point, the relationship was found to be significant, for right-handed participants only. For right-handers then, participants who performed a low frequency of switches (i.e. rarely picked up the object with their left hand to transfer it to the right hand to use, instead preferring to pick up the object and use it with their preferred hand), would also be more likely to not have a cross-over point (i.e. the participant made over 50% of reaches with their preferred hand for all positions in hemispace) or to have a cross-over point farther into contralateral space. Participants who made a high frequency of switches, and therefore used their non-preferred hand to lift up the object, were more likely to have a cross-over point closer to the midline. Although left-handers tended to make more switches than did right-handers, the correlation between switches and cross-over point was not significant for left-handed participants. This may mean that left-handers were more variable in their reaching patterns than were right-handers.

The third goal of this experiment was to examine the effect of reaching to different objects. The use of the dowel provided interesting insight into object use and the preferred hand. First, there was an increased frequency of preferred hand use for the tool than the dowel for both handedness groups. This highlights the association between tools and the preferred hand. This finding also supports the idea of affordances, which posits that there is a learned association between tool use and the preferred hand, in that the particular features of a tool serve to limit the range of possible actions that can be performed with it by a particular organism (Gibson, 1979). A tool affords certain actions and therefore enables stronger use of the preferred hand. Because tools are predominantly used by the preferred hand it was hypothesized that there would be more preferred hand reaches to the tools than the dowels, which lack such affordances. This hypothesis was indeed supported by the results, for both handedness groups. Further evidence for this association can be found by the close examination of ancient tools used by *H. habilus* and *H.*

erectus (for example, markings on artifacts indicate that the base object was held in the left hand and struck by an object held in the right hand), which indicated that early in human evolutionary history there was evidence of a link between the use of one hand (the preferred hand) and tool use (Bradshaw & Rogers, 1996). Second, the task by position interaction was similar for both objects, with the frequency of preferred hand reaches increasing from the Lift to PUO to Use tasks in contralateral space. This suggests that in the PUO and Use tasks (in which the participants were asked to treat the dowel as a tool), participants did respond to the change in intention by performing more preferred hand reaches to the dowel for the PUO and Use tasks compared to the Lift task. If the intent to use the dowel as a tool had had no effect on the reaching patterns of participants, then there should have been no difference in the frequency of preferred hand reaches to the dowel for the Lift, PUO, and Use tasks. The difference in the frequency of preferred hand reaches to the dowel for the tasks speaks to the effect of the action intention or goal on the planning of the reaching movement. This finding lends support to the work of Tucker and Ellis (2004), who posited that an object did not need to be visible in order to generate affordance compatibility effects, instead it was the object-action association that appeared to be critical. In this case, the intent to use the dowel as a tool in the PUO and Use tasks was sufficient to generate the particular tool representation, and this was reflected in the behaviour of the participants who performed an increased frequency of preferred hand reaches for those tasks.

The intent to use an object in some way led to increased preferred hand use (as reflected by the increased frequency of preferred hand reaches for the PUO and Use tasks compared to the Lift tasks), regardless of whether the object was a tool or a dowel. Therefore there was a similar effect of intent on both objects. But there was still the over-riding difference in favour of the tool in terms of preferred hand reaches (indicated by an even higher frequency of preferred hand reaches to the tool for the PUO and Use tasks), indicating the strength of the affordances between tools and preferred hand use. These findings also suggest that affordances were affected by the intent of the action, since fewer preferred hand reaches were made for the Lift task than the PUO and Use tasks with the dowel. Some support for this idea comes from a recent study that examined the grip postures for different actions in patients with left brain damage, patients with right brain damage, and healthy controls (Osiurak, Aubin, Allain, Jarry, Etcharry-Bouyx, Richard, & Le Gall, 2008). Participants had to perform two actions: grasp-to-transport (moving a dowel to different locations) and grasp-to-use (use a familiar object, such as a hammer). The position or grasp of the hand was examined for each condition. Rosenbaum's end-state comfort hypothesis (1990) was used as a basis to define the grasps, such that an appropriate grasp was one where the participant grasped the object in such a way as to afford a comfortable final position, rather than a comfortable initial position (an inappropriate grasp). The results showed that while several patients with brain damage made inappropriate grasps for the grasp-to-transport condition, only two patients made inappropriate grasps in the grasp-to-use condition. The authors posit that the dissociation between the grasp-to-transport versus grasp-to-use actions lends support to the different constraint hypothesis, that is, that different constraints exist when the intent is to use a object versus when the intent is to merely move it. This finding suggests that the hand-object interaction involved with tool use may be distinguished from other hand-object interactions such as object transport (Osiurak et al., 2008). Overall, the intent of the action (i.e. to pick up and use the object versus lifting the object) affected both tools and dowels, however the tool exhibited an advantage in terms of an overall increased frequency of preferred hand reaches compared to the dowel, reflecting the privileged association between the preferred hand and tool use.

Third, left- and right-handers differed in the extent of their willingness to treat the dowel as a tool. For both handedness groups the frequency of preferred hand use was greater for the tool than for the dowel at the positions in contralateral space. For the right-handed participants, at the Midline position the frequency of preferred hand reaches for the dowel increased to the level seen with the tool for all three tasks. This indicated that right-handed participants were treating the dowel as if it were a tool (in terms of the frequency of preferred hand reaches) at this position. Thus for right-handers there was no difference between the tool and the dowel at the Midline position. This may reflect an overall tendency for greater preferred hand use among right-handed participants. For left-handed participants, there was a higher frequency of preferred hand use for the tool than for the dowel at both the contralateral positions and at the midline position. This indicated that for left-handed participants, there was no point at which the dowel was treated as a tool in term of the frequency of preferred hand reaches. This finding also showed that left-handed participants were more willing to use their non-preferred hand to reach for and interact with the dowel. This finding lends support to the Right-Sided World hypothesis (Porac & Coren, 1981). The Right-Sided World hypothesis posits that left-handers, due to the fact that many of the manufactured objects in the environment were designed for right-handers, have had greater experience over their lifetime with using their non-preferred hand than have right-handers simply due to these environmental pressures. This greater experience with using the non-preferred hand may have been reflected by the willingness of left-handers to use their non-preferred hand more frequently to reach for and interact with the dowel. This observation was confirmed by the analysis that directly compared the handedness groups.

This difference between the handedness groups when interacting with the dowel was one of the few statistically significant differences found in the analysis directly comparing left- and right-handed participants. Another difference between the handedness groups became apparent by examining the task by position effect for each group. For both left- and right-handers, all three tasks were significantly different from one another at both contralateral positions. It was at the midline position that differences between the handedness groups emerged. For right-handers, only the Lift and Use tasks were significantly different from each other. The PUO task did not differ from either the Lift or Use tasks, and was in-between the Lift and Use tasks in terms of the frequency of preferred hand reaches. In contrast, for left-handers significantly fewer preferred hand reaches were made for the Lift task than for the PUO and Use tasks, which did not differ. Thus at the midline position, left-handers showed a clearer separation between the PUO task and the Lift task than did right-handers. When the intent was to simply lift the object, left-handers were more likely to use their non-preferred hand at the midline position than when the intent was to pick up the object and use it. Left-handers had a larger range within working space in which they used their non-preferred hand compared to right-handers.

Overall, one of the most striking results from the analysis directly comparing the handedness groups was that there were very few differences between the groups in terms of their patterns of hand use within working space. This was similar to the findings of Mamolo et al. (2006), who also found similar reaching patterns with the handedness groups. The similarity between the groups was highlighted by the fact that the main effect of group was not significant, indicating that there was no difference between the handedness groups in terms of the overall frequency of preferred hand use. In other words, right-handed participants were not more likely to use their preferred hand than were left-handed participants. This was in contrast to previous research that showed a higher frequency of preferred hand use for right-handed participants within contralateral space compared to left-handed participants (e.g. Gabbard, Iteya, & Rabb, 1997).

Although not part of the direct analysis comparing the handedness groups, an examination of the frequency of switching behaviour also revealed differences between the handedness groups. For right-handed participants the mean number of switches performed was 3.0, whereas for left-handed participants the mean number of switches performed was 5.0. This indication that on average left-handed participants performed more switches was corroborated by the number of participants in each handedness group who did not perform any switches during the experiment: 32.9% of right-hander compared to only 1.3% of left-handers. These participants always performed the PUO task and the Use task with the same hand. Therefore, right-handed participants were much more likely to use their preferred hand to perform both the simple lift component (PUO) and Use component of a reaching movement. In contrast, left-handed participants were more likely to use their non-preferred hand to perform the simple PUO component, and then switch the object to their preferred hand to actually use it. This finding based on switching behaviour further supported the idea that left-handed participants were more likely to use their non-preferred hand than were right-handed participants in certain situations, especially to perform simpler, unskilled tasks (Gabbard, Iteya, & Rabb, 1997; Calvert & Bishop, 1998; Steenhuis & M. P. Bryden, 1999). Alternately, left-handed participants may have been less willing to reach across the body midline to use their preferred hand in contralateral space. Some support for this idea comes from Experiment 2 in Mamolo et al. (2006), which had participants rate the comfort of reaching movements to tools. For the position in far contralateral space, right-handers rated it more comfortable to reach across their body to use their preferred hand, whereas left-handers rated it more comfortable to use their non-preferred hand. In any case, the switching behaviour may have revealed a difference in the way the handedness groups deal with the biomechanical challenge of reaching across the body midline for objects within contralateral space.

2.6 Conclusions

The results of Experiment 1 replicate and extend the findings from my previous performance-based measure of hand preference experiment (Mamolo, Roy, Rohr, & P.J. Bryden, 2006) by describing the reaching patterns of left- and right-handed participants to objects within working space. The frequency of preferred hand reaches was affected by both the skill demands of the task as well as the position of the object in working space. In contralateral space preferred hand reaches increased with the skill demands of the task (from Lift to PUO to Use). Furthermore, the degree of handedness was correlated with the frequency of preferred hand reaches for both handedness groups: the stronger the degree of preference, the greater the number of preferred hand reaches made by the participant.

The PUO task was incorporated to examine instances when participants would pick up the object with the non-preferred hand and then transfer the object to the preferred hand in order to use it (switches). Analysis of the difference between the Use and PUO tasks reflecting the frequency of switches was not correlated with the degree of hand preference. However, left-handers performed on average more switches than did right-handers. As well, almost one third of right-handers did not perform any switches at all, whereas this was rarely the case with left-handers. These findings lend support to the idea that left-handers were more willing to use their non-preferred hand to perform simpler, less skilled tasks, or that left-handers may have been less willing to reach across the body midline to use their preferred hand than were right-handers.

The PUO task also highlighted another aspect of hand use in that the frequency of preferred hand reaches significantly increased from the Lift to PUO task, for both handedness groups. This is of interest because both reaching movements (Lift and PUO) were the same; the tasks only differed in the goal of the movement. The difference in the frequency of preferred hand reaches between the lift movements highlights how the final goal of the reaching movement affects its initial planning through choice of hand. This finding lends further support to the end-point comfort hypothesis (Rosenbaum et al., 1990), as well as other research on the relationship between the goal of the movement and action planning.

Incorporating the dowel provided additional insight into the relationship between tool use and the preferred hand. First, both left- and right-handed participants made significantly more preferred hand reaches to the tool than the dowel, suggesting the presence of a stronger relationship between the tool and the preferred hand, than with the dowel. However, in spite of the neutrality of the dowel, there were instances when the dowel was treated as if it were a tool. This occurred with right-handed participants at the midline position: here the frequency of preferred hand reaches increased for the dowel to the level seen with the tool. In other words, right-handers were treating the dowel as if it were a tool for all three tasks at the midline position.

Comparing the handedness groups highlighted that in general, the reaching patterns of left- and right-handed participants were largely similar. One of the few differences between the groups concerned the treatment of the dowel in that right-handers made significantly more preferred hand reaches to the dowel but the handedness groups did not differ in reaches to the tool. Since the interaction of group by task by object was not significant, both handedness groups were able to use the dowel as a tool (as reflected by the increased frequency of preferred hand reaches as the task demands increased). But the tendency for right-handers to show a higher frequency of preferred hand use for the dowel than did left-handers may be a reflection of greater preferred hand use by right-handers when the association between the hand and tool is removed. This may reflect the task-specific nature of hand preference.

In conclusion, Experiment 1 used a performance-based measure of hand preference to examine manual asymmetries for reaching movements to tools and dowels in response to varying task demands. These findings highlighted more similarities than differences between the handedness groups. The results also showed that using tools to increase the task demands was an acceptable method of eliciting differences in hand preference. In Experiments 2 and 3, the focus will shift from the effect of task demands on a preference measure of handedness to the use of performance measures to elicit manual asymmetries.

Chapter 3: Introduction to Goal-Directed Movements

In Experiment 1, a performance-based measure of hand preference was used to explore the effects of task demands on manual asymmetries. The frequency of preferred hand reaches in response to task demands was the variable of interest. In Experiments 2 and 3, the effect of task demands on manual asymmetries was explored using measures of performance. The second experiment explored whether manual asymmetries were apparent in other measures of hand performance, namely movement initiation (reaction time) and execution (movement time). In Experiments 2 and 3 the focus shifts from the frequency of preferred hand use to a performance-based measure that reflects the time required to initiate and execute reaching movements. In order to look at these measures the experimental paradigm shifted from one of free choice as to which hand to use (as in Experiment 1) to a forced choice paradigm wherein the participant was forced to use one hand or the other based on precues provided by the experimental program. The question of interest in this experiment was whether the increased frequency of preferred hand use for reaching in the free-choice paradigm would be reflected in the initiation and execution of reaching movements in a forced-choice paradigm? It was possible that in a forced-choice situation when the performer must initiate the reaching movement with one hand or the other, that this tendency to use the preferred hand more frequently may translate into a shorter time to initiate the movement with this hand. Furthermore, just as the tendency to use the preferred hand in the free-choice reaching paradigm increased with task complexity, so the preferred hand advantage for movement initiation may increase with task complexity in this forced-choice paradigm.

The methodology used in Experiment 1 provided information on the preferences for choice of hand in a variety of situations; however no information was available regarding the planning of these movements or the way in which these movements were controlled. Motor variables such as reaction time and movement time can be used to provide such information. The aim of Experiments 2 and 3 was to investigate more closely the planning and control of reaching movements, using the time to initiate movements (reaction time) as a measure of movement planning prior to movement initiation and movement time as a measure of on-line movement planning and movement control. In all three experiments, manual asymmetries in response to manipulations of task demands for reaching movements to tools were of interest.

Experiment 2 was a computer-based experiment in which participants reached for and performed different tasks with tools using reaction time and movement time on each trial as measures of performance. Such trials usually begin with the presentation of a warning signal. After a variable foreperiod a go signal is presented. Reaction time is the time from the presentation of the go signal to the lift of the finger from its sensor. Movement time is the time from the lift of the finger to lifting the tool off its sensor. For these experiments, movement time comprises the time it takes to reach to and lift the tool from its sensor. It does not include the time that is spent interacting with the tool to complete the movement.

The warning signal serves to alert the participant. For previously learned movements, during the variable foreperiod the motor program is retrieved from long-term memory and held in temporary memory storage until the go signal (Christina, 1992). The motor program is the cognitive representation of the entire movement response. Reaction time is believed to be comprised of several steps. The first step is the detection of the go signal. A decision is then made whether to respond to the signal. The motor program is retrieved from temporary storage, and is read out in the appropriate supraspinal motor centers where it is converted into efferent commands. The relevant parts of the motor system are readied and the efferent commands for the initial part of the motor response are sent to the appropriate motor units. The muscle needed to initiate the response contracts. Reaction time can therefore be thought of as involving two components – the premotor and motor time. Motor time involves the contraction of the muscle needed to initiate the movement. It therefore reflects the earliest portion of the movement execution. Motor time starts at the first sign of heightened electromyographic (EMG) activity in the responding muscle. Premotor time comprised all the steps from the presentation of the go signal to the muscle contraction. It reflects the time needed to detect the go signal, decide to respond, and program and prepare the movement response (Christina, 1992). For the purposes of Experiments 2 and 3, it is the entire reaction time period (both the premotor and motor components) that will be discussed.

The methodology used in this experiment is rooted not only in these measures reflecting the preparation and control of movement but also in experiments studying visually-guided aiming movements (please refer to Section 3.1 for a review, including Woodworth, 1899; Roy, Kalbfleisch & Silcher, 1999). In such experiments, the participant is required to point to a target, and various kinematic measures (including reaction time and movement time) are recorded. Although Experiments 2 and 3 involved grasping a target object as opposed to pointing to a target, there are many findings from the visually-guided aiming movement literature that are of relevance to which we now turn.

3.1 A Review of Visually-Guided Aiming Movements

3.1.1 The Right Hand Advantage

One area of research that has received a considerable amount of study is the role of vision in aiming movements. In 1899 Woodworth proposed a two-component model for the control of visually guided upper limb movements. First, a quick, ballistic movement brings the hand into the approximate range of the target. This is followed by a second, visually guided movement that brings the hand to the exact location of the target (Woodworth, 1899). In Woodworth's landmark study, participants were required to make horizontal sliding movements with a pencil over a piece of paper attached to a large drum that rotated at a constant speed. Speed was manipulated by having participants perform to the beat of a metronome. The participants' task was to attempt to reproduce their prior movements with the same spatial endpoint. Error was determined as the difference in the endpoints of consecutive lines. Furthermore, vision was also manipulated: on some trials participants had to close their eyes, and on other trials participants had full view of their arm and the drum. The most striking result of this experiment was the superior performance of the right hand in both the presence and absence of vision. The only condition in which the left hand achieved comparable accuracy to the right hand was with vision and at a very slow speed. Furthermore, this right hand advantage increased in magnitude as the speed increased. Thus there was an advantage for the right hand in both the accuracy and speed of movements. Since Woodworth's initial experiments, the right hand advantage seen in visual-aiming accuracy and movement speed has been replicated in many experiments, as will be shown in the following experiments.

These findings led Woodworth to propose possible reasons for the observed right hand advantage for movement time. First, he concluded that the superior performance of the right hand was due to the presence of the motor centers (regions of the brain that controlled movements) in the left hemisphere of the brain. Second, since even in the absence of vision the performance of the right hand was superior to the left, he concluded that it was possible that the right side is more sensitive to kinesthetic feedback (Woodworth, 1899). Since Woodworth first proposed these theories, the exact nature of manual asymmetries and the role of vision in aiming movements have been extensively studied.

In general, studies of visually guided aiming movements have revealed a left hand advantage for the initiation of movements (represented by reaction time, to be discussed in Section 3.1.2) and a right hand advantage for the execution of movements (represented by movement time). As well, movements made to targets in ipsilateral hemispace tend to be faster than movements to targets in contralateral space. A set of experiments by Roy, Kalbfleisch, and Silcher (1999) highlights these general findings.

In the first experiment, right-handed participants used a graphics tablet to move a cursor to a target. The target location was either along the midline or 33º to the right or left of the midline. Participants made aiming movements with the left and right hands to each target location in a blocked presentation style. The findings showed that in terms of peak velocity, movements to the left target were made faster with the left hand, whereas movements to the right target were made faster with the right hand. No differences between the hands were seen for the target at the midline. Thus movements made to ipsilateral space were faster than movements made to contralateral space, for both the left and right hands. Similar results have been found in other experiments (such as Elliott & Chua, 1996). In the second experiment, a blocked presentation condition was compared to a random presentation condition. Only right hand movements were examined, since the effects of hemispace were similar for each hand in the first experiment. The results showed that reaction time was shorter for the blocked presentation condition than the random condition, however this did not interact with the target location.

Therefore the advantage for ipsilateral space was independent of advance knowledge of the target position. The ipsilateral hemispace advantage is thought to arise from the fact that both visual feedback processing and the control of hand movement are controlled within the same hemisphere. The ipsilateral hemispace advantage highlights a manual asymmetry that is driven by target location, and not due to underlying differences in motor performance between the hands. In contrast, a right hand advantage for movement execution was also seen in these experiments, reflected by the decreased time spent in movement deceleration for the right hand. This manual asymmetry was not spatially sensitive and may reflect a left hemisphere/right hand advantage for processing feedback. This hypothesis is discussed in the next section.

3.1.1.1 The Visual Feedback Processing Hypothesis

One theory that attempts to explain these results is the feedback processing theory. The preferred (usually the right) hand is thought to be associated with neural substrates that use sensory information, mainly visual, to make “on-line” changes in the movement trajectory more efficiently than the non-preferred (usually the left) hand. In 1975, Flowers hypothesized that a “corrective mode of control” existed during aiming movements, and that differences in implementing this lead to manual asymmetries. This was based on a manual-aiming task he conducted with strongly lateralized left- and right-handed participants (Flowers, 1975). In this experiment, Flowers noted that these strongly lateralized participants performed better with their preferred hand. Similar to Woodworth’s findings, Flowers also found that the preferred hand advantage increased as the accuracy demands of the aiming task increased. Thus Flowers concluded that the advantage seen with the preferred hand stems from an advantage in visual feedback and motor control for the dominant hemisphere. Since most people are right handed, it is thus believed that the left hemisphere/right hand system is more efficient at processing visual feedback from the ongoing movement (Carson, 1992).

One experiment conducted by Roy, Kalbfleisch, and Elliott (1994) examined manual asymmetries and the visual feedback hypothesis. In this experiment, right-handed participants pointed to targets in conditions either with or without vision. They were also given instructions to move either as fast as possible or as accurately as possible. Several hypotheses were made. First, that the differences between the hands would be greater in the condition emphasizing accuracy over speed, since there would be more time to analyze visual feedback in this condition. Also, if manual asymmetries were dependent on the efficient processing of visual information, then the differences between the hands should disappear on trials when visual information is removed while the hand is moving to the target. Finally, the kinematic measure, time after peak velocity, (which reflects deceleration), has been found to be sensitive to visual feedback processing. Thus it was expected that the right hand would spend less time in deceleration if the left hemisphere/right hand system was indeed more efficient at processing visual information.

The results of this experiment showed the usual right hand advantage for both movement time and accuracy. Differences between the hands were also observed in the deceleration times, with the left hand requiring more time for deceleration than the right hand. This advantage for the right hand was also greater in the accuracy conditions. However, the hypothesis regarding the effects of vision was not supported: the right hand advantage occurred whether or not vision was available. These results therefore do not support the visual feedback processing hypothesis. However, the superior performance of the right hand in the presence and absence of vision did confirm the early findings of Woodworth (1899). Although the visual feedback processing hypothesis was not supported, the right hand advantage might be due to more efficient processing of feedback information in general.

To test this theory, an experiment by Buekers and Helsen (2000) manipulated the amount of vision available during both single and reciprocal aiming movements. Single aiming movements involved an arm movement by the participant to the target. A reciprocal aiming movement required an arm movement aiming to the target and then moving back to the starting point. All twenty participants were classified as strongly right-handed based on a questionnaire of hand preference. If the left hemisphere/right hand system was indeed better at processing visual information, then it should not have been as affected when the amount of vision available during the movement was reduced. Thus the degree of manual asymmetries should increase with longer visual occlusion times. The results showed the expected right hand advantage for movement time; however, the right hand advantage did not interact with the visual conditions. Therefore the manual asymmetries in terms of a right hand advantage for movement time did not increase with longer visual occlusion times as predicted. Both hands showed similar patterns of performance across the different visual conditions, indicating that both hands were equally affected by the different visual conditions. Thus the left hand did not suffer a greater decrease in performance than the right hand from the loss of vision. The results of this experiment therefore failed to support the hypothesis that the left hemisphere/right hand system was more efficient at processing visual feedback. However this finding did support the general right hand advantage for feedback processing regardless of the presence or absence of vision observed by Roy, Kalbfleisch and Elliot (1994) and Woodworth (1899). These results also highlighted the general importance of vision in the control of aiming movements: as the amount of vision available during the movement decreased, both the initiation time and movement time increased.

Another experiment examined the relationship between eye movements and aiming movements in right-handed participants (Helsen, Starkes, Elliott, & Buekers, 1998). It has been suggested that the right hand advantage may reflect an attentional bias of the left hemisphere which results in greater monitoring of the right hand. Thus, eye-hand coordination was examined to determine if there was indeed preferential visual monitoring of one hand over the other. Participants performed both simple and reciprocal aiming movements. At the same time the eye movements of the participants were recorded. For the simple aiming movements, it was found that the primary saccadic eye movement started 70 milliseconds prior to the initiation of the aiming movement. Eye gaze always arrived at the target before the hand, and this usually occurred when approximately 50% of the total movement time had elapsed. This timing pattern for eye-hand coordination did not vary. Although the movements were completed more quickly with the right hand, there was no difference in the pattern of eye-hand coordination between the hands. For both the right and left hands, the initial saccade usually undershot the target slightly (for 63% of the trials with the right hand and for 69% of the trials with the left hand). In the majority of cases, participants were able to take advantage of visual information to produce a second, smaller, corrective saccade which brought the fovea exactly onto the target. Although the eye-hand coordination pattern was identical between the hands, movements were still made more rapidly when participants used their right hand. This absence of manual asymmetries in eye-hand coordination therefore does not support the attentional bias and visual feedback explanations for the right hand advantage.

For the reciprocal aiming movement, a similar temporal pattern of coordination between eye gaze and hand movement was found. However, it was only during this more complex movement that differences between the hands became apparent. With the left hand, participants made larger initial saccades and they also made more corrective saccades. Saccadic eye movements were therefore not as precise when aiming with the left hand. One possibility was that the right hemisphere/left hand system received less precise ocular motor information, and this leads to its disadvantage in performing saccadic movements.

The results of this experiment also highlighted the efficiency of the eye-hand coordination system. With the initial saccade, the eyes moved to the target while the hand was in the ballistic phase of the aiming movement. Since the eyes always arrived at the target ahead of the hand, this strategy allowed for time to process the visual information and adjust the position of the hand relative to the target if necessary. These results supported Woodworth's two component model of limb control (1899), and emphasized the importance of vision in the production of efficient and accurate aiming movements.

Overall, the results of these representative experiments emphasized several important findings regarding vision and manual asymmetries. One perhaps obvious but nevertheless important result was the essential role vision plays in aiming movements. In trials where vision was occluded, the accuracy and speed of the movements declined. The importance of vision was also exemplified by the highly efficient temporal coordination of eye and hand movements. Finally, the results showed a lack of support for the visual feedback hypothesis. However, there was still the possibility that the left hemisphere/right hand system was more adept at processing feedback information in general (including perhaps proprioceptive information) than the right hemispehere/left hand system.

3.1.1.2 The Motor Variability Hypothesis

The previous experiments gave evidence disproving the visual feedback hypothesis as an explanation for the right hand advantage for movement time. Another possible explanation given for the right hand advantage was related to the motor impulse variability hypothesis which describes the production of rapid aiming movements (Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979). According to this hypothesis, variability in the initial motor impulse that produced the aiming movement leads to variability in the endpoint of the movement. Endpoint variability was directly proportional to the initial impulse variability. Impulse variability was dependent on the absolute value of the motor impulse that must be specified to move a particular distance within a particular amount of time. Aiming movements that required larger initial impulses (such as rapid movements) would therefore be less spatially consistent due to the larger forces required to move the limb. Right-handed individuals typically perform aiming movements more rapidly and accurately with their right hand. One hypothesis was that the left hemisphere/right hand system is less variable in the production of the initial motor impulse. As the amount of force increases, the differences between the hands should increase if the left hand truly was more variable at producing forces.

An experiment by Binsted, Cullen, and Elliott (1998) was performed to test this theory. Right-handed male participants had to produce target forces ranging from 20 to 100 N through a flexion of the wrist. The accuracy and variability of the force produced was monitored for both hands. The results showed that there was no difference between the hands in either the average force produced or the variability of the force production. Contrary to the predictions of the motor output hypothesis, there was even a trend towards the left hand being more consistent in its force production than the right hand. Thus manual asymmetries do not appear to result from more variable force production in the left hand. However, the right hand advantage might stem from better timing of the onset and offset of the muscular forces.

To test this idea, a second experiment was conducted in which participants were required to produce target force peaks of 20, 30, or 40 N in time with a visual metronome (Binsted et al., 1998). The visual signal was removed 10 seconds into the trial, while participants were required to continue generating the force for another 10 seconds. This was done to determine how well participants could internalize the timing pattern. The most striking result of this experiment was the lack of any effects involving the hands. Both hands were equally consistent and accurate in the production of the forces. Also, there was no difference between the hands in the precision and consistency in the timing of the forces. Thus the results provided no support for the idea that manual asymmetries were caused by differences between the hands in the timing of their motor output.

This was not the only experiment to disprove the motor variability hypothesis. Elliott, Heath, Binsted, Ricker, Roy and Chua (1999) tested another aspect of the motor variability hypothesis. Meyer, Abrams, Kornblum, Wright, and Smith (1988) proposed the optimized submovement model to describe movement trajectories and endpoints. Similar to Woodworth's model, the optimized submovement model proposed that there is a primary, preprogrammed movement. Meyer et al., (1988) argued that random neuromuscular noise during the movement would result in a normal distribution of the aiming endpoints around the target. This noise should increase in proportion to the amount of force required for the movement. If the movement falls outside the target boundaries, a small corrective submovement would be made to bring the hand to the target region. This corrective submovement was also preprogrammed, and was based on visual or kinesthetic feedback.

In the Elliott et al., (1999) experiment conducted to test the optimized submovement model, participants were required to make aiming movements with a metal stylus. In this experiment an electromagnetic plate situated at the movement home position was used to manipulate the force required to initiate the aiming movement. During control conditions, a force of 25 N was required to lift the stylus from the home position. On other trials, the magnetic attraction was unexpectedly raised or lowered, requiring forces of either 40 N or 0 N, respectively, to lift the stylus. It was expected that on the trials with added resistance, the participants' initial movement would undershoot the target, while on the trials with no resistance the initial movement would overshoot the target. The authors believed that participants would be able to successfully adjust their final movements in the perturbed conditions to arrive at the target. However, according to the motor output hypothesis, the right hand should be less variable at making these corrections than the left hand.

The results of this experiment contradicted the Meyer et al., (1988) prediction regarding the distribution of the primary submovement endpoints. Instead of a normal distribution around the target, participants tended to undershoot the target. This occurred even on trials when it had been predicted that participants would overshoot the target (when the initial resistance was unexpectedly lowered). Instead, the typical movement pattern showed an initial undershooting of the target, followed by a second acceleration to reach the target. This movement strategy was in agreement with the idea that it was easier and more efficient to extend a movement with a second muscle agonist burst, than it was to overshoot a target and have to reverse the direction of the movement. Although the right hand did show a movement time advantage, there was no hand by force interaction. Participants made faster aiming movements with the right hand and the variability of the endpoints around the target was decreased when aiming with the right hand than with the left hand regardless of the force required to initiate the movement. Thus these findings did not support the motor output hypothesis regarding manual asymmetries, which predicted that the left hand would show more variability for movements requiring greater force.

Elliott et al., (1999) also conducted a second experiment manipulating the effects of vision. The same procedure was used as in the first study, except that on some trials vision was eliminated at the start of the movement through the use of liquid-crystal goggles. The results showed that when vision was removed, the accuracy of the movements was decreased and the variability of the ending positions around the target increased. Although the presence or absence of vision had no effect on the overall movement time, the movement trajectories were quite different for each condition. With vision, movements had a higher peak velocity that was reached earlier in the movement. This resulted in a greater proportion of time spent in the deceleration phase, when the hand was closest to the target. This allowed for the visual guidance of any necessary corrective submovements. Similar to the first experiment, the primary movement almost always undershot the target, followed by a small correction to reach the target. Interestingly this finding is similar to the description of ballistic movements proposed by Woodworth (1899) over one hundred years ago: that when vision is available individuals make a fast ballistic movement that brings the hand close to the target.

Regarding manual asymmetries, in the second experiment a right hand advantage was seen for movement time in both the presence and absence of vision, and regardless of the force required to initiate the movement. The right hand reached higher peak velocities and spent less time in the deceleration phase than the left hand. Also, the left hand had to make more discrete corrections to achieve the same level of consistency and accuracy in reaching the target endpoints as the right hand. The lack of a hand by vision interaction suggested that manual asymmetries were not the result of differences in visual feedback processing. The lack of a hand by force interaction also suggested that manual asymmetries were not due to differences in impulse variability between the hands. The right hand advantage might result from a more general proficiency at using feedback or at specifying any movement corrections. This was supported by the kinematic data, which indicated that the right hand movements were more proficient close to the target and at making corrective submovements than the left hand.

The results of these experiments indicated that both the visual feedback hypothesis and the motor variability hypothesis could not fully explain the right hand advantage for movement time. The greater efficiency of the right hand at producing corrective submovements suggests that the right hand advantage might arise from the greater proficiency of the left hemisphere/right hand system at processing general feedback information during aiming movements.

3.1.2 The Left Hand Advantage

3.1.2.1 Spatial Mapping

Woodworth's early manual aiming experiments highlighted a right hand advantage for movement speed and accuracy (Woodworth, 1899), and this review has described several experiments supporting those results. However, although the left hemisphere/right hand is dominant for many aspects of motor control in right-handed participants, there are areas in which the right hemisphere/left hand system is believed to specialize. One example was the consistent finding in the movement literature for a left hand advantage for the initiation of aiming movements (e.g. Goodman & Kelso, 1980; Haaland & Harrington, 1989; Carson, Chua, Elliot, & Goodman, 1990; Carson, Goodman, Chua, & Elliott, 1993).

One experiment that highlighted the left hand advantage for movement initiation was designed to investigate the role of vision in manual aiming movements (Carson et al., 1990). An aiming task was performed under four visual conditions: (1) full vision of the hand and target throughout the movement; (2) ambient illumination off (room lights turned off upon movement initiation, thus the limb was not visible); (3) target-off (target extinguished upon movement initiation); and (4) no vision (room lights and target extinguished upon movement initiation). Although the presence or absence of vision had a noticeable effect on movement accuracy, reaction time, and movement time, the extent of this effect did not differ between the hands. Furthermore, a left hand advantage for reaction time was observed throughout the various visual conditions.

Two theories were proposed to explain the left hand advantage for reaction time. The movement planning theory proposed that the right hemisphere was involved in early planning of the movement, such as determining the spatial position of the target relative to the body and the environmental context. Thus manual asymmetries should be seen when movement to a particular spatial target was involved. The left hand advantage for reaction time should also be more pronounced in conditions with greater uncertainty, such as when less information was provided by a cue in advance of the movement. In such cases, greater spatial planning would be required during the reaction time interval. The attentional theory stated that the right hemisphere was more involved in the direction of attention for both intrapersonal and extrapersonal space. Attentional mechanisms must be directed to a target before the movement can be initiated. Since the right hemisphere was involved in directing attentional resources, the left hand should have earlier access to this information than the right hand, resulting in a left hand advantage for reaction time.

An experiment by Mieschke, Elliott, Helsen, Carson, and Coull (2001) was conducted in an attempt to distinguish between the movement planning theory and the attentional theory. The experiment examined the relationship between reaction time and the amount of advance information about the target available to participants. One group of participants made aiming movements with the left or right hand to one of four targets that were either uncued, precued with respect to direction (left or right), precued with respect to amplitude (near or far), or precued for both direction and amplitude (a simple reaction time task). A second group of participants received the same precue information, but instead of making aiming movements, performed a simple finger lift. For this group, there was the same uncertainty regarding spatial information, however, no movement planning was required. On alternating blocks of trials these movements were performed with the right and left hands. The attentional hypothesis predicted that a left hand reaction time advantage should be seen for both groups of participants. In contrast, the movement planning hypothesis predicted that the left hand advantage for reaction time should occur only when movement to a particular spatial target was required. Therefore a left hand advantage for reaction time should be seen for the movement group but not the finger lift group.

The results of this experiment largely supported the movement planning hypothesis. When targets were to the left of the midline, the movement group showed a left hand advantage for reaction time, while the participants who were only required to make a finger lift showed either a right hand advantage or no difference between the hands for reaction time. In contrast, for targets to the right of the midline, both groups of participants showed no difference between the hands. Also, for the group that only had to make a finger lift, reaction times were faster with the right hand. Thus it was only for trials where goal-directed movements were required that the left hand advantage for reaction times was seen. According to the attentional hypothesis, the left hand should have faster reaction times regardless of whether a movement was required or not, since attentional resources would need to be directed to the target regardless of the movement to be performed. Thus these results provided support for the movement planning hypothesis (Mieschke et al., 2001).

In addition, there was an overall effect of group on reaction time, with participants in the finger lift group responding more quickly than the participants in the movement group. This suggested that the complexity of the task to be performed (a simple finger lift versus movement to a target) had an effect on movement planning and initiation (Mieschke et al., 2001).

The results of this experiment also highlighted the effect of the type of precue information on reaction time. First, there was a reliable increase in reaction time as the degree of uncertainty about the movement increased. However, the reaction times for the precue amplitude condition were similar to those for the uncued condition (no advance information). This suggests that knowing the amplitude of the movement in advance was not of much use unless the direction of the movement was also known in advance. Overall, these findings suggested that there is a fixed order for movement preparation and processing, with direction processed before amplitude (Mieschke et al., 2001).

In general, the results of these experiments supported the movement planning hypothesis which proposed that the left hand advantage for reaction time for movements to complex spatial targets arises from the greater proficiency of the right hemisphere/left hand system at processing spatial information. This leads to the ability of the right hemisphere/left hand system to plan movements more rapidly than the left hemisphere/right hand system.

Another experiment raised some interesting ideas regarding the types of information derived from peripheral versus foveal eye gaze. Boulinguez, Barthelemy, and Debu (2000) conducted an aiming experiment with right-handed participants. In one block of trials, the amplitude of the target was manipulated, with targets at different distances along the midline. In a second block of trials, direction was manipulated, with targets appearing in locations either in left or right hemispace. The results showed that the movement times for the right hand were shorter than those for the left hand, while the left hand had faster reaction times. However, there was an effect of movement parameter on reaction time. For the trials where amplitude was manipulated, reaction times were shorter for targets within the central visual field compared to targets outside this range. An ocular saccade was necessary to foveate targets outside the central visual field. This effect was not seen for the direction condition, indicating that there was no need for foveation. Foveation thus seems necessary to determine the distance of the target, while its direction can be obtained from peripheral visual information. Thus direction can be programmed automatically from visual information received through the peripheral retina, while programming amplitude required the translation of target information into egocentric coordinates, a process that depended on central vision (foveation). This difference between amplitude and direction was supported by the Mieschke et al. (2001) findings.

Although amplitude and direction might depend on separate visual processes, the left hand advantage for reaction time was seen in both conditions. There was also an effect of hemispace: reaction times were shorter for targets in ipsilateral than contralateral space. This finding seems to indicate that visuomotor processing occurred within a single hemisphere. Interhemispheric transfer of information is required for movements into contralateral space, since one hemisphere receives the information while the other must produce the aiming movement. If the movement does not require the regulation of amplitude, then either hemisphere is able to determine the direction of the movement. Also, in the direction condition, the stimulus information was lateralized, going to either the right or left hemisphere. For the amplitude condition, both hemispheres received the stimulus information about the target, since it was located along the midline. Thus this experiment highlights the different visual processes that are involved in the production of aiming movements.

Another example of right hemisphere/left hand superiority was for tasks involving tactile discrimination and spatial positioning. This suggested that the right hemisphere/left hand system might be more efficient at the processing of spatial information (Maraj, Lyons, Elliott, Roy, & Winchester, 1998). An experiment by Maraj et al. (1998) was designed to test whether spatial mapping abilities have an effect on manual asymmetries. In the first experiment, right-handed participants were required to make aiming movements with a computer mouse on a graphics tablet to targets of three different diameters. The mouse rested on the graphics tablet in front of the participant. The movement of the mouse was constrained by a wooden track so that the movement was one-dimensional. The participant was required to slide the mouse from the starting position, across the tablet (away from the body along the Y axis) as rapidly as possible to the target. This first experiment required direct mapping: that is, there was a correspondence between the plane of movement and the visual display. As expected, the movement times for the right hand were significantly faster than for the left hand. In the second experiment, the spatial complexity of the task was increased by hiding the mouse and graphics tablet under a cover. Instead of being able to see the graphics tablet and their hand, participants now had to view the movement of the cursor on a computer monitor. The location of the mouse on the graphics tablet was translated into the location of the cursor on the computer monitor, thus providing real-time feedback of the aiming movement. This also resulted in a translation of 90 degrees between the graphics tablet target to the monitor target, and mouse cursor to the effector (hand). Tasks such as this, which required the translation of spatial information, were believed to require increased involvement of the right hemisphere. This should result in a decrease or even absence of the typical right hand advantage for movement times, if the right hemisphere/left hand system was indeed better at the processing of spatial information. The results of this second experiment supported this hypothesis. First, compared to the first experiment, movement times increased with the added difficulty of the task. Second, in contrast to the right-hand advantage for movement time seen in the first experiment, in this case there was no significant difference between the hands for movement time. These findings suggested that when spatial mappings were indirect, manual asymmetries may not be as robust. This was interpreted as support for the increased involvement of the right hemisphere in tasks that required a greater degree of spatial processing.

The results of these experiments also highlighted that the nature of manual asymmetries was highly dependent on the type of task being performed. By manipulating different components of a task, performance differences favouring one hand or the other can be observed. However, in general the following manual asymmetries have been observed for aiming movements:

1. a left hand advantage for reaction time, which reflects the superiority of the right hemisphere/left hand system for movement planning/initiation
2. a right hand advantage for movement time, which reflects a left hemisphere/right hand system superiority for movement execution

3.1.3 Comparison of Left- and Right-Handers

An experiment was conducted to determine whether the direction of manual asymmetries was the same for both left- and right-handed participants. Boulinguez, Nougier, and Velay (2001a and 2001b) examined the effects of manipulating amplitude or direction during aiming movements in two separate studies with right- and left-handers. Participants were required to make rapid pointing movements from a central starting position (moving away from the body), to a lighted target within an array of three possible targets. The target remained lighted until movement completion (unperturbed trials). However, on 25% of trials after the start of the movement the target light was unexpectedly turned off and a second target adjacent to the first was illuminated. This gave the appearance that the target light had moved (perturbed trials). In the direction condition the target was displaced either to the left or right. In the amplitude condition the target was displaced to a near or far position. Participants were instructed to point to the target as rapidly as possible while maintaining accuracy. In the control condition participants were told that no perturbed trials would occur, whereas in the experimental condition perturbed trials were included.

First the results of the experiment involving directional changes will be described, beginning with the right-handed participants (Boulinguez et al., 2001a). For the experimental unperturbed trials, the expected left hand advantage for reaction time was observed. A qualitative examination of the kinematic profiles of the unperturbed trials showed bell-shaped velocity profiles for both the control trials and the unperturbed experimental trials for the right hand (quantitative results of the kinematic profiles, such as peak velocity and time to peak velocity, were not discussed). For the left hand the bell-shaped velocity profile was observed only for the control trials, and in contrast an irregular velocity profile was observed for the unperturbed experimental trials. These findings suggested a trend that the left hand may have been more affected by the possibility of having to modify the movement direction than the right hand (although the hand by condition interaction for movement time did not reach significance, there was a trend in this direction). Turning now to the perturbed experimental trials, the expected right hand advantage was seen for movement time. The time for trajectory correction was also examined. The time for trajectory correction was the time between the beginning of the movement (which triggered the presentation of the second target) and the first modification of the movement trajectory – in other words, the time needed to react to the presentation of the second target. This was shorter for the right hand in response to the perturbations than for the left hand. Overall, these findings with regard to movement direction for right-handers revealed an advantage for one hand or the other depending on the performance measure. For programming direction as seen in reaction time, there was an advantage for the right hemisphere/left hand system reflecting its superiority for spatial processing. For correcting the direction of a movement, the left hemisphere/right hand system had the advantage, (seen in the faster movement time for the right hand on the perturbed trials), reflecting its superiority for the control of movement execution.

Interestingly, when the same experiment was performed with left-handed participants, a number of similarities were observed (Boulinguez et al., 2001b). For the control trials, a left hand advantage for reaction time was seen. The same pattern for the velocity profiles was observed: smooth, bell-shaped velocity profiles for the control and unperturbed experimental trials with the right hand and for the control trials with the left hand and irregular velocity profiles for the unperturbed experimental trials with the left hand. This suggested that for both handedness groups, the left hand was more affected by the possible need to perform movement corrections than the right hand. The irregular velocity profiles seen in the unperturbed experimental trials for the left hand (with both left- and right-handers) suggested that participants performed online corrections to the movements when there was the potential for the target to be displaced. Thus the left hemisphere/right hand system appeared to be more efficient at the correction of movements.

Some differences were observed between the left- and right-handed participants in the direction experiment. For left-handed participants, the left hand advantage for reaction time was seen in the control trials, however there was no difference between the hands for the unperturbed experimental trials. In contrast for right-handed participants there was a left hand advantage for both the control and the unperturbed experimental trials. For left-handed participants performing aiming movements with their left hand, in the unperturbed experimental trials reaction time increased compared to the control trials, thus eliminating the left hand advantage for reaction time when participants were anticipating a perturbation.

Another difference between the handedness groups appeared when movement time for the perturbed experimental trials was examined. For left-handed participants, there was no difference between the hands for movement time, whereas for right-handed participants there was a right hand advantage. An examination of the time to make the correction (which can be thought of as the reaction time for the perturbation) was shorter for the right hand for both handedness groups. Taken together, these results were interpreted as suggesting that left-handers were less skilled at using their right hand during the correction phase of the movement, even though they were able to initiate the corrections just as rapidly.

The second experiment examined changes in the amplitude of the movement, so that the target was either closer to or farther from the participant along the midline. Interestingly, there was no difference between the hands for reaction time for either the control trials or the unperturbed experimental trials. This was seen for both left- and right-handed participants. Programming movement direction induced manual asymmetries in reaction time whereas programming movement amplitude did not. It therefore seems that movement direction was a more critical component to movement planning than was movement amplitude, and that uncertainty about movement direction can lead to manual asymmetries. Similar findings regarding amplitude and direction were also observed in the precue experiment conducted by Mieschke et al. 2001.

For the perturbed experimental trials in the amplitude condition, both left- and right-handers showed a left hand advantage for movement time. In other words, there was a reversal in the usual pattern of manual asymmetries for movement time, in which the right hand typically is faster. Participants in both handedness groups corrected their movements earlier with their left hand, and these movements also showed a smoother velocity profile than movements made with the right hand. Since these results were seen in both left- and right-handers, it suggested that the left hand advantage for correcting movement amplitude did not depend on hand preference, but rather the hemisphere/hand system. The authors posed two possible hypotheses to explain the amplitude movement time results (Boulinguez et al., 2001a). First, that this left hand advantage resulted from the superiority of the right hemisphere in the visuospatial processing of target distance relative to the body. This explanation agrees with other findings that showed that the processing of amplitude requires visual fixation on the central retina, while direction can be determined through peripheral visual information (Boulinguez, Barthelemy, & Debu 2000). The second hypothesis was that directional corrections involved the use of distal musculature in the hand and forearm, which was under contralateral control. In contrast, amplitude corrections involved the shoulder also, which was innervated both ipsilaterally and contralaterally.

Perhaps the findings of greatest interest in these two experiments (Boulinguez et al., 2001a and 2001b) were the similarity of the motor patterns observed for both left- and right-handed participants. In general, the right-and left-hand advantages seen in these experiments were the same for both right- and left-handers, which indicated that these asymmetries were not linked to hand preference per se but rather reflected the superiority of the particular hemisphere/hand system for different tasks. Also, the results highlighted that manual asymmetries were specific to the task being performed and the measure of interest. In summary, the following manual asymmetries were observed:

- For perturbations to amplitude there was a left hand advantage for movement time. A left hand advantage was clearly evident for making movement corrections, for both left- and right- handed participants. There were no differences between the hands for reaction time when amplitude was perturbed for either left- or right-handers;
- For perturbations to direction: a right hand advantage for movement time was seen with right-handed participants; in contrast no difference between the hands was observed for left-handed participants. The time to trajectory correction was also shorter for the right hand than the left hand; this was the case for both handedness groups.

Thus the experiments by Boulinguez et al. (2001a and 2001b), supported a task-specific view of movement programming and execution, and showed that manual asymmetries were relative to the task being performed, for both left- and right-handed participants.

3.1.4 The Effect of Movement Complexity

Much of the previous research on manual asymmetries in movement initiation and execution has been with simple pointing movements. Henry and Rogers (1960) performed an early experiment examining movement complexity. Participants were instructed to perform three tasks of increasing movement complexity. The first and simplest movement involved lifting the finger up a few millimeters from a starting position. For the second movement (medium complexity) the participant lifted their finger from the starting position, and moved their hand forward and upward to grasp a tennis ball hanging from a string. Grasping the tennis ball stopped a timer, which recorded movement time. For the third and most complex movement, a second tennis ball was suspended by a string to the right of the first tennis ball. The participant had to lift their finger from the starting key, move forward and upward to touch the first tennis ball with the back of their hand, move forward and downward to push a button, and then move forward and upward to the right to touch the second tennis ball. Participants knew on any given trial which movement to perform, and the stimulus for the trials was the same. The only difference was the movement to be performed. Results showed that reaction time increased with the complexity of the movements (from the simple to the medium to the most complex task). Since the stimuli did not change, the differences in reaction time could not have been due to differences in processing the stimuli. Instead Henry and Rogers (1960) stated that the increase in reaction time for the more complex movements was due to an increased amount of time required to program the increasingly difficult movements.

It is of interest to note that the complexity of the movements in the Henry and Rogers (1960) experiment was due to a number of factors. First was the number of movement parts involved. The most complex movement involved a number of steps (lifting finger, touching a ball, pushing a button, touching a second ball) compared to the simplest task of lifting the finger. Second, the simple finger lift task did not require an accuracy component, unlike the medium complexity and most complex tasks in which the tennis balls had to be touched to properly complete the movement. Third, the duration of the movement was much longer for the complex tasks than for the simple task. Many experiments have been conducted to determine which of these factors were crucial to the response complexity effect.

Fischman (1984) extended the research of Henry and Rogers (1960) by manipulating the number of movement parts, while standardizing the movement itself. Fischman used a finger-tapping test where the number of taps varied from one to five. Recall from Section 3 that premotor time was the component of reaction time from the presentation of the go signal to the first sign of electromyographic activity above baseline for the muscle of interest. Premotor time was believed to be a more exact measure of programming time than reaction time, which also included the initiation of the motor response. The results of Fischman's 1984 experiment showed that as the number of movement parts (taps) increased, premotor time linearly increased. This supported the hypothesis that response complexity was related to the number of movement parts. Christina and Rose (1985) also conducted experiments replicating and extending the original work by Henry and Rogers (1960). Christina and Rose (1985) found that both the number of movement parts and accuracy demands contributed to the response complexity effect. As the number of movement parts increased and accuracy demands increased, the programming time for the movement (or premotor time) also increased.

The accuracy hypothesis was proposed as an alternative explanation to the response complexity effect. Fitts's law (1954) specifying the index of movement difficulty (ID) was central to the accuracy hypothesis. Fitts found that movement time was linearly related to the ID for movements of amplitude A to targets of width W, by the following equation: ID = $\log_2(2A/W)$. Fitts also found that mean movement time (MT) was linearly related to ID, as in the following equation: MT = $a + b$(ID); where a and b are constants. Movement time therefore increased as the index of difficulty increased. The relationship between reaction time and ID has also been studied, with Fitts and Peterson (1964) reporting a 0.79 correlation between ID and reaction time. For the accuracy hypothesis, ID was used to quantify the accuracy demands of movement responses. Sidaway, Christina, and Shea (1988) hypothesized that for circular targets subtending smaller angles (and therefore a larger ID) more complex programming was involved, and therefore more programming time was required, than for movements to circular targets that subtend larger angles. The accuracy hypothesis was that the response complexity effect may be due to directional accuracy constraints rather than the number of movement parts. Support for the accuracy hypothesis has been provided by a reevaluation of a number of earlier experiments that examined the response complexity effect (Christina, 1992). Sidaway (1991) also conducted a series of experiments to directly evaluate the accuracy hypothesis. These experiments were based on the Fischman (1984) tapping experiments, however target size and movement distance was manipulated. The main finding was that premotor time and reaction time increased as the subtended angle got smaller (ID increased). However the number of taps and the interaction between number of taps and subtended angle did not reach statistical significance. These findings thus provided support for the accuracy hypothesis for response complexity.

Using tasks similar to the simple and complex movements used by Henry and Rogers (1960), Teixeira, Gasparetto, and Sugie (1999) examined if manual asymmetries were present for more complex movements. Two reaction time tasks were compared. The first was a simple movement that consisted of lifting the index finger in response to the presentation of a stimulus.

For the second, more complex task, upon presentation of the stimulus participants were required to reach to and grasp a tennis ball, and then touch the tennis ball to a target on the opposite side of working space. Both hands were tested on each task. The results of the task by hand analysis for reaction time were clear: there was a main effect of task, such that the reaction time for the simple task was faster than for the complex task. This showed the expected effect of task complexity: as the number of steps in a task increased, so too did the time to initiate the movement. However, the main effect of hand, as well as the interaction of task by hand, were not significant. Therefore, performance was similar for both hands, irrespective of the complexity of the task. This was in contrast to the left hand advantage for reaction time that was frequently observed in the literature. The authors suggested two possible explanations for these results: (1) that both the left and right hemispheres were able to similarly prepare for the generation of reaching movements in conditions that did not involve spatial uncertainty (since the left hand advantage was often elicited by choice reaction time tasks, and therefore involved a degree of spatial uncertainty), and (2) that the degree of complexity of the tasks was not sufficient to elicit manual asymmetries. In summary, reaction time was shown to increase in accordance with the complexity of the task (as represented by the number of steps or components to the movement), and both cerebral hemispheres were adept at preparing for the generation of reaching movements in conditions that did not involve spatial uncertainty.

3.2 Grasping a Target

The experiments described in the previous section generally involved visually-guided aiming movements. As such, these experiments examining reaction time and movement time have involved tasks that require the participant to *point* to a target, usually with a cursor. Fewer experiments have studied the reaction time and movement time for reaching movements that involve actually *grasping* a three-dimensional target object. A grasping (or prehension) movement is more complex than a pointing movement in that it can be considered the coordination of two distinct components: a reaching or transportation component and a grasping or manipulation component. The reaching component involves proximal joints and muscles and through the visual system, specifies a point in space. The grasping component involves distal joints and muscles, and requires the encoding of the object features, such as size and shape, to form the proper hand grasp (Jeannerod, 1984; Soechting & Flanders, 1993). The coordination of both components is essential for the successful grasping of an object. This next section discusses the few reaching experiments that required the participant to grasp a target object

One experiment by Marteniuk, MacKenzie, Jeannerod, Athenes, and Dugas (1987) compared pointing to a target to grasping a target. In the first experiment, right-handed participants were required to either point to a target or grasp a disk. The target and disk had the same diameter (either 2 or 4 centimeters), and were placed 12 centimeters away from the participant along the midline. Participants were instructed to move as quickly and accurately as possible. The movement trajectories were captured by infrared emitting diodes (IREDS) placed on the index finger, thumb and wrist. The results showed that the resultant peak velocity was very similar for the pointing and grasping movements. However, the movement time for the grasping movement was significantly longer than for the pointing movement. An examination of the acceleration and deceleration phases of the movements revealed that a greater percentage of time was spent in the deceleration phase of the movement for grasping compared to pointing. This finding was replicated in a later study of pointing versus grasping in younger and older participants by Roy, Weir, Desjardins-Denault, and Winchester, 1999. This experiment showed that for both younger adult and older adult participants (mean ages of 23 and 69 years old, respectively), greater time was spent in movement deceleration for the grasping movement than the pointing movement. Marteniuk et al. (1987) noted that by examining the velocity profiles for the pointing movements, the participants did not require a precise approach to the target, and let the target decelerate their hand. In other words, participants did not decelerate to zero velocity upon approaching the pointing target. In contrast for the grasping movements, deceleration of the hand occurred until zero velocity was reached at the point of contact with the target, when the target was then grasped. This required a more controlled approach than what was observed for the pointing task. The authors made two further observations. First, within a condition (pointing or grasping), similar movement trajectories were observed, indicating that the motor planning and control mechanisms were capable of consistent movement production. The second observation was that changes in movement trajectory resulted from changes in the task from pointing to grasping. This indicated that the motor planning and control mechanisms were finely tailored to the demands of the task. Therefore, what the participant wanted to do, (that is, their goal or intent for the movement), affected movement planning and control processes.

The authors further examined the issue of movement goals in a second experiment (Marteniuk et al., 1987) in which participants were asked to perform a two-part movement. The first part of the movement was the same for both conditions: to use their thumb and index finger to grasp a 4 centimeter disk. For the second part of the movement participants were asked to either toss the disk into a relatively large box (20cm x 40cm x 15cm), or place the disk into a small 4.1cm diameter well. Placing the disk into the well was judged to be a more complex task than tossing the disk into the box, since it required a much higher degree of spatial precision. As in the first experiment, movement trajectories were recorded with IREDS, and participants were asked to move as quickly and accurately as possible. The results showed that there was no difference in peak velocity between the two grasping movements. Movement time, in contrast, was significantly longer for the grasping movement that was followed by placing the disk into a well compared to throwing the disk. Therefore, similar to the results of the first experiment, movement time increased as the complexity of the task increased. As well, the percentage of time in the deceleration phase of the movement was longer for the grasp movement when it was followed by the placing task as opposed to the tossing task. That is, as the precision requirements of a task increased, movement time increased as well, largely due to the disproportionate lengthening of the deceleration phase.

In a third experiment examining the effect of movement goals, (Marteniuk et al., 1987), the kinematics of reach-to-grasp movements to different targets were analyzed. In this experiment the targets were a tennis ball and a fragile light bulb. Both objects were approximately the same size, therefore the fragility of the object was the main constraint of the movement. The results showed that there were indeed subtle differences in the movements made between reaching to the light bulb compared to the tennis ball. The total movement time as well as the time spent in the deceleration phase of the movement were significantly longer when participants were reaching to the fragile object. This finding makes intuitive sense, as individuals tend to slow down their reaching movement and are generally more careful when grasping fragile objects. This experiment highlighted how the individual performing the action was able to adjust the reaching movement in order to meet the demands of the environmental constraints of the task. The environmental constraints formed the context in which movements take place.

As these experiments demonstrated, the intent or goals of the individual performing the action were also relevant to the movement. Motor planning and control processes were highly tuned to the goals of the performer (e.g. point versus grasp), as well as the environmental constraints (e.g. toss versus place; sturdy versus fragile object). In this respect, a task is the interaction of a performer with the environment under given movement goals. Movements are functionally specific and are planned and organized for the unique requirements of an individual interacting motorically with the environment. These experimental results therefore support a task-specific view of movement planning and control - the dynamic interaction between the individual and the environment in which actions are performed.

Roy (1996) examined the effect of movement goal by using a reach and place task which varied in the precision demands. Movement goal was defined in two ways. First, by the phases of the task: the reach phase (to reach and pick up the object) and the move phase (to move and place the object). The second way movement goal was defined was by the precision demands of the move phase: to either toss or place the object. To explore these definitions of movement goals, three movement conditions were studied: (1) place the dowel in a receptacle about the same size as the dowel (small place); (2) place the dowel in a large receptacle (large place); and (3) toss the dowel into the large receptacle (large toss). Movements were recorded by placing infrared markers on the wrist, thumb, and index finger. The results showed that during the reach phase, the movement time to grasp the dowel was longer and the peak aperture of the grasp was larger in the conditions that involved placing the dowel (small place and large place conditions) than tossing the dowel. Thus the precision demands, or the goal of the movement, affected the planning of the movement. This supports the work of Marteniuk et al., (1987). No differences between the hands were observed for the reach phase. The results of the move phase showed that the execution of the placing movements was affected by the spatial precision demands. For the move phase, the small place task exhibited a longer movement time, longer time after peak velocity, and smaller peak velocity than the large place task. Participants moved slower and took a longer time to complete the movement for the more precise small place task. For the move phase a right hand advantage for movement time was observed, and the right hand also reached a greater peak velocity than the left hand. This occurred regardless of the precision demands of the tasks. Task demands therefore affected the presence but not the magnitude of manual asymmetries.

Carnahan conducted two experiments to directly compare manual asymmetries in pointing and grasping movements (Carnahan, 1998). Both experiments examined the kinematics of reaching movements of the left and right hands to three targets (midline, to the left, and to the right). In the first experiment participants were required to point to an illuminated target. For the control condition on each trial one target would light up and would remain lighted for the duration of the trial. For the perturbed condition, 66% of the trials involved perturbations to the location of the target. For the perturbed condition the center target would be illuminated, but upon initiation of the reaching movement, the center target was extinguished and either the left or right target was illuminated. In this condition on 33% of the trials the central target was not perturbed; that is, the central target was illuminated and remained illuminated throughout the trial. These unperturbed trials were compared to the control trials.

The results of the control trials showed the expected right hand advantage for movement time. For peak velocity there was a statistically significant hand by target interaction: peak velocity was greater for the right hand than the left hand for movements to the central and right targets, however there was no difference between the hands for the left target. Thus for the control trials small performance differences in favor of the right hand were observed. Differences between the hands were more evident for the perturbed trials. For the perturbed trials, each hand showed an advantage when reaching into its ipsilateral space. When the target was perturbed to the left, movement time was shorter for the left hand than the right hand. When the target was perturbed to the right, movement time was shorter for the right hand than the left hand. Thus adjustments in reaching movements were more rapid when the hand was pointing to a target in its corresponding hemispace (the effect of hemispace on movement time was not examined for the control trials). There was also a significant hand by target interaction, such that movement time did not differ between the targets for the left hand. However movement time was significantly longer for the right hand when pointing to the left target than the central and right targets. Kinematic analysis showed that there were no early trajectory corrections for the perturbed trials for either hand. Also, when the targets were perturbed to the left, participants modified the displacement of their trajectories faster than when the target was perturbed to the right. This finding may be related to the right hemisphere advantage for the processing of spatial information, as would be required by a modification in the target position.

Since formation of a hand grasp was required for interactions with tools and other goal-directed actions, it was hypothesized that larger performance differences between the hands may be observed with grasping movements than what were seen with the pointing movements. Using a similar design to the first experiment, in the second experiment (Carnahan, 1998) participants were required to grasp small frosted acrylic dowels, which were illuminated from underneath by a red light diode. In the perturbed trials, when the light diode under the center target was extinguished, either the right or left light diode was illuminated. Thus it appeared to the participant as if the dowel had suddenly changed position. In the control trials, the same dowel would remain illuminated throughout the trial.

The results of the control trials showed a significant hand by target interaction, such that the movement time was longer for the right hand than the left hand to grasp the left target. For the right and central targets there was no difference in movement times between the hands. Grasp formation, as measured by peak aperture, showed no differences between the hands.

For the perturbed grasping trials, there was no difference in movement times between the hands. For the perturbed grasping trials, there was evidence of early trajectory corrections in that peak velocity was reached earlier when the target was perturbed to the right (240ms) but not to the left (253ms) relative to the unperturbed trials (266ms). This effect though did not differ between the left and right hands, suggesting that both were equally skilled at generating early trajectory corrections for grasping movements. This finding is consistent with a similar, earlier experiment by Carnahan, Goodale, and Marteniuk (1993) that also demonstrated the presence of early corrections (before peak velocity) to the movement trajectory for grasping movements made with the right hand. For the other kinematic measures, there were no differences between the hands. Thus the hypothesis that grasping movements would result in greater manual asymmetries than pointing movements was not supported by these results. Overall these results indicated that there was little difference in processing of visual information for generating reaching movements with the left and right hands.

Carnahan concluded by noting that the instances of a right hand advantage that were seen in these experiments were consistent with the literature (e.g. for movement time in the control pointing trials). As well, there was a performance advantage for both hands (and seen in both experiments) for reaching movements to targets in ipsilateral space. The right hand advantages that were observed were more evident for the pointing than the grasping movements. In terms of differences between pointing and grasping movements, the most significant finding was in regard to time to peak velocity. For grasping movements, the time to peak velocity showed that early trajectory corrections were made, and that both hands were equally skilled in altering the movement trajectories in response to the perturbations. In contrast, there was no evidence of such early trajectory corrections for pointing movements. Thus grasping movements may be more readily modified, whereas subtle manual asymmetries may be more evident in pointing movements.

In summary, the few studies that have examined differences between pointing and grasping movements have highlighted a number of subtle differences:

1. Movement time for grasping movements was significantly longer than for pointing movements (Marteniuk et al., 1987; Roy et al., 1999). Although a direct analysis comparing movement time for the pointing and grasping trials was not performed in the Carnahan (1998) experiments, the results for the control trials seem to suggest the same pattern.
2. Greater time is spent in the deceleration phase of the movement for grasping as opposed to pointing movements (Marteniuk et al., 1987; Roy et al., 1999)
3. An examination of the time to peak velocity revealed that early trajectory corrections were evident for grasping but not pointing movements (Carnahan, 1998)
4. Manual asymmetries were more pronounced for pointing movements compared to grasping movements (Carnahan, 1998)

As the Marteniuk et al., (1987) experiments demonstrated, grasping movements, like pointing movements, can be tailored to meet the specific demands of the task, and as such support a task specific view of movement organization and planning. Manual asymmetries, although more pronounced for pointing movements, were also evident for grasping movements (Carnahan, 1998). One observation was that, unlike the visually-guided aiming studies in the literature, reaction time was not examined in these grasping studies. One of the goals of Experiments 2 and 3 was to explicitly examine the reaction time for reaching movements to grasp tools. The next section describes the precue paradigm, which was used in Experiments 2 and 3 in order to further examine the effects of task demands on manual asymmetries for reaction time and movement time when reaching to tools.

3.3 The Precue Paradigm

The original precue paradigm was developed by Rosenbaum (1980) in order to determine how motor programs for voluntary reaching movements are constructed prior to movement initiation. With the precue paradigm, on each trial a precue presented before the reaction stimulus (or go signal) provided information about all, some, or none of the movement parameters (e.g., hand to be used) of the upcoming response. Regardless of the amount of information contained in the precue, the participant was not allowed to initiate the movement until the go signal was presented. In Rosenbaum's original experiment, the information about the movement that was provided by the precue was always accurate and reliable. For example, if the precue indicated that the target would appear to the right, the location of the target was indeed to the right. No unreliable precues were presented (for example, on none of the trials would the precue indicated that the target would appear to the right, and then the target location for that trial would be to the left). For these experiments, reaction time referred to the time from the presentation of the go signal until the beginning of the reaching movement. Movement time referred to the time to move from the starting position to the target of the reaching movement.

Rosenbaum's first experiment (1980) using the precue paradigm examined three movement parameters or dimensions, each of which had two possible response options. The three dimensions of movement were: (1) the arm that was used to make the movement; (2) the direction of the movement; and (3) the extent of the movement. Rosenbaum then assigned two possible choices or values to each dimension. For the arm dimension, the movement values were either to use the left or right arm. For the direction dimension, the movement values were either towards or away from the participant along the frontal plane. For the extent dimension, the movement values were either near or far. Capital letters were used to convey the precue information and the letter X served as a neutral cue that provided no information. Each precue consisted of three letters (one for each dimension) presented together in a horizontal row. For example, the precue "RBX" indicated a reaching movement made with the right hand, in the backwards direction, extent unknown. The go signal was a colored dot and each color corresponded to one particular reaching movement. The participant was required to reach to the target button corresponding to the colored dot. The results showed that the mean reaction time for the movement increased as the number of unknown values increased. The amount of available precue information therefore had an effect on reaction time. Reaction time was also affected by the three dimensions such that mean reaction time for when extent had to be specified was significantly faster than when direction had to be specified, which in turn was significantly faster than when arm had to be specified. In contrast, there were no significant differences between the two different values of a dimension. For example, for the arm dimension there was no difference in reaction time for reaching movements made with the left arm compared to the right arm. In other words, a left hand advantage for reaction time (as would be predicted by Carson et al., 1990) was not apparent. Furthermore, there were aspects of the data that supported the hypothesis that arm, extent, and direction for reaction time were specified serially, as opposed to specified in parallel. Reaction time increased as the number of values to be specified increased, and this increase appeared to be additive. This was suggestive of serial processing.

In contrast to the reaction time results, for movement time there was a significant difference between reaches performed with the left and right arms, with movement time for the right arm faster than for the left arm. Extent also had a significant effect on movement time, with movements to near targets performed faster than movements to far targets. The effect of direction on movement time was not significant. Although there was a main effect of precue, this did not interact with arm, direction, or extent. When the precue specified two dimensions (and the third was unknown), the effect of precue was not statistically significant. However, when only one dimension was specified in the precue, there was a significant main effect for the type of precue. When extent and direction had to be specified, movement time was significantly longer than when extent and arm had to be specified. A further analysis compared all the precues that differed by the presence of only a single precue. There was only one significant interaction: this occurred when the condition in which no values had to be specified was compared to the condition in which extent only had to be specified. The difference in movement time between the near and far targets was larger in the condition when extent had to be specified than in the condition when no values were specified. Rosenbaum reasoned, “since the differences in movement time for near and far movements was affected by whether extent had to be specified, extent decisions apparently could be made during movement time” (page 460). As well, there was no evidence that arm and direction were specified during movement time (based on the lack of any other significant interactions when the precues that differed by one value were compared).

These findings suggested that decisions regarding extent could be made during movement time, and in turn that arm and direction could not. Since the specification of extent could occur during movement time, it was possible that the specification of extent could at least partly occur sometime after the specification of arm and direction. A follow-up experiment by Rosenbaum eliminated the possibility that the above results were attributable to differences in stimulus-identification times (Rosenbaum, 1980).

Carson, Chua, Goodman, and Byblow (1995) conducted an experiment using the precue paradigm. In this experiment, participants made aiming movements to visual targets with their left and right hands under conditions of varying ambiguity using a precue paradigm. There were eight possible targets, and the precue information served to limit the possible position of the target ahead of movement initiation. The rationale was that when advance information specifying the target was available, participants would be able to at least partially prepare the movement prior to the "go" signal (indicating movement initiation). When no advance information was provided, participants would be unable to prepare the movement in advance, and therefore movement preparation would only begin upon presentation of the target stimulus. In the simple reaction time condition, complete information regarding the target position was provided. In the four-choice condition, partial information was given, indicating that the target was part of a subset of positions (one of four possible positions). In the eight-choice condition, the position of the target was completely ambiguous (one of eight possible positions). The results of this experiment indicated that when the advance information was completely ambiguous concerning the position of the target, a left hand advantage for reaction time was observed. However, when complete information regarding the target position was provided prior to the movement, there was no difference in reaction time between the left and right hands. Thus the degree of uncertainty affected the left hand advantage. This finding was later corroborated by the results of Teixeira et al. (1999).

The second experiment conducted by Carson et al. (1995) used a similar design to cue the response hand instead of the target position in advance. In this experiment, the hand to be used to perform the movement was cued by an auditory tone either prior to, or simultaneously with, the presentation of the "go" signal. The results showed that when participants were cued as to the response hand prior to the target presentation, reaction time was faster than when response hand was cued simultaneously with the target. Furthermore, there was an interaction between cue condition and hand, such that in the precue condition there was a left hand advantage for reaction time. However, in the simultaneous condition, the right hand initiated the movement faster than the left hand. The authors suggested that the left hand advantage could be reversed in circumstances when participants had to parameterize the movement along additional dimensions (such as response hand selection) during movement preparation.

3.4 Summary

This review of the literature for goal-directed reaching movements highlighted several key findings. An exploration of visually-guided aiming movements revealed that, in general, the presence of a right hand advantage for movement time (Woodward, 1899; Roy, Kalbfleisch & Elliott, 1994; Elliott et al., 1999; Roy, Kalbfleisch & Silcher, 1999) and a left hand advantage for reaction time (Carson et al., 1990; Mieschke et al., 2001). However, depending on the nature of the task to be performed, there were situations where the typical manual asymmetries did not occur. For example, the second experiment conducted by Maraj et al., (1998) involved an indirect spatial mapping between the visual display of the target and the movement of the hand.

In this situation, there was no difference between the hands in terms of movement time. A direct spatial mapping was used in the first experiment by Maraj et al., (1998), which resulted in the expected right hand advantage for movement time. As this example showed, the presence of manual asymmetries for reaction time and movement time was dependent on the nature of the task that was performed.

The effect of movement complexity, first addressed by Henry and Rogers (1960), showed that as the complexity of the movement increased, so did reaction time. Further experiments addressed a number of factors that could explain the movement complexity effect, such as the number of movement components (Fischman, 1984) and accuracy demands (Sidaway, 1991).

A few studies also directly examined the differences between aiming movements to a target and reaching movements to grasp a target object. For example, movement time for grasping a target was found to be significantly longer than for pointing to a target (Marteniuk et al., 1987; Roy et al., 1999). The goal of a task was found to have an effect on movement time (Marteniuk et al., 1987; Roy, 1996). For example, the results of the Roy (1996) experiment showed that the movement time for a more precise placing task was longer than for a simpler tossing task. Carnahan (1998) also showed that manual asymmetries were more pronounced for pointing movements than for grasping movements. This research will be built upon in Experiments 2 and 3. Of note is that although movement time was examined in the grasping experiments described in Section 3.2, reaction time was not. Therefore one of the goals of Experiments 2 and 3 will be to examine reaction time for reaching and grasping movements to tools.

Finally, the precue paradigm developed by Rosenbaum (1980) was reviewed and found to be a useful method for examining how different variables affect reaction time and movement time for reaching movements. In Experiments 2 and 3, a version of the precue paradigm was used to provide advance information regarding the choice of hand and task to be performed for the upcoming reaching movement. Differences between the hands in terms of reaction time and movement time were the variables of interest.

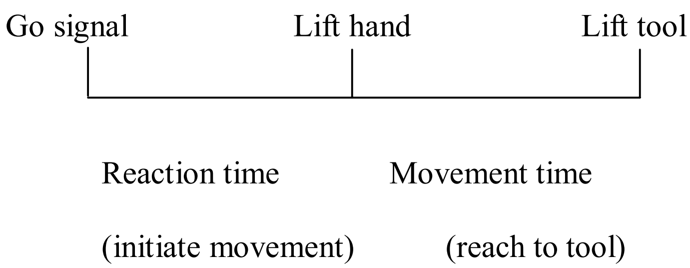
Chapter 4: The Precue Experiment

In this experiment, the effect of advance information and task demands on manual asymmetries for the initiation and execution of reaching movements to tools is examined

4.1 Introduction to the Precue Experiment

In Experiment 2, a version of the precue paradigm was developed that was designed to be analogous to the basic trial design employed in Experiment 1. Experiment 1 was a free-choice reaching experiment in that participants were told the task to be performed (e.g. Lift or Use) and the location of the object to interact with, but were free to choose which hand to use to perform any particular trial. In Experiment 1, the task to be performed was told to the participant, and the participant was then allowed to start the reaching movement. Thus for all trials the participant knew the task to be performed in advance of starting the movement. Participants would choose to use one hand or the other after the information regarding the task and object location were given by the experimenter.

In Experiment 2, the basic trial design used in Experiment 1 was adapted for use with the precue paradigm. This analogous precue condition was termed the Task precue. With the Task precue, the information regarding the task to be performed was given in advance of the Go (reaction) signal. The information given in the precue can be programmed in advance before the start of the movement, while the participant is waiting for the Go signal. In contrast, the information given at the Go signal must be programmed during movement initiation, and so will affect reaction time. For the Task precue condition the information regarding which hand to use to perform the task was given at the Go signal. The Task precue condition corresponded to the free-choice reaching paradigm used in Experiment 1, in that participants were told which task to perform in advance, whereas choice of hand was determined during reaction time. A schematic illustrating the trial design is shown below:



The Task precue condition was compared to two other precue conditions that varied the amount of advance information that was presented. In the Both precue condition, information about both the hand to be used and the task to be performed were presented in advance of the Go signal. In other words, complete information regarding the movement was given in advance, and the participant merely had to wait for the Go signal to initiate the movement. In contrast, no advance information was given in the No precue condition. Both the task and hand information were presented at the Go signal and thus had to be processed during reaction time. In Experiment 2 the reaction time and movement time for reaching movements with the left and right hands were examined for the performance of tasks of varying difficulty with three different tools at the midline position. The tasks chosen (Lift, Pantomime, and Use) were the same as those used in the free-choice reaching experiment used in previous research on performance-based measures of hand preference (Mamolo et al., 2006).

The variables studied in Experiment 2 were: (1) Precue condition (Task, Both, and No precues); (2) Task to be performed (Lift, Pantomime, Use); and (3) Hand to use to perform the task (Left, Right). The precue conditions varied the timing of the presentation of the task and hand variables.

4.2 Hypotheses

The hypotheses for Experiment 2 were based on the results of Experiment 1 as well as the findings of the reaction time and movement time literature for goal-directed movements.

1. A right hand advantage for reaction time. It was predicted that the increased frequency of preferred hand reaches seen in the performance-based measure of hand preference used in Experiment 1 would translate into a shorter movement initiation time. This was similar to the results of the second experiment by Carson et al. (1995) in which the response hand was cued either prior to or simultaneously with the presentation of the "Go" signal.
2. Reaction time will decrease as the amount of advance information increases (Rosenbaum, 1980).
3. The right hand advantage will increase as the amount of advance information decreases (increasing from the Both to Task to No precue conditions) (Rosenbaum, 1980).
4. Reaction time will increase as the task complexity increases (from Lift to Pantomime to Use) (Henry & Rogers, 1960; Teixeira et al., 1999).
5. The increase in reaction time with task complexity will interact with the hand that is used for the task. In other words, there will be a right hand advantage for reaction time that increases as the task complexity increases. This hypothesis was based on the observation

in Experiment 1 that preferred hand reaches increased as the skill demands of the task increased.

6. There will be a three-way interaction of hand, task, and precue condition. It is possible that both task complexity and the amount of advance information will affect reaction time. Therefore it was predicted that the right hand advantage will be largest in the No precue condition, and the size of this advantage will increase as the task complexity increases. This three-way interaction subsumes the other effects predicted above.

The following predictions were made for movement time:

1. There will be a right hand advantage for movement time. This prediction is supported by previous research (e.g., Rosenbaum, 1980; Roy, Kalbfleish, & Elliott, 1994).
2. Movement time will increase as the task complexity increases, from Lift to Pantomime to Use. This prediction is consistent with other work (e.g. Marteniuk, 1987; Roy, 1996).
3. The right hand advantage for movement time will increase as the task complexity increases. This should be seen as a hand by task interaction, such that the right hand advantage for movement time increases as the task complexity increases.
4. Movement time will decrease as the amount of advance information increases. Rosenbaum (1980) found that when only one movement dimension was specified in the precue, movement time was significantly affected by the type of precue condition.

4.3 Methodology

4.3.1 Participants

Participants were 24 right-handed undergraduate students at the University of Waterloo. The average age was 19.1 years with14 female participants and 10 male participants**.** Handedness was determined through the use of the Waterloo Handedness Questionnaire (Appendix 1). This experiment received full ethical clearance from the Office of Research Ethics at the University of Waterloo.

4.3.2 Apparatus

Three tools were chosen for Experiment 2: a hammer, pencil and saw. The hammer and saw were small, plastic children's toys. Toys were chosen out of consideration for participant safety and ease of use. The tools were wrapped in tin foil in order to complete a circuit with the metal sensors on the testing apparatus. The testing apparatus, which was attached to a computer, consisted of a flat wooden block made up of two interlocking pieces. The first piece of the wooden block had a metal sensor across it. When the tools, which were wrapped in tin foil, were placed across the sensor a circuit was completed. The computer recorded each time the circuit was broken when the tool was lifted off the sensor. This allowed for the accurate timing of the movements. The second piece of the testing apparatus was unique to each tool: it was the proper object on which each tool acts. For example, for the hammer the second piece of the testing apparatus consisted of a raised block of wood with three nails driven into it. For the saw, it was a raised block of wood with three grooves cut into it. For the pencil, a pad of paper was attached to the second piece. The second piece of the testing apparatus for each tool interlocked with the first piece to form the complete testing apparatus. The second piece was changed to correspond to the correct tool for each block of trials. The first piece (the tool sensor) did not change throughout the experiment. The testing apparatus was placed so that the first piece with the metal sensors was closest to the participant, with the tool laid across it. The testing apparatus was between the keyboard and monitor of the testing computer.

4.3.3 Task and Hand Cues

Participants were required to perform three different tasks with the tool:

1. Lift. The participant lifted the tool from the testing apparatus, then placed it back down in its original position on the testing apparatus.
2. Use. The participant lifted the tool from the testing apparatus, used it on its corresponding object (the second piece of the testing apparatus), then placed it back down in its original position on the testing apparatus.
3. Pantomime. The participant lifted the tool from the testing apparatus, pantomimed its use in the air above the testing apparatus, and then placed it back down in its original position on the testing apparatus.

Each task was cued by its capital letter (i.e. L, U, P). Tasks were completed using either the left or right hand, as cued on each trial. The hand cue consisted of a colored square outline. The left hand was signaled by a yellow square outline, while the right hand was signaled by a purple square outline. The midline position was chosen as it was the same distance from either hand, and therefore free from lateral asymmetries caused by the hand used or the side in hemispace of the target.

4.3.4 Precue Conditions

The precue conditions are presented in order of the amount of information provided by the precue:

1. No Precue. In this condition, a neutral precue that did not provide any information was given. This consisted of a white square outline (similar to the colored square outlines used to cue hand). This was followed by the simultaneous presentation of the task and hand cues, which acted as the Go signal.
2. Task Precue. In this condition, the task was cued first, then the hand was cued. The presentation of the hand cue was also the Go signal.
3. Both Precue. In this condition, the task and hand were cued simultaneously. The participant had to wait for the Go signal before initiating the movement. In the centre of the square outline (which signaled which hand to use), was the task signal.

4.3.5 Trial Design

Participants pressed and held down two starting position keys on the top row of a computer keyboard with their left and right index fingers (the number 1 and 0 keys). These starting position keys were marked on the keyboard with bright pink stickers for ease of identification. The participant was seated in a chair in front of the computer and testing apparatus. The positions of the participant and the keyboard were adjusted so that the keyboard was centered with the body midline of the participant, which was also lined up with the computer monitor. The participant's hands were therefore positioned at an equal distance from the testing apparatus. During development of the experiment, the keyboard and testing apparatus had been measured to determine where to place the testing apparatus so that it would be accurately positioned along the midline of the keyboard, to ensure an equal distance from either hand. The keyboard had been marked to show the exact placement of the testing apparatus so that it would be centered. As well, the testing apparatus and the keyboard were centered with the midline of the computer monitor.

The ready signal (a plus sign) appeared on the screen between trials. Once the participant was ready, the experimenter pressed a key to begin the trial. An auditory tone provided the warning signal that a trial was about to begin. The precue signal then appeared. After a variable foreperiod (between 200 and 700 milliseconds) the Go signal appeared. The participant lifted their cued hand from the start key and then grasped and lifted the tool from the metal sensors on the testing apparatus. The time between the Go signal and when the participant lifted their hand was the reaction time while the time between the participant lifting their hand and lifting the tool off the sensor was the movement time.

The testing sessions consisted of three blocks of trials, corresponding to each of the precue conditions. Each block was further divided into three sections, corresponding to each of the three tools (hammer, pencil, saw). The order of the precue conditions and the order of the tools within each block was randomized across the participants. For each tool section, six repetitions of each of the three tasks (Lift, Use, Pantomime) for each hand occurred in a randomized order. If a trial was performed incorrectly, it was repeated at the end of that section. For example, the tool may have slipped from the participant's hand just after contact (in other words, a firm grip was not established), resulting in an error trial. The program would not have counted this trial, and the same trial would have been repeated at the end of that section. Similarly, if the participant used the wrong hand to perform the trial, this error would also have been detected by the program (since the wrong starting key would have been released), resulting in a repetition of the same trial at the end of the section. Overall there were 36 correct trials per section, for a total of 108 trials for each precue condition. Since there were three precue conditions, this gave a total of 324 trials per participant.

4.3.6 Procedure

Participants were seated in front of the testing computer, with their left and right index fingers pressed down on the start keys. The participant was instructed to move as quickly and accurately as possible for each trial. At the Go signal the participant lifted their cued hand and reached for the tool resting on the testing apparatus, then performed the indicated task with it. At the completion of the movement the participant placed the tool back on the testing apparatus. Part of the intent of these experiments was to observe naturalistic reaching movements, therefore there were no artificial physical constraints used to limit the performance of the task. However, participants were instructed to perform the Lift and Pantomime tasks in the air above the testing apparatus. The result was that the vertical and horizontal displacement for all tasks was, in general, reasonably similar.

4.3.7 Data Analysis

An outlier analysis was first applied to the data. The program used was one developed by Van Selst and Jolicouer to determine outliers that is unaffected by sample size (Van Selst & Jolicouer, 1994). This program removed trials that were outliers, either too short or too long, and therefore indicative that the participant did not properly perform the movement. For reaction time 1.4% of trials were removed, and for movement time 8.2% of trials were removed.[5] For all analyses, the Bonferroni adjustment was applied for multiple comparisons. A value of $p < 0.05$ was used as the level of significance. For a list of non-significant main effects and interactions please refer to Appendix 4.

4.4 Results

4.4.1 Reaction Time

A repeated measures analysis of variance was performed that examined precue condition (3: Both, Task, No) by task (3: Lift, Pantomime, Use) by hand used (2: Left, Right). The results will be discussed within the context of the hypotheses.

<u>1. A right hand advantage for reaction time.</u>

[5]With this program, if a reaction time trial was removed as an outlier, that same trial would also be removed from the movement time data set, and vice versa.

This hypothesis was not supported by the results: the main effect of hand was not significant (right hand mean = 1016.02ms, SE = 19.37ms; left hand mean = 1025.03ms, SE = 17.21ms). Therefore, there was not an overall right-hand advantage for reaction time.

2. Reaction time will decrease as the amount of advance information increases.

This hypothesis was supported by the significant main effect of precue {$F(2, 46) = 94.56$, $p < 0.001$, □^{2}= 0.81}. Post-hoc analyses confirmed that all of the precue conditions were significantly different from each other. It was found that as more information was provided by the precue, reaction time was shortened, such that the reaction time decreased from the No condition (mean = 1159.32ms, SE = 21.82ms), to the Task condition (mean = 1014.13ms, SE = 19.84ms) to the Both condition (mean = 888.13ms, SE = 22.39ms).

3. The right hand advantage will increase as the amount of advance information decreases.

The interaction between precue condition and hand was significant {$F(2, 46) = 3.33$, $p < 0.05$, □^{2}= 0.13; see Figure 13}, however it did not conform to the hypothesis that the right hand advantage would increase as the amount of advance information decreased (from the Both to Task to No precue condition). In contrast to the prediction, post-hoc analyses revealed that for the Both and Task precue conditions, there was no difference between the hands in terms of reaction time. However a right hand advantage was evident in the No precue condition: the reaction time for the right hand (mean = 1146.84ms, SE = 20.71ms) was significantly faster than for the left hand (mean = 1171.07ms, SE = 23.96ms).

4. Reaction time will increase as the task complexity increases.

A main effect of task was predicted, such that reaction time would increase as task complexity increased from the Lift to Pantomime to Use task. While there was a significant main effect of task $\{F(2,46) = 23.92, p < 0.001, \eta^2 = 0.51\}$ it did not conform to the prediction. It was found that the reaction time for the Pantomime task (mean = 1051.22ms, SE = 21.14ms) was significantly longer than for both the Lift (mean = 998.46ms, SE = 16.51ms) and Use (mean = 1011.90ms, SE = 18.02ms) tasks, which did not differ from each other.

5. The right hand advantage for reaction time will increase as the task complexity increases.

In contrast to the hypothesis, the interaction between task and hand was not significant $\{F(2, 46) = 1.32, p = 0.28\}$. There was no difference between the hands in terms of reaction time across the three tasks.

6. There will be a three-way interaction of hand, task, and precue.

In contrast to the hypothesis, the three-way interaction of hand by task by precue was not significant $\{F(4, 92) = 0.62, p = 0.65\}$.

4.4.2 Movement Time

An analysis was performed that examined precue condition (3: Both, Task, No) by task (3: Lift, Pantomime, Use) by hand used (2: Left, Right). Precue was examined in order to confirm that this variable had no effect on movement time. The results will be discussed within the context of the hypotheses.

1. There will be a right hand advantage for movement time.

This hypothesis was supported by the results. There was a significant main effect of hand {$F(1,23) = 5.40$, $p < 0.05$, $\eta^2 = 0.61$} such that the movement time for the right hand (mean = 563.26ms, SE = 24.57ms) was shorter than for the left hand (mean = 591.38ms, SE = 18.95ms). Therefore a right hand advantage for movement time was evident.

2. Movement time will increase as the task complexity increases.

A main effect of task was predicted, such that movement time would increase as task complexity increased, from the Lift to Pantomime to Use task. While there was a significant main effect of task {$F(2, 46) = 10.24$, $p < 0.001$, $\eta^2 = 0.99$; see Figure 14}, it did not conform to the hypothesis. Movement time for the Lift task (mean = 507.57ms, SE = 22.59ms) was significantly faster than for the Use (mean = 641.65ms, SE = 20.26ms) and Pantomime tasks (mean = 595.92ms, SE = 31.83ms), which did not differ from each other.

3. The right hand advantage for movement time will increase as the task complexity increases.

This hypothesis was not supported by the results. The interaction of task and hand was not significant for movement time {$F(2, 46) = 0.40$, $p = 0.67$}. Therefore the right hand advantage did not increase as the skill demands of the task increased, although there was a trend in this direction.

4. Movement time will decrease as the amount of advance information increases.

The main effect of precue was not statistically significant for movement time {$F(2, 46) = 1.90$, $p = 0.16$}. Furthermore, the interactions of precue by hand {$F(2, 46) = 2.10$, $p = 0.13$} and precue by task {$F(4, 92) = 0.89$, $p = 0.47$} were also not statistically significant. This contrasts with the findings of Rosenbaum (1980), which showed a main effect of precue on movement time when only one movement dimension was specified in the precue. These results support the conclusion that precue condition affects movement initiation (as seen with reaction time) but not movement execution (movement time).

4.5 Discussion

Experiment 2 used a precue paradigm to study the effects of reaction time and movement time for reaching to and grasping tools. The results of Experiment 2 corroborated and extended several findings in the literature regarding the preparation of visually-guided movements. The results will be discussed using the framework of the hypotheses. First reaction time will be discussed:

<u>1. A right hand advantage for reaction time.</u>

The hypothesis was made that a right hand advantage for reaction time would be seen in Experiment 2. This was based on the idea that the increased preferred hand use seen in Experiment 1 in the preferential-reaching paradigm might be translated into a right hand advantage for reaction time in the precue paradigm. This was not supported by the results. Instead the results of Experiment 2 supported the findings of the original precue experiment conducted by Rosenbaum (1980) that showed no difference between the hands in terms of reaction time.

<u>2. Reaction time will decrease as the amount of advance information increases.</u>

This hypothesis was supported by the results. In other words, as the amount of information that must be processed during reaction time decreased, so too did the reaction time. This corroborated the findings of Rosenbaum (1980). Of note was that the Rosenbaum (1980) precue experiment involved pointing to a target. In contrast Experiment 2 involved reaching and grasping a tool. Therefore this experiment was the first to confirm the initial findings of Rosenbaum (1980) by using a precue paradigm for grasping movements to a tool.

3. The right hand advantage will increase as the amount of advance information decreases.

Although there was a significant interaction between precue condition and hand, the results did not conform to the hypothesis. For the Both and Task precue conditions there was no difference in reaction time between the hands. This did, however, support the findings of Carson et al. (1995), who also showed that in conditions with advance information specifying the target (i.e. less ambiguity) prior to the Go signal, (and thus allowing for some movement preparation in advance), there was no difference between the hands in terms of reaction time.

For the No precue condition, the reaction time for the right hand was significantly faster than for the left hand; therefore a right hand advantage was evident. The No precue condition could be considered the most difficult of the three precue conditions since it required both pieces of information to be processed during reaction time. This finding suggested that it was only under conditions with greater ambiguity (and therefore with greater processing demands) that differences between the hands emerged in terms of reaction time. This was similar to the findings of the second experiment by Carson et al. (1995), in which a right hand advantage for reaction time was found when the response hand was cued simultaneously with the Go signal. In the No precue condition, the simultaneous presentation of both the hand and task cues acted as the Go signal.

It should also be noted that the right hand advantage for reaction time seen in the No precue condition could not be due to fundamental differences between the hands per se. If that was the case, then a right hand advantage should have been evident across all precue conditions. Instead when partial information (Task precue) or complete information (Both precue) was given in advance, there was no difference in reaction time between the left and right hands.

4. Reaction time will increase as the task complexity increases.

Although the main effect of task was significant, the results did not conform to the hypothesis. Instead, reaction time was significantly increased for the Pantomime task compared to the Lift and Use tasks, which did not differ. The increased reaction time for the Pantomime task compared to the other tasks may reflect the effect of novelty, since this was a more novel task than lifting or using a tool. Pantomiming the use of a tool is a relatively unusual task that would be rarely performed during a typical day. In contrast lifting and using tools were more familiar tasks that are commonly performed throughout everyday life, and therefore represent more practiced or automatic tasks. This automaticity may be reflected in the shorter movement initiation for the more automatic Lift and Use tasks compared to the Pantomime task.

In Experiment 1 it was shown that the frequency of preferred hand reaches increased as the complexity of the task increased within contralateral space and at the midline positions. This was not reflected here by an increase in reaction time from the Lift to Use task.

The Henry and Rogers (1960) and Teixeira et al. (1999) experiments found an increase in reaction time as the complexity of the movement increased. The results of Experiment 2 may be interpreted to provide some support for this, in that reaction time was longer for the Pantomime task than for the Use and Lift tasks. Perhaps the novelty of the Pantomime task contributed to its complexity. In contrast to the hypothesis that the Use task would be the most complex task (due to the fact that it required the proper interaction between the tool and its object) perhaps for the participants the Pantomime task was really the most complex task due to its unfamiliarity and novelty. However a comparison between Experiment 2 and the earlier experiments must be interpreted with caution due to the different natures of the tasks used in each experiment. For example, in the Teixeira et al. (1999) experiment, the simple task consisted of a finger lift, whereas the complex task involved reversing direction after reaching and grasping a ball. These tasks were very different from the tasks used in Experiment 2. In Experiment 2, the Lift task was more complex than just lifting the finger; it involved reaching to, grasping, and lifting the tool. The more complex tasks in Experiment 2 were the Use task (reach to, grasp, and interact with the tool) and the Pantomime task (reach, lift, and pretend to use the tool), neither of which involved a reversal of direction as seen in the Teixeira et al. (1999) complex task.

5. The right hand advantage for reaction time will increase as the task complexity increases.

This hypothesis was not supported by the results: there was no difference between the hands in terms of reaction time for the three tasks.

6. There will be a three-way interaction of hand, task, and precue.

This interaction was not significant. The lack of a three-way interaction with task indicates that the hand by precue interaction seen in Hypothesis 3 occurred irrespective of which task was about to be performed. Thus in the No precue condition, the difference between the hands was similar across all three tasks. For the Task and Both precue conditions there was no difference between the hands for any of the tasks.

For the movement time results:

1. There will be a right hand advantage for movement time.

This hypothesis was confirmed. The right hand advantage for reaction time has been supported by numerous other findings in the literature for pointing movements (Woodworth, 1899; Roy, Kalbfleisch & Elliott, 1984). However this experiment confirmed that the right hand advantage for movement time exists for grasping movements to objects also.

2. Movement time will increase as the task complexity increases.

The movement time for the Lift task was significantly faster than for the Pantomime and Use tasks. This result supports a complexity hypothesis, in that movement time increased with the complexity of the action. Both the Use and Pantomime tasks can be broken down into two components: lifting the tool and then either using it or pantomiming with it. In contrast, the Lift task has only one component: lifting the tool. Note that movement time in this experiment does not include the time spent interacting with the tool. Rather movement time was defined as the time taken from lifting the hand to lifting the tool, and this process was the same regardless of the task about to be performed. Thus the increase in movement time for the Pantomime and Use tasks corresponded to the increase in task complexity. These findings are consistent with results found in other research examining task complexity and movement time (Marteniuk et al., 1987; Roy et al., 1996).

4. <u>The right hand advantage for movement time will increase as the task complexity increases.</u>

This interaction was not significant, indicating that the right hand advantage for movement time was not affected by the task demands. This corroborates the results of Roy 1996.

4.6 Conclusions

Experiment 2 was designed to test whether the reaching patterns seen in Experiment 1 could be replicated using other measures of manual asymmetries, specifically reaction time and movement time. To that end a computer program was developed that provided varying amounts of advance information through the use of different precue conditions.

The Task precue was designed to be similar to a typical trial used in a performance-based measure of hand preference experiment such as Experiment 1: information regarding the task to be performed was given in advance, and information regarding the hand to use had to be processed during reaction time. It was predicted that a right hand advantage would be evident in this condition, reflecting the increase in preferred hand reaches in the free-choice reaching paradigms. The results however, did not support this. It was only when the amount of information to be processed during reaction time was greatest (in the No precue condition) that a right hand advantage was evident. This was the only instance when a right hand advantage occurred. The nature of this finding will be further explored in Experiment 3. In the experiment by Carson et al. (1995), a right hand advantage was seen when response hand was cued simultaneously with the Go signal. This is similar to the findings of this experiment, in which a right hand advantage for reaction time was seen in the No precue condition. The Carson et al. (1995) experiment also showed that the amount of ambiguity (and therefore, the degree of movement preparation) affected reaction time, such that no difference in reaction time between the hands was observed when advance information was available. This was seen in the Task and Both precue condition of this experiment as well.

The right hand advantage for movement time seen in this experiment was consistent with the results of many previous experiments. Furthermore, the relationship between movement time and task complexity observed in this experiment supported what has been found in previous research. In Experiment 2, movement time increased from the Lift task (a simpler movement) to the Pantomime and Use tasks (more complex movements). Similarly, in the Marteniuk et al. (1987) experiment, the movement time for reaching and grasping a disk and then placing it into a slot (more complex movement) was greater than the movement time for reaching and grasping the disk and then tossing it into a box (less complex movement).

To the best of my knowledge, Experiment 2 represents the first time a precue paradigm has been used to study reaching movements for grasping a target object, in particular a tool. It is worth noting that many of the findings of this experiment (which involved reaching, grasping, and interacting with tools) were similar to much of the findings of the previous literature that involved visually-guided aiming movements (pointing to targets). Although many of the findings may not have been new in terms of the visually-guided aiming movement literature, these findings were new in that they applied specifically to movements for reaching and grasping a tool. This suggests that although there are fundamental differences between pointing and grasping movements, many of the basic principles of motor control were shared. As well, the similarities supported the rationale for using of the precue paradigm to study grasping movements with tools. If the results of Experiment 2 had completely contradicted the findings of the reaction time and movement time literature, one would have questioned the usefulness of the paradigm for studying grasping movements to tools. As well, although movement time for grasping objects has been previously reported in the literature (Marteniuk et al., 1987; Roy, 1996; Carnahan, 1998), reaction time was not examined in these studies. Therefore Experiment 2 was the first experiment to explicitly examine reaction time for grasping movements. Experiment 2 provided for the first time a comprehensive examination of a number of factors (advance information, task demands, and choice of hand) on manual asymmetries for reaction time and movement time to reaching and grasping tools.

Chapter 5: Revised Precue Experiment

The goals of this experiment were a) to explore whether it was the type or amount of advance information that lead to the right hand advantage in reaction time seen in the No precue condition in Experiment 2, and b) to replicate and extend the findings of Experiment 2.

5.1 Introduction

Experiment 2 was the first experiment to use a precue paradigm to systematically explore the effect of different variables on manual asymmetries for reaching movements to tools. One of the goals of Experiment 3 was to replicate and extend these findings.

Experiment 2 revealed that when no advance information was available, there was a right hand advantage for reaction time (Figure 13). This was the only instance in which a right hand advantage occurred for reaction time. The right hand advantage could be due to either the amount or the type of information that was needed to be processed during reaction time. When there was no advance information, both the hand and task information had to be processed during reaction time. Thus there was a greater amount of information to be processed during reaction time in the No precue condition compared to the other precue conditions. One possibility was that the greater amount of information that had to be processed during reaction time in the No precue condition was responsible for the right hand advantage in this condition. Perhaps having no advance information (the No precue) versus having any advance information (the Task and Both precues) led to this difference. However, it was also only in the No precue condition that information regarding the task to be performed had to be programmed during reaction time. In the Task and Both precue conditions the task information was included in the precue. It would seem equally likely that having to program the task during reaction time may have lead to the right hand advantage present in the No condition. The next experiment was designed to determine if the amount of advance information contained in the precue or the type of advance information in the precue had lead to the right hand advantage in the No precue condition.

The goal of Experiment 3 was to replicate and extend the findings of Experiment 2. In order to do so, a few modifications were made for Experiment 3. First, a fourth precue condition was added, the Hand precue. For the Hand precue condition the task must be programmed during reaction time, that is, information regarding which hand to be used is given in advance of the Go signal. Therefore, similar to the No precue condition, task was programmed during reaction time. Also, the Hand precue condition was similar to the Task precue condition in that only one piece of advance information was specified by the precue. If the *amount* of information to be processed during movement initiation was the cause of the right hand advantage, then hand differences in reaction time should be seen only in the No precue condition (when both hand and task must be programmed during reaction time) and there should not be a right hand advantage for the Hand precue. In contrast, if it was the *type* of advance information, then there should also be a right hand advantage in the Hand precue condition because, similar to the No precue condition, information regarding the task must be programmed during reaction time.

The second revision for this experiment was that only two tasks were used: the Lift and Use tasks. The Pantomime task was removed in order to provide a simpler and more direct focus on the question of task complexity, by contrasting the Lift and Use tasks. Also, the Pantomime task is a novel movement, compared to the Lift and Use tasks that are movements frequently performed in everyday life. Therefore another reason for excluding the Pantomime task was to remove a potential novelty factor.

The third change was that, in order to increase the number of repetitions, participants were no longer tested on all three tools. Instead, participants were randomly assigned to use one tool for the entire experiment. Because this greatly shortened the experiment (from three tools to one), an increased number of repetitions of each task by hand combination was made possible. As well, the sample size was increased for this experiment.

Lastly, the time for the tool to be placed back on the sensor was also collected. This variable (Replacement Time) was the time from when the tool was lifted off the sensor to the time when it was replaced back on the sensor. Replacement time therefore represented the time it took the participants to actually perform the lift and use tasks. The three dependent variables for this experiment (reaction time, movement time, replacement time) are represented schematically below:

Go signal → Lift hand → Lift tool → Replace tool on sensor

Reaction time	Movement time	Replacement Time
(initiate movement)	(reach to tool)	(perform task with tool, replace on sensor)

Since one of the aims of this series of experiments was to examine reaching movements to tools in a naturalistic context, few restrictions were placed on the performance of the movements. Participants were observed to make sure that they performed the Use tasks properly (e.g. actually tapped the nail with the hammer at least once) and that for the Lift task, they actually lifted the tool well off the sensor and into the air by at least a few centimeters.

5.2 Methodology

5.2.1 Participants

Participants were 42 right-handed undergraduate students (21 males and 21 females, average age 18.6 years) at the University of Waterloo. Handedness was determined through the use of the Waterloo Handedness Questionnaire (Appendix 1). This experiment received full ethical clearance from the Office of Research Ethics at the University of Waterloo.

5.2.2 Apparatus

The same apparatus that had been used for Experiment 2 was used for this experiment.

5.2.3 Task and Hand Cues

The same task and hand cues that were used for Experiment 2 were used for this experiment. The only change was that the Pantomime task was no longer included.

5.2.4 Precue Conditions

The No, Task, and Both precues remained unchanged from Experiment 2. In addition a fourth precue was added:

Hand Precue: in this condition, the hand was cued first then the task was presented with the Go signal. The same stimuli representing the hand and task cues that were used in Experiment 2 were also used for the Hand precue condition.

5.2.5 Trial Design

A trial design similar to the one used in Experiment 2 was used in this experiment with three exceptions. First, while three tools were used in the experiment only one tool instead of all three was used by each participant. The tool to be used was randomized across participants. Second, only two tasks were used in this study, Lift and Use. These first two exceptions lead to the third, the number of trials of each task by hand combination. This number was increased to twenty. This gave a total of eighty trials per precue condition, for an overall total of 320 trials per participant.

One change was made to the appearance of the stimuli. Recall that in Experiment 2 task was cued by a capital letter, and that hand was cued by a colored square outline. In the Both precue condition a letter and colored square outline appeared as the precue. In the Task precue condition a letter appeared as the precue and in the No precue condition a white square outline appeared as the precue. After Experiment 2 was completed, it was noted that in order to balance the appearance of the stimuli, there should have been a neutral square outline around the task cue in the conditions in which the task cue appears separately from the hand cue. Therefore, for Experiment 3, a neutral white square outline (identical to that used in the No precue condition) was added around the task cue in the conditions in which it appears apart from the hand cue. This white square outline did not provide any information regarding the task, it was simply included to balance the presentation of the stimuli across the four different precue conditions. This change only affected the Task and Hand precues, as these were the precue conditions in which the stimuli representing task and hand did not appear simultaneously. In all other respects (e.g. the timing of the presentation of the stimuli, the color of each stimuli, etc) the appearance of the trial stimuli and the trial design did not change from Experiment 2 to 3.

5.2.6 Procedure

The same procedure used in Experiment 2 was used for this experiment. One change was made for the detection of errors. In Experiment 2, if a trial was performed incorrectly, it was repeated at the end of that section. For example, if the tool slipped from the participant's hand just after contact (in other words, a firm grip was not established), this would have resulted in an error trial, which would be repeated at the end of the section. Similarly, if the participant used the wrong hand to perform the trial, this error would also have been detected by the program (since the wrong starting key would have been released), resulting in a repetition of the trial at the end of the section. This procedure was again used in Experiment 3. However after Experiment 2 was completed it was noted that this method did not allow for the capture of errors when the participant performed the wrong task with the tool. Therefore in Experiment 3 an additional procedure was added: the experimenter could press a specific key on the keyboard which would indicate that the trial should not be counted and should be repeated at the end of the section. This was done to capture any mistakes made by the participant in the performance of the task.

5.2.7 Data Analysis

The method of data analysis used in Experiment 2 was also applied to Experiment 3. An outlier analysis was first applied to the data. The program used was developed by Van Selst and Jolicouer to determine outliers and is unaffected by sample size (Van Selst & Jolicouer, 1994). This program removed trials that were outliers, either too short or too long, and therefore indicative that the participant did not properly perform the movement. For example, the tool may have slipped from the participant's hand just after contact (in other words, a firm grip was not established), resulting in an error trial. Of the reaction time trials, only 0.26% were removed. For the movement time trials 5.53% were removed. And for the Replace trials (tool replaced on sensor after movement), 4.22% were removed.[6]

For all analyses, the Bonferroni adjustment was applied for multiple comparisons. A value of $p < 0.05$ was used as the level of significance. For a list of all non-significant main effects and interactions, please refer to Appendix 5. For reaction time and movement time, reference will be made to the specific hypotheses outlined in Experiment 2, although the hypotheses will not be addressed in the same order.

5.3 Results

5.3.1 Reaction Time

A repeated measures analysis of variance was performed that examined precue condition (4: Both, Task, No, Hand) by task (2: Lift, Use) by hand used (2: Left, Right). This three-way interaction was not significant {$F(3, 123) = 0.98$, $p = 0.40$}. This replicated the result of Experiment 2, hypothesis 6. First, the main hypothesis for Experiment 3, regarding the right hand advantage for reaction time for the No precue condition will be addressed. Then the other main effects and interactions will be discussed.

The results of this experiment showed that the interaction of precue by hand was not significant {$F(3, 123) = 0.91$, $p = 0.44$}. This was in contrast to Experiment 2, where a right hand advantage was found for the No precue condition. Four a priori t-tests were then performed to examine the hand effect for each precue condition. The results of the t-tests were not significant for any of the precue conditions in Experiment 3: Both precue {$t(41) = 0.76$, $p =$

[6] With this program, if for example, a reaction time trial was removed as an outlier, the same trial was also removed from the movement time and replacement time data.

0.80}, Task precue {$t(41) = 0.04$, $p = 0.99$}, No precue {$t(41) = 0.09$, $p = 0.92$}, and Hand precue {$t(41) = 1.43$, $p = 0.74$}.

Turning to the other reaction time results, first, there was no difference between the hands in terms of reaction time, as the main effect of hand was not significant {$F(1, 41) = 0.01$, $p = 0.94$}, with a mean reaction time of 897.80ms, SE = 10.43ms for the left hand, and a mean reaction time of 898.11ms, SE = 9.62ms for the right hand.

The main effect of task was not significant {$F(1,41) = 2.12$, $p = 0.15$}. In other words, there was no difference in reaction time between the Lift (mean = 895.68ms, SE = 9.92ms) and Use (mean = 900.24ms, SE = 9.92ms) tasks. The interaction of task by hand was also not significant.

The main effect of precue {$F(3,123) = 170.63$, $p < 0.001$, $\eta^2 = 0.81$; see Figure 15} was significant. As was found in Experiment 2, there were significant differences between all precue conditions, and reaction time increased as the amount of advance information decreased: from the Both (mean = 789.39ms, SE = 13.01ms) to the Task (mean = 912.61ms, SE = 8.15ms) to the No (mean = 1039.59ms, SE = 15.63ms) precue condition. The Hand precue was significantly different from all the other precue conditions (mean = 850.25ms, SE = 10.26ms), and in terms of order, came between the Both and Task precue conditions.

Next, the interaction of precue by task was found to be significant {$F(3, 123) = 5.51$, $p < 0.001$, $\eta^2 = 0.12$} (Figure 16). Post-hoc analyses were performed to determine the source of the difference. Four one-way anovas were performed in which the lift and use task were compared for each precue condition. The Lift and Use tasks were significantly different for the Both precue {$F(1, 41) = 8.68$, $p < 0.05$, $\eta^2 = 0.18$} and for the Hand precue {$F(1, 41) = 8.81$, $p < 0.05$, $\eta^2 = 0.18$}. In both cases, the Lift task was initiated significantly faster than the Use task. In contrast there was no difference between the tasks for the Task precue {$F(1, 41) = 0.81$, $p = 0.42$} and for the No precue {$F(1, 41) = 1.13$, $p = 0.27$}.

5.3.2 Movement Time

As with the reaction time data, a 3-way repeated measures analysis of variance was performed examining the precue condition (4: Both, Task, No, Hand) by task (2: Lift, Use) by hand used (2: Left, Right) interaction. This interaction was not significant {$F(3, 123) = 0.01$, $p = 1.00$}.

The results of the movement time data replicated and extended the work of Experiment 2. First, the main effect of hand was significant {$F(1,41) = 9.93$, $p < 0.01$, $\eta^2 = 0.20$} such that the right hand (mean = 341.33ms, SE = 11.63ms) was significantly faster than left hand (mean = 380.38ms, SE = 20.19ms).

Second, movement time increased as task complexity increased, as evidenced by the significant main effect of task {$F(1,41) = 10.27$, $p < 0.01$, $\eta^2 = 0.20$}. Movement time was significantly faster for the Lift task (mean = 343.80ms, SE = 12.08ms) than for the Use task (mean = 377.91ms, SE = 19.42ms).

Next, as shown in Figure 18, a significant interaction between task and hand was observed {$F(1,41) = 4.11$, $p < 0.05$, $\eta^2 = 0.12$). Post-hoc paired samples t-tests examining the difference between the hands for each task revealed a significant difference for the Lift task {$t(41) = 2.29$, $p < 0.05$, $\eta^2 = 0.09$} as well as the Use task {$t(41) = 2.81$, $p < 0.01$, $\eta^2 = 0.10$}. For both tasks, the right hand was significantly faster than the left hand. However, the difference between the hands was greater for the Use task (59.8m) than for the Lift task (18.3ms).

Finally the effect of precue on movement time was also examined in this experiment. Neither the main effect of precue nor any interactions with precue were significant. This indicated that movement time was not affected by the amount of advance information that was available, findings that replicate those seen Experiment 2.

5.3.3 Replacement Time

Replacement time, the time taken to perform the two tasks, was examined using a precue condition (4: Both, Task, No, Hand) by task (2: Lift, Use) by hand used (2: Left, Right) repeated measures analysis of variance. The results revealed only a main effect of Task {$F(1, 41) = 81.20$, $p < 0.001$, effect size = 0.66} with the replacement time for the Use task (mean = 388.98ms, SE = 34.58ms) being significantly longer than for the Lift task (mean = 140.02ms, SE = 11.75ms).

5.4 Discussion

By and large, the results of this experiment replicated the results of Experiment 2. First, there was no difference between the hands in terms of reaction time, as the main effect of hand was not significant. This supports the results of Experiment 2 (hypothesis 1), as well as the findings of the original precue experiment by Rosenbaum (1980).

Second, reaction time did not increase with an increase in task complexity, as the main effect of task was not significant. This also confirmed the results of Experiment 2 (hypothesis 4). Although the main effect of Task was significant in that case, recall that three tasks were used (Lift, Use, and Pantomime), and that post-hoc analysis determined that reaction time was significantly longer for the Pantomime task compared to the Lift and Use tasks, which did not differ. Thus this experiment confirms the main findings regarding the Task effect, as it relates to the Lift and Use task which were common to both experiments.

Third, the interaction of task by hand was not significant. This replicated the findings of Experiment 2 (hypothesis 5).

Fourth, the significant main effect of precue both replicated and extended the findings of Experiment 2 (hypothesis 2). First, regarding the three precue conditions used in the first experiment (Both, Task, No), the results were replicated. As was found in Experiment 2, there were significant differences between all precue conditions, and reaction time increased as the amount of advance information decreased: from the Both to Task to No precue. Second, the findings regarding the Hand precue extended the work of Experiment 2. The Hand precue was significantly different from all the other precue conditions. In terms of the relationship of increasing reaction time seen with increasing complexity of the precue conditions, this placed the Hand precue between the least complex precue condition (Both) and before the Task precue condition. In terms of the order of complexity of the precue conditions, the complexity increased from the Both, to the Hand, to the Task, to the No precue condition. Thus having advance information regarding the choice of hand while the task to be performed is unknown placed fewer demands on movement processing than having advance information regarding the task to be performed, with the hand to be used unknown. These findings make some intuitive sense, as it seems easier to prepare for an action, regardless of its difficulty, when you know what hand you will use. This was supported by the results of Rosenbaum (1980) who found that reaction time was greatest when the arm to be used was not known in advance, compared to both the direction and extent of the movement.

The significant interaction of precue by task highlighted several interesting results. It was found that for the Both and Hand precue conditions, the Lift task was initiated significantly faster than the Use task. However there was no difference between the tasks for the No and Task precue conditions. It is interesting that a task effect emerged for the two precue conditions in which the choice of hand was known in advance (the Hand and Both precue conditions). This further supported the idea that knowing hand in advance allowed for greater advance preparation of the subsequent movement (and was therefore a less demanding, or easier situation) than when the hand to be used was unknown in advance (a more difficult situation, as indicated by the reaction time results), as seen in the Task and No precue conditions.

One of the goals of this experiment was to determine whether the right hand advantage seen in the No precue condition of the first precue experiment (Experiment 2, hypothesis 3) was due to the type or amount of advance information. This was tested with the addition of the Hand precue condition, in which information regarding the choice of hand was known in advance (Figure 17). In this experiment, the interaction of precue by hand was not significant.

There were several interesting implications based on these results. As this analysis showed, there was no difference between the hands for the Hand precue condition, in other words, there was no right hand advantage. At first, this would seem to suggest support for the hypothesis that it was the *amount* of advance information that led to the finding of a right hand advantage in the No precue condition in the first experiment. However, this hypothesis was not entirely supported because in this experiment there was not a significant difference between the hands for the No precue condition. In the original hypothesis, if the *amount* of advance information was the key factor (e.g. no advance information versus some advance information), then a right hand advantage should have been seen only in the No precue condition, and not in the Hand, Task, or Both precue conditions.

These results also do not support the hypothesis that it was the *type* of advance information that was the key factor (i.e. programming task during reaction time), because in that case a right hand advantage should have been seen in both the Hand and No precue conditions.

Furthermore, the main effect of precue showed a significantly faster reaction time for the Hand precue condition than the Task precue condition. Both the Hand and Task precue conditions contained one piece of advance information and differed only in the type of advance information presented. However, since reaction time was faster for the Hand precue it seems likely that the type of advance information (e.g. knowing choice of hand in advance) was relevant. Note that this rests on the assumption that the one piece of advance information provided by the Hand and Task precues was equal in both cases.

The results noted above do not support the original hypotheses that either the amount or type of precue information alone was most relevant for the right hand advantage for reaction time seen in the No precue condition in Experiment 2. However, the results of Experiment 3 do suggest that both factors (amount and type of advance information) play a role. First, the amount of advance information was important in that the four precue conditions were clearly ordered in terms of increasing reaction time, from the Both precue condition (which provided full advance information) to the Hand precue condition, to the Task precue condition, and to the No precue condition (which provided no advance information). Although reaction time was longer when hand had to be programmed during reaction time (the Task precue condition) than when task had to be programmed during reaction time (the Hand precue condition), it was even longer when both hand and task had to be programmed during reaction time (the No precue condition).

Therefore the amount of advance information was important. This finding also demonstrated that the type of advance information was important. Since both the Task and Hand precue conditions provided one piece of advance information, if only the amount of advance information mattered then the reaction times for the Task and Hand precue conditions should not have differed. Instead, since the Hand precue had a significantly faster reaction time than the Task precue condition, this demonstrated that knowing the choice of hand in advance was more useful for movement planning than knowing the task to be performed in advance. Therefore, the type and amount of advance information were both important factors.

In contrast to Experiment 2 in which a right hand advantage was present only for the No precue condition, in this case there was not a right hand advantage for the No precue condition. In Experiment 2, the absolute difference between the left and right hands for the No precue was 25ms, whereas in this experiment the absolute difference between the hands for the No precue was less than one millisecond. The decrease in the size of the difference between the hands from Experiment 2 to Experiment 3 was most likely due to differences between the experiment designs. A few changes were made to the design of Experiment 3, including removing the Pantomime task, having each participant use only one tool, adding a precue condition, increasing the number of trials, and adding the neutral white box around the task stimuli in the Task and Hand precue conditions. Any of these factors may have caused the different results between Experiments 2 and 3 for this effect, although the increased number of trials for each task by hand by precue condition seems likely to have contributed to the different results.

The movement time results of Experiment 3 also largely replicated the results of Experiment 2. A right hand advantage for movement time was observed. This was consistent with the results of Experiment 2 (hypothesis 1), as well as much other research in the literature (Woodworth, 1899; Roy, Kalbfleisch & Elliott, 1984).

Movement time also increased as the complexity of the task increased, from the one component Lift task to the two component Use task (made up of lifting and using components). This also supported the results of Experiment 2 (hypothesis 2) as well as other previous research (Marteniuk et al., 1987; Roy et al., 1996).

The significant interaction between task and hand revealed that the right hand performed both tasks significantly faster than the left hand. This difference between the hands was greater for the Use task than the Lift task. Thus, the right hand advantage for movement time increased as the task complexity increased. This interaction was not significant in Experiment 2 (hypothesis 3), however the results in Experiment 3 exactly conformed to the predictions of hypothesis 3 from Experiment 2. The increase in movement time with task complexity was smaller for the preferred right hand. This hypothesis had stemmed from the results of Experiment 1, which showed an increase in the right hand advantage (in terms of preferred hand reaches) as the complexity of the task increased. This is one of the first experiments in the literature to show a manual asymmetry in response to task complexity for movement time.

As with Experiment 2, the main effect of precue on movement time was not significant, nor were any of the interactions involving precue. Thus there was no effect of precue on movement time (hypothesis 4).

For replacement time there was a main effect of task, such that the replacement time was significantly longer for the Use task than the Lift task. This finding makes sense: the Use task which involved two components, lifting and manipulating the tool, took more time to perform than the Lift task which involved only one component, lifting the tool. Also, replacement time was not affected by hand. In other words, the time to complete the tasks did not differ between the hands. Although a right hand advantage was evident for movement time, this difference between the hands disappeared for replacement time. This suggests that the early execution of the movement (reflected by movement time) was sensitive to the effect of hand although performing and completing the movement (represented by replacement time) was not.

5.5 Conclusions

The results of this second precue experiment both confirmed and extended the work of the first precue experiment. Several findings, such as the right hand advantage for movement time, no difference between the hands for reaction time, and that movement time increasing as the complexity of the task increased, all replicated the work of both Experiment 2 and previous literature.

Adding the Hand precue condition, in which the hand to be used was known in advance, illuminated several key findings for reaction time. This precue condition was added in order to determine whether the right hand advantage observed in the No precue condition in Experiment 2 was the result of the amount or type of advance information available. The lack of a right hand advantage in the Hand precue at first seemed to suggest that the right hand advantage in Experiment 2 was due to the amount of available advance information as seen in the No precue condition. However, in Experiment 3, there was also no significant difference between the hands for any of the precue conditions, including the No precue condition. Thus the hypothesis that it was the amount of advance information that was the key factor could not be the explanation. The lack of a right hand advantage for the No precue condition in this experiment was likely due to changes in the experimental design from Experiment 2. Based on the lack of a right hand advantage for the No precue condition in Experiment 3, it cannot be conclusively determined whether the cause of the right hand advantage for the No precue condition seen in Experiment 2 was due to the amount or type of advance information available. Based on the results of Experiment 3 however, it seems likely that both factors (type and amount of advance information) were relevant.

There were two findings in Experiment 3 that suggest that knowing the choice of hand in advance was an important factor in movement planning. First was that the reaction time for the Hand precue condition was significantly faster than the Task precue condition. Since both the Hand and Task precue conditions provided one piece of advance information, it must be easier to program or plan movements in which the choice of hand was known (and the task was unknown, i.e. the Hand precue) than movements in which the choice of hand was not known in advance (but the task was known, i.e. the Task precue). This finding was also supported by the results of the original precue experiment by Rosenbaum (1980). In that experiment, Rosenbaum found that of the three movement dimensions studied (arm, direction, and extent), reaction time was longest when the choice of arm (similar to choice of hand in this experiment) was not known in advance. Second, the interaction between precue and task also distinguished between the precue conditions in which the choice of hand was known in advance (the Both and Hand precues) and the precue conditions in which the choice of hand was not known in advance (the Task and No precues). These findings suggest that both the type of information provided in advance, as well as the amount of advance information, have an effect on reaction time. If only the amount of advance information mattered, then the reaction time for the Task and Hand precue conditions should not have been different, since the Task and Hand precue conditions each contained one piece of advance information. However as the Hand precue condition demonstrated, knowing the choice of hand in advance appeared to be more useful for movement planning than did knowing the task to be performed in advance. This was similar to the findings of Mieschke et al., (2001), that showed that knowing the amplitude of a movement in advance was more useful for movement planning than knowing the direction in advance.

One important finding of Experiment 3 was the significant interaction between task and hand for movement time (Figure 18). The right hand performed both tasks significantly faster than the left hand, however, this difference between the hands was greater for the Use task than the Lift task. This suggests that the movement execution time to pick up a tool (as reflected by movement time) increased with task complexity and that this effect was greater for the left hand. This interaction was not significant in Experiment 2, although there was a trend in this direction. One possibility was that the presence of the Pantomime task in Experiment 2 obscured the overall effect of task complexity, which was observed more directly in this experiment by the comparison of the Lift and Use tasks in isolation. One other possibility was that the sample size was larger in Experiment 3, which increased the power and therefore allowed for the detection of this result. The experiment by Roy (1996) showed an overall right hand advantage for movement time, however this was unaffected by task complexity. The Roy (1996) experiment involved moving dowels, and complexity was defined as placing the dowels in to smaller or larger receptacles. Perhaps the different nature of the tasks used in the Roy (1996) experiment and in Experiment 3 may account for the different findings. In any case, this finding makes Experiment 3, which involved grasping and interacting with tools, one of the first experiments to demonstrate a task complexity effect on manual asymmetries for movement time, with task complexity having a greater effect on the left hand than the right hand.

This experiment further extended the findings of Experiment 2 by examining replacement time (the time between lifting the tool and replacing it back on the sensor). This represented the time participants spent performing the tasks with the tool. Of all the variables studied in this experiment, only the task performed with the tool affected replacement time, with the Use task requiring a significantly longer replacement time than the Lift task. One important finding to note was that the task by hand interaction was not significant for replacement time. In other words, the time to complete the tasks did not differ between the hands. Although a right hand advantage was evident for movement time, this difference between the hands disappeared for replacement time. This suggests that movement execution (reflected by movement time) was sensitive to the effect of hand although interacting with the tool and completing the movement (represented by replacement time) was not as sensitive to the effect of hand. Finally, the precue conditions had no effect on replacement time, or on movement time.

In summary, Experiment 3 replicated many of the findings of Experiment 2, and also provided new insight into the importance of both the amount and type of precue information on reaction time. Furthermore Experiment 3 is one of few experiments in the literature that has found a significant interaction of hand and task for movement time, such that the right hand advantage for movement time increased as the task complexity increased.

Chapter 6: General Discussion

The goal of this research was to use simple manipulations of task demands in order to examine manual asymmetries during the performance of reaching movements to tools. These experiments were designed to replicate and extend earlier research on manual asymmetries, and add to these findings by exploring new directions (e.g. the use of the precue technique for studying grasping movements to tools, and the systematic exploration of different variables on movement initiation and execution for grasping movements to tools). Manual asymmetries were of interest because it is an observable behaviour that provides insight into hemispheric specialization for different motor tasks; and in particular, the planning and execution of grasping movements to tools.

In the first experiment, task demands (lift or use) and type of object (tool or dowel) were manipulated in order to examine differences in terms of patterns of hand preference between the hands for reaching movements within working space, with both left- and right-handed participants. In the second and third experiments, the effect of the amount of advance information (precue condition) and task demands (lift, use or pantomime), was manipulated to examine manual asymmetries for reaction time and movement time for reaching movements to tools. The results of these experiments illustrated how manual asymmetries may be influenced by simple manipulations of task demands. In Experiment 1, a preference-based measure of hand performance was used to examine the effects of task demands on manual asymmetries. In Experiment 2 and 3, the effect of task demands on manual asymmetries for performance measures such as reaction time and movement time were examined.

The first experiment used a performance-based measure of hand preference to assess several aspects of reaching movements to objects. In this experiment participants were free to choose which hand to use to perform the task. Several findings support the task-specific view of movement planning. The first example of this is evident from comparisons of the Lift task to the PUO (pick-up object) task. Recall that for this experiment, participants were asked to perform two tasks: lift and use the object. The use task can be understood as being comprised of two components: lifting the object and using the object. When the Lift task and PUO tasks were compared, both left- and right-handed participants made significantly more preferred hand reaches to the PUO task than the Lift task. Thus although PUO and Lift represent the same action (lifting the object), the intent of the tasks was different (to either simply lift the object or to lift and then use the object). This difference in intent was reflected in the significantly higher frequency of preferred hand reaches for the PUO task compared to the Lift task. This finding supported a task-specific view of movement planning because although the tasks were the same, participants reacted differently to the tasks based on the ultimate goals of the movement (Rosenbaum, 1990; Roy, 1996).

A comparison of the PUO and Use tasks also highlighted another example of the task-specific view of movement planning. Within contralateral space, left- and right-handers both performed significantly more preferred hand reaches to the Use task than the PUO task. Since the PUO task was the lifting component of the use task, this finding indicated that on a number of occasions, participants must have picked up the object with their non-preferred hand and then switched the object to their preferred hand to use it. Within contralateral space, this switching of the object makes some sense from a biomechanical perspective, since to pick up the object with the preferred hand in contralateral space would require reaching over the body midline, a somewhat awkward movement. The relative comfort or awkwardness of reaching movements was examined in my master's research (Mamolo et al., 2006), which found that reaching movements made to contralateral positions by the preferred hand were indeed significantly less comfortable than reaching movements made to ipsilateral positions.

Experiment 1 was the first experiment to report and examine switching behaviour in detail. This was done through the explicit observation of the PUO task. Switching behaviour was of interest because it represented a strategy employed by some participants in response to the task and location demands of some trials (e.g. having to use a tool within contralateral space). Whereas some participants would lift and use the object with their preferred hand in contralateral space, other participants adapted what may perhaps be considered a more biomechanically efficient approach, and lifted the object with their non-preferred hand and then switched the object to their preferred hand to use it. Because this experiment allowed participants to react naturally to the given task, it was possible to observe and study switching behaviour.

An examination of switching behaviour revealed differences between the handedness groups. Right-handers made an average of 3.0 switches each, and 32.9% made no switches at all. In contrast, left-handers made an average of 5.0 switches each, and only one participant did not make any switches at all. These findings indicated that right-handers were more likely to persist in using their preferred hand in most situations, even within contralateral space, whereas left-handers were more willing to use their non-preferred hand to perform simple tasks.

Experiment 1 was also the first experiment to directly compare reaching movements between tools and other neutral objects, in this case dowels. Several novel findings emerged. First, each handedness group made significantly more preferred hand reaches to the tool than to the dowel. This finding highlighted the association between tools and the preferred hand. Second, for the dowel, preferred hand reaches increased from the Lift to the PUO to the Use task within contralateral space. If participants had treated the dowel as a neutral object, then there should not have been any differences in terms of preferred hand reaches between the tasks. Instead the goal of the movement to be performed with the dowel affected the choice of hand.

Another interesting difference emerged when the reaching patterns to the dowel for left- and right-handed participants were compared. Right-handers made significantly more preferred hand reaches to the dowel than did left-handers. In contrast there was no difference between the groups in the frequency of preferred hand reaches to the tool. This finding suggested that right-handers were more willing to treat the dowel as if it were a tool, in terms of the frequency of preferred hand reaches. Left-handers instead showed greater willingness to use their non-preferred hand to interact with the dowel, again supporting the notion that left-handers more often than right-handers gain greater experience with using their non-preferred hand for simple tasks (Porac & Coren, 1981; Calvert & Bishop, 1998; Steenhuis & M.P. Bryden, 1999).

One limitation of Experiment 1 was that the complexity of the task demands may not have been challenging enough. Because this experiment addressed reaching movements to tools and dowels, even using the objects (although more demanding a task than just lifting the object) may have been considered relatively easy, even when reaching to the farthest contralateral position. One possibility for increasing the complexity of the task may be to have participants perform tasks with tools that require more precision or dexterity, such as tracing a small detailed line drawing with a pencil or using a spoon to move small particles such as peppercorns into a narrow container. This could be addressed in a future experiment that compares the tasks used in this experiment to ones that involve a higher degree of spatial and motor precision. The use of tasks requiring greater precision may draw out further laterality differences between the hands.

An alternate possibility to increase task complexity may be to make the working space area more crowded. With Experiment 1, and most other performance-based measures of hand preference experiments, the objects were placed in an array within working space, with nothing in between the participant and the objects. It may be interesting to examine the effect of adding distracting non-target objects to the area between the participant and target objects, such that the participant has to reach between or around the distractor objects to get to the target objects. This would have the effect of making the reaching movements to the target objects more difficult. Furthermore, this would also have the effect of making the working space area slightly less artificial, in that a more crowded space with non-target objects are regularly part of the everyday environment. People often have to reach around non-target objects, or do no have a clear reaching path, in order to grasp their target object. It may be interesting to see what effect this would have on reaching patterns within working space.

Another possible extension of Experiment 1 would be to place IREDS on the hands of participants during the experiment. With IREDS, kinematic measures can be collected, such as peak velocity, deceleration, and time to peak velocity. It may be interesting to examine these variables and compare the preferred and non-preferred hands for reaching into contralateral space to grasp and interact with dowels and tools.

Overall, Experiment 1 therefore replicated and extended several key findings in the literature regarding performance-based measures of hand preference. Novel findings from Experiment 1 included the examination of switching behaviour and the comparison of reaching patterns to tools and dowels.

The second and third experiments used the precue paradigm to examine the effect of different variables, including task demands, on manual asymmetries for reaching to and interacting with tools. Experiment 2 was the first experiment, to my knowledge, to use the precue paradigm to examine reaching movements for grasping tools. In particular, although movement time had been previously examined for reach-to-grasp movements, Experiments 2 was the first to explicitly address movement initiation time, represented by reaction time for reach-to-grasp movements of tools. Interestingly, the results of Experiment 2 were similar to many of the findings within the visually-guided aiming movement literature. Experiment 2 therefore provided the first comprehensive examination of manual asymmetries for reaching and grasping movements to tools. These results were largely replicated by Experiment 3.

In Experiment 2, it was demonstrated that as the amount of advance information available in the precue decreased, reaction time increased (from the Both to Task to No precue condition). In contrast movement time was not affected by the precue condition. Thus movement planning and initiation (reaction time) but not movement execution (movement time) was sensitive to the amount of advance information. With Experiment 3, the addition of the fourth precue condition (Hand) provided more insight into movement planning, as reaction time was found to increase from the Both to the Hand to the Task to the No precue condition. Thus the Hand precue (which provided one piece of advance information) had a significantly faster reaction time than the Task precue (which also provided one piece of advance information). This finding demonstrated that the type of information provided in advance, as well as the amount of advance information, had an effect on reaction time. If only the amount of advance information mattered, then the reaction time for the Task and Hand precue conditions should not have been different. As the Hand precue condition demonstrated, knowing the choice of hand in advance appeared to be more useful for movement planning than did knowing the task to be performed in advance. Similar findings regarding the importance of knowing which hand to use in advance were observed with Rosenbaum (1980). In Experiment 3, the precue conditions that provided advance information on the choice of hand (the Both and Hand precue conditions), the Lift task was initiated in less time than the Use task. In contrast for the Task and No precue conditions (in which choice of hand was not known in advance) there was no difference in reaction time between the Lift and Use tasks.

In Experiment 2, a right hand advantage was observed for the No precue condition. In Experiment 3, the Hand precue condition was added to study this effect in more detail. However in Experiment 3 there was no difference between the hands for any of the precue conditions. This was likely due to a decrease in power for the precue by hand interaction from Experiment 2 to 3.

Experiment 3 showed a significant task by hand interaction for movement time, such that the right hand advantage for movement time increased as the difficulty of the task increased (from the Lift to the Use task). This interaction had been hypothesized based on the results of Experiment 1, which showed an increased frequency of preferred hand reaches as task difficulty increased. Although this interaction was not significant in Experiment 2, the results showed a trend in this direction. It is likely that the greater sample size and increased power in Experiment 3 led to the significant finding.

Replacement time was added to Experiment 3 to study if manual asymmetries were present for the time spent interacting with the tool and completing the movement. The right hand advantage seen for movement time was not present for replacement time. Thus by the completion of the movement there was no difference between the hands. These findings indicate that the early execution phase of the movement (represented by movement time) was most sensitive to manual asymmetries.

One limitation to the interpretation of the results was that some changes were made to the design of Experiment 3. For example testing each participant on one tool only, the removal of the Pantomime task, and the addition of the neutral white box to balance the trial designs for the

Task and Hand precues were differences between the two experiments. Although Experiment 3 replicated many of the findings of Experiment 2, there were some differences, most importantly the lack of a right hand advantage in the No precue condition in Experiment 3. Because of the changes made to the experimental design for Experiment 3, it was not possible to determine the source of these differences in the results. Therefore, if this experimental paradigm is to be used for a future experiment, it would be advisable to carefully consider the trial design and appearance of the stimuli.

Another limitation for Experiments 2 and 3 was the appearance of the stimuli. Recall that the task was cued by a letter and the choice of hand was cued by a colored square outline. The choice of hand cue was therefore not a direct or explicit mapping. Although participants learned this mapping fairly quickly during the practice trials, it may be beneficial in the future to use a more direct mapping between the appearance of the cue and the choice of hand. A simple alternative may be to use a left and right arrow to indicate the left and right hands, respectively. This may make the trials simpler in the future, and therefore easier for participants.

There are several possibilities for future experiments involving this precue paradigm. First, it would be interesting to test left-handed participants. Although the results of the first experiment (as well as the work of Boulinguez et al., 2001a and 2001b) found that in general there were many more similarities than differences between the handedness groups, it would still be of interest to observe the results with left-handers. The results of Experiment 1, for example, illustrated that there are subtle differences between left- and right-handers that would be of interest to explore in the precue paradigm. Second, dowels could be incorporated into the experiment. This would provide the opportunity to examine if the differences observed in the reaching patterns between tools and dowels in the first experiment would be manifested as differences in reaction time and movement time. Another experiment would be to use EMG recordings to examine premotor time, in addition to reaction time and movement time. Premotor time is believed to be a purer representation of movement planning than reaction time. It would therefore be interesting to observe premotor time for grasping movements to tools.

Another possibility would be to address one limitation of Experiment 2 and 3 by adding more positions. Only the midline position was used for Experiments 2 and 3. This was largely due to practical reasons. Since this was the first time the precue paradigm had been tested in grasping movements as opposed to aiming movements, it was important to make sure the paradigm worked, and so to start only one position was used. Second, there were already a large number of variables being studied (amount of precue information, task demands, choice of hand) with a correspondingly large number of trials. In the interests of simplicity, it was decided to limit the number of positions tested. Now that Experiments 2 and 3 have demonstrated the feasibility of using the precue paradigm for reaching movements to grasp a tool, it seems reasonable that a future experiment could examine the effect of position. One possibility would be to use three positions – a midline, left, and right position.

In all three experiments grasping movements to tools were examined. Experiment 1 provided insight into the differences between tools and neutral objects such as dowels. Experiments 2 and 3 were the first to systematically study movement initiation and execution for grasping movements to tools. Tools were of interest because of their relevance to activities in everyday life. Also, because tools are designed for a particular function, they allow for a simple manipulation of task demands. Tools can be grasped with the intent to simply lift it, or they can be grasped with the intent to use it to perform its particular function. The use of tools demonstrated the privileged association between preferred hand use and tool use, and also how the intent or goal of the movement has a very real effect on movement planning.

Manual asymmetries were observed across all three experiments. In Experiment 1, manual asymmetries in the form of patterns of hand preference were examined. Hand preference was shown to be sensitive to the position of the object in working space, the skill demands of the task, and the type of object that was involved. There was a greater frequency of preferred hand reaches for objects within ipsilateral space, for more demanding tasks, and for the tool. In Experiment 2 manual asymmetries were observed in the form of a right hand advantage for the No precue condition for reaction time and as an overall right hand advantage for movement time. In Experiment 3, no right hand advantages were observed for reaction time. However there was an overall right hand advantage for movement time, and this interacted with task demands such that the difference between the hands increased for the more skill demanding task. Experiment 3 also examined replacement time, for which there were no right hand advantages. The results of Experiment 3 therefore indicate that the early movement execution phase, as represented by movement time, was most sensitive to manual asymmetries. It is interesting that when given the choice to use one hand or the other, as in Experiment 1, participants showed clear patterns of preference for their preferred hand. In contrast, the results of Experiments 2 and 3 demonstrated that the differences between the hands in terms of performance were much more subtle. Both hands were largely equally skilled at performing the tasks, with only small differences in favour of the right hand; for movement time for example. Differences in preference therefore seem to overshadow the differences in performance between the hands.

As these experiments demonstrated, manual asymmetries for the performance of reaching movements can be elicited by simple manipulations of task demands. The variables that were studied under controlled circumstances in these experiments, such as task demands, type of object, and amount of advance information, make up just a few of the factors that are commonly involved in the planning and execution of reaching movements. In everyday life these variables are seamlessly integrated and thousands of reaching movements to tools and other objects are performed every day. That we usually perform these actions flawlessly, and with little conscious thought or effort, underscores the remarkable adaptation of human motor control to the demands of the external environment to produce these task-specific actions.

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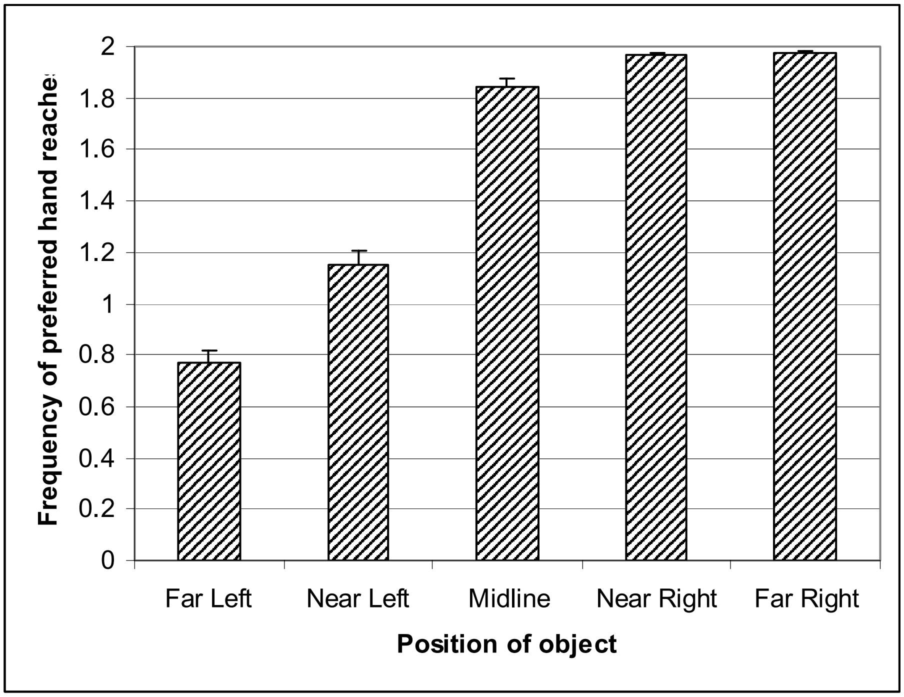
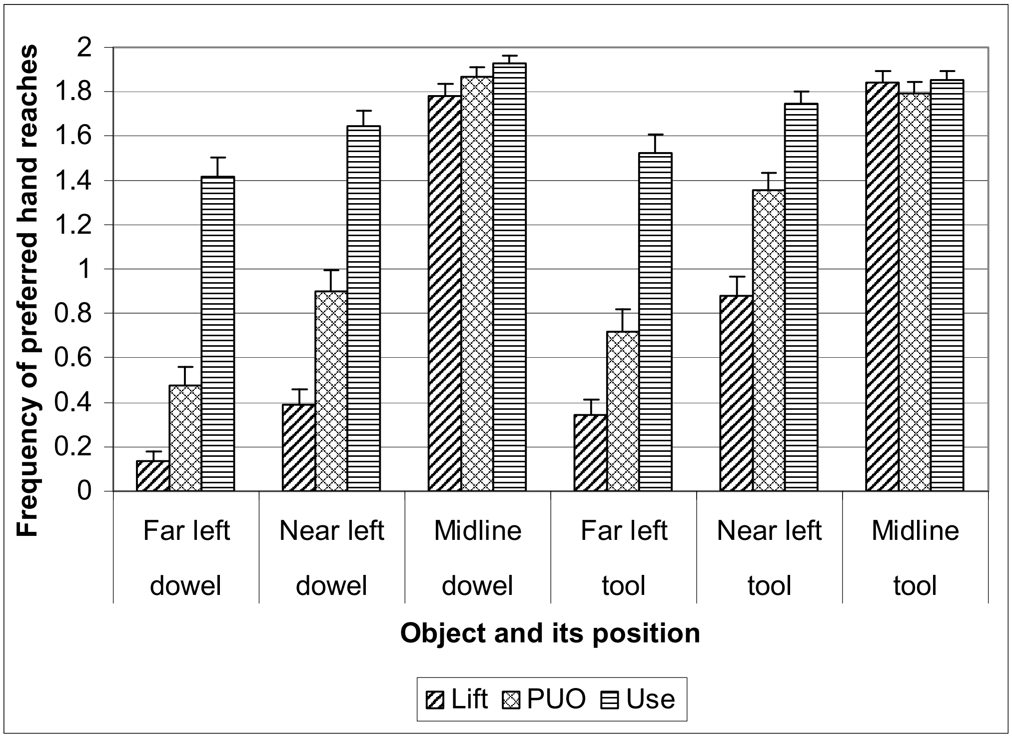
Figures

Figure 1: Frequency of preferred hand reaches across the 5 positions in hemispace, for right-handed participants.



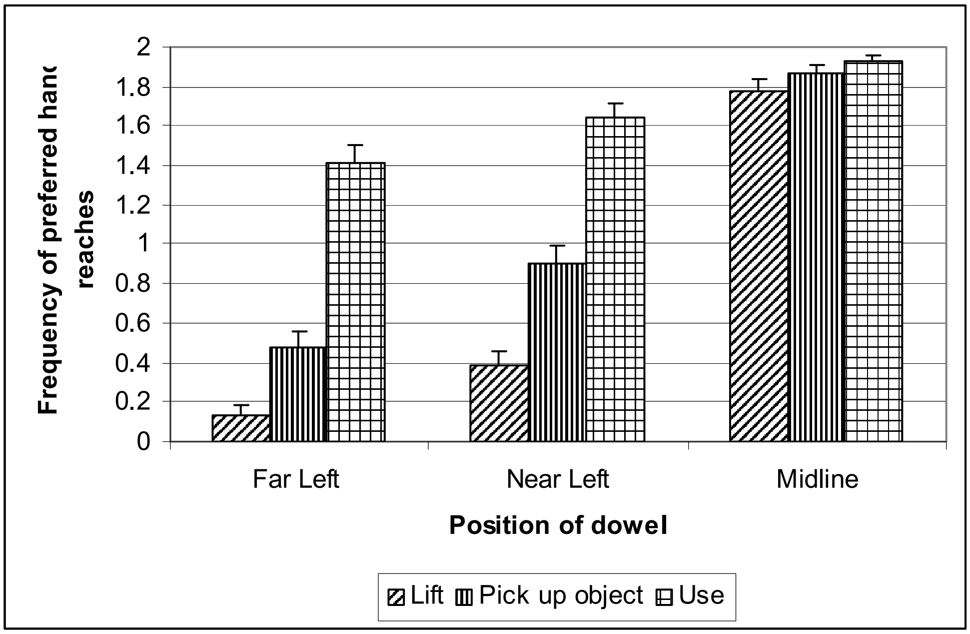
The frequency of preferred hand reaches performed by right-handed participants is shown for each of the positions across working space. Preferred hand reaches are at a maximum for the Near and Far Right positions within ipsilateral space.

Figure 2: The three-way interaction of object by task by position (3) for right-handed participants.



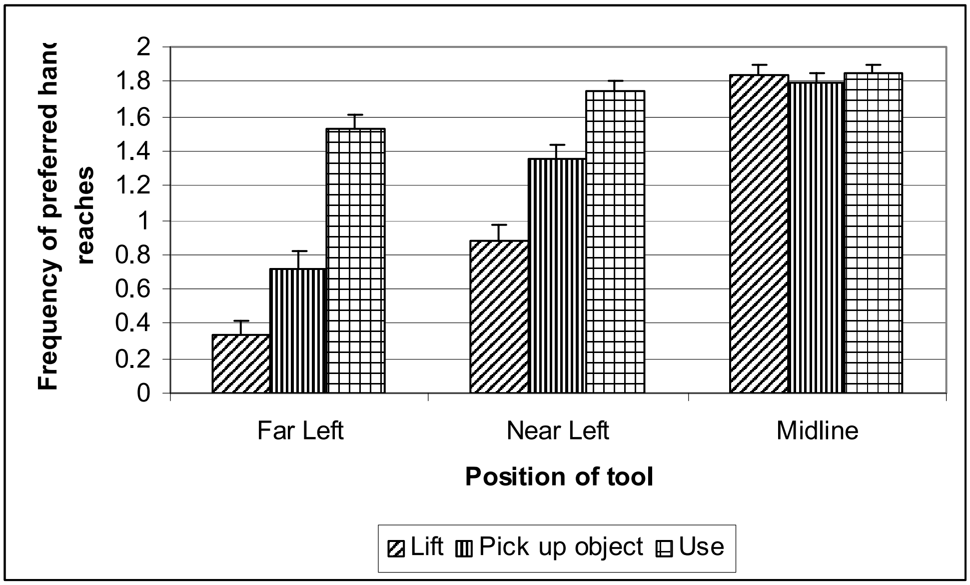
This figure illustrates the three-way interaction of object, task, and position (for the contralateral and midline positions) for right-handed participants. This interaction was decomposed by examining the task by position interaction for each object separately (shown in Figures 3 and 4).

Figure 3: The task by position interaction for the dowel, for right-handed participants.



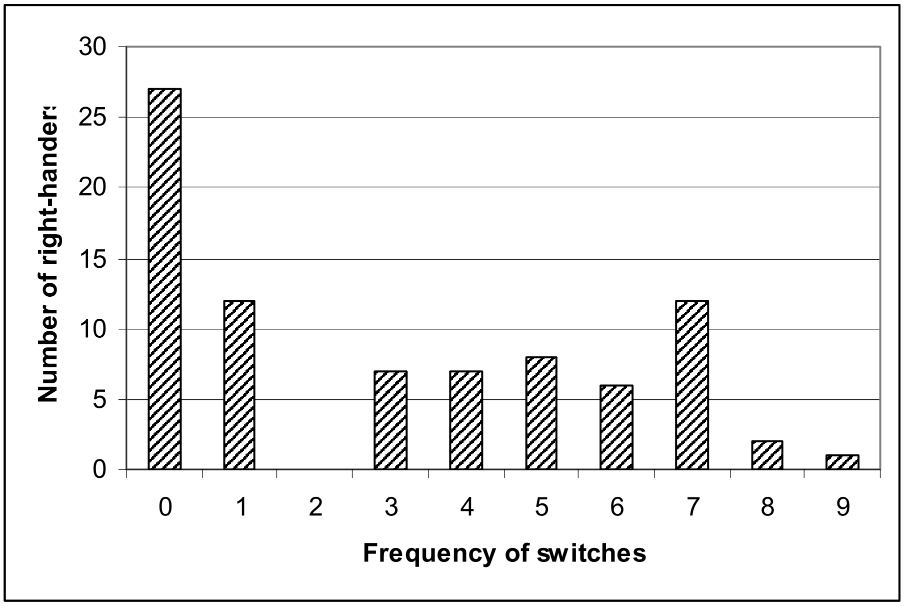
This figure shows the significant task by position interaction for the dowel, for right-handed participants. At the Far Left and Near Left positions, each task is significantly different from each other, with preferred hand reaches increasing from the Lift to PUO to Use tasks. In contrast at the Midline position only the Lift and Use tasks differed significantly from each other.

Figure 4: The task by position interaction for the tool, for right-handed participants.



This figure shows the significant interaction of task by position for the tool, for right-handed participants. Similar to the dowels, at the Far Left and Near Left positions each task differed significantly in terms of the frequency of preferred hand reaches. However at the midline position the task effect was not significant, with no difference in the frequency of preferred hand reaches performed for all three tasks.

Figure 5: The number of switches (Use - PUO) performed by each right-handed participant.

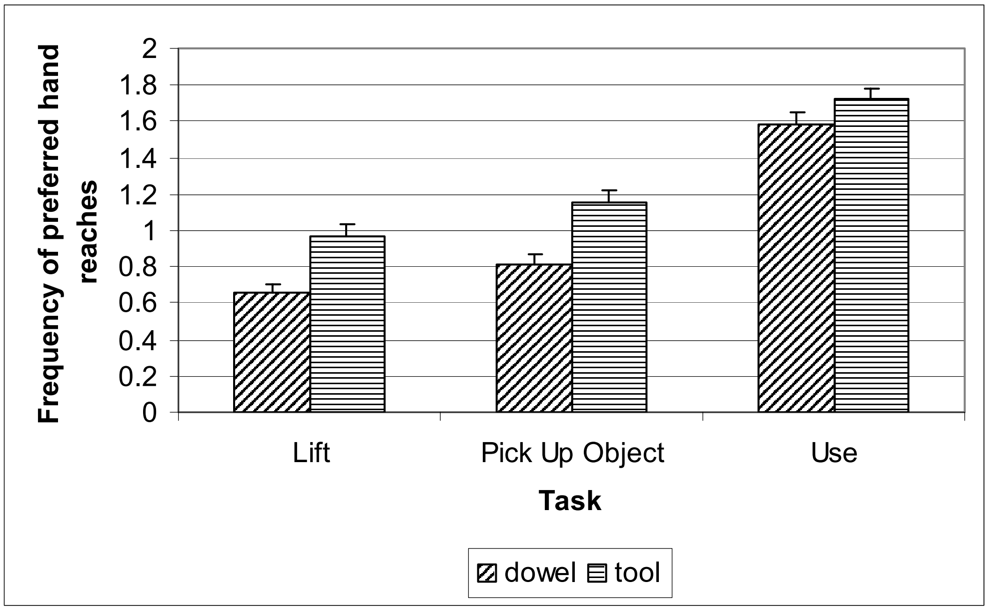


The number of switches (the frequency of preferred hand reaches for the Use task minus the frequency of preferred hand reaches for the PUO task) is shown in this figure. Almost one third of all participants did not perform any switches, indicating that they always lifted the object and then used it with the same hand. The average number of switches performed by each right-handed participants was 3.0.

Figure 6: The frequency of preferred hand reaches across the 5 positions, for left-handed participants.

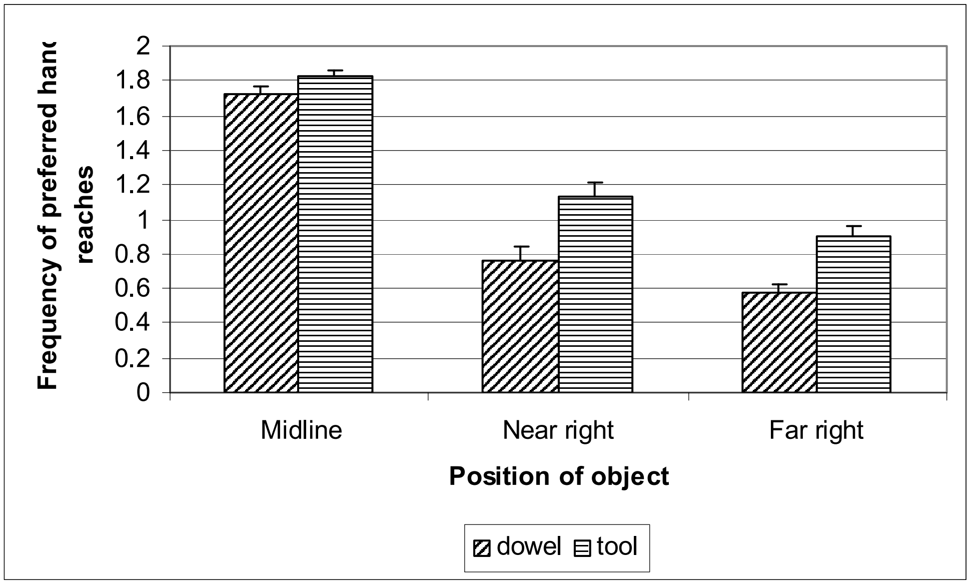
This figure shows the frequency of preferred hand reaches for left-handed participants, across the 5 positions in working space. At the Near and Far Left positions, the frequency of preferred hand reaches is at a maximum.

Figure 7: The interaction of object by task for left-handed participants.



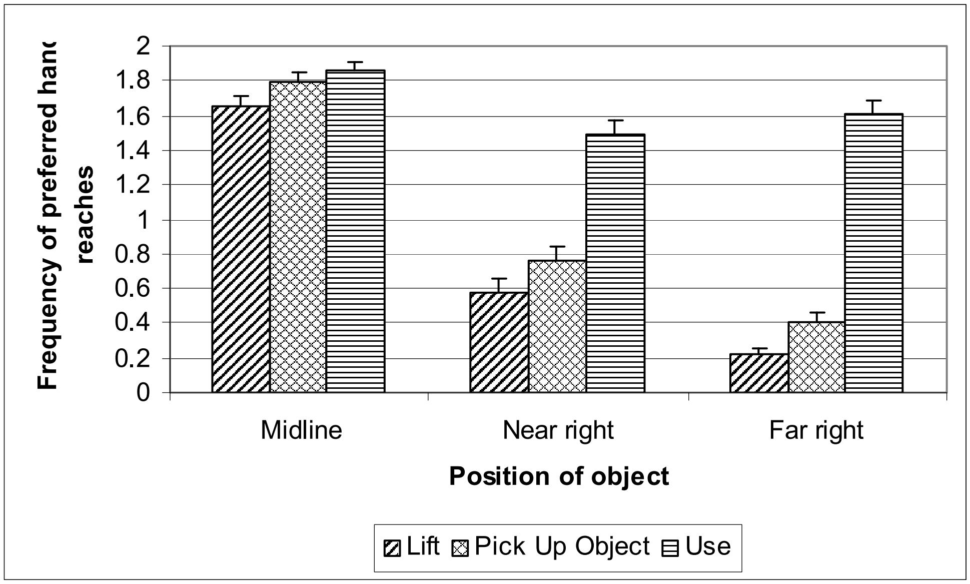
The significant interaction of object by task for the left-handed participants is shown in this figure. Significantly more preferred hand reaches were performed for the tool than the dowel for each task; however this difference was smaller for the Use task than the Lift and PUO tasks.

Figure 8: The interaction of object by position for left-handed participants.



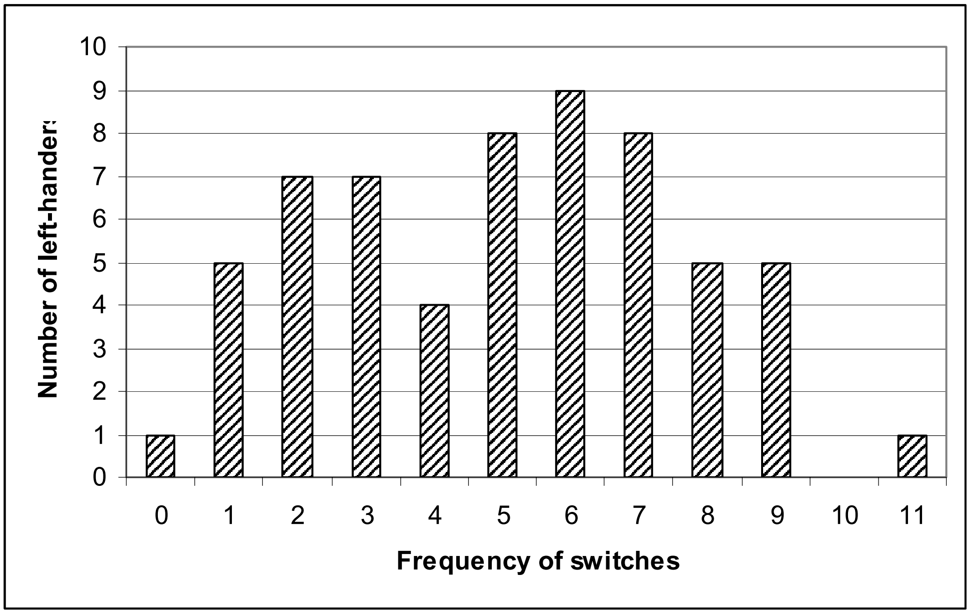
This figure shows the significant interaction of object by position for the left-handed participants. Significantly more preferred hand reaches were performed for the tool than the dowel for the at all three positions. However, the difference between the objects was greater for the positions in contralateral space (Near and Far Right) than the Midline position.

Figure 9: The interaction of task by position for left-handed participants.



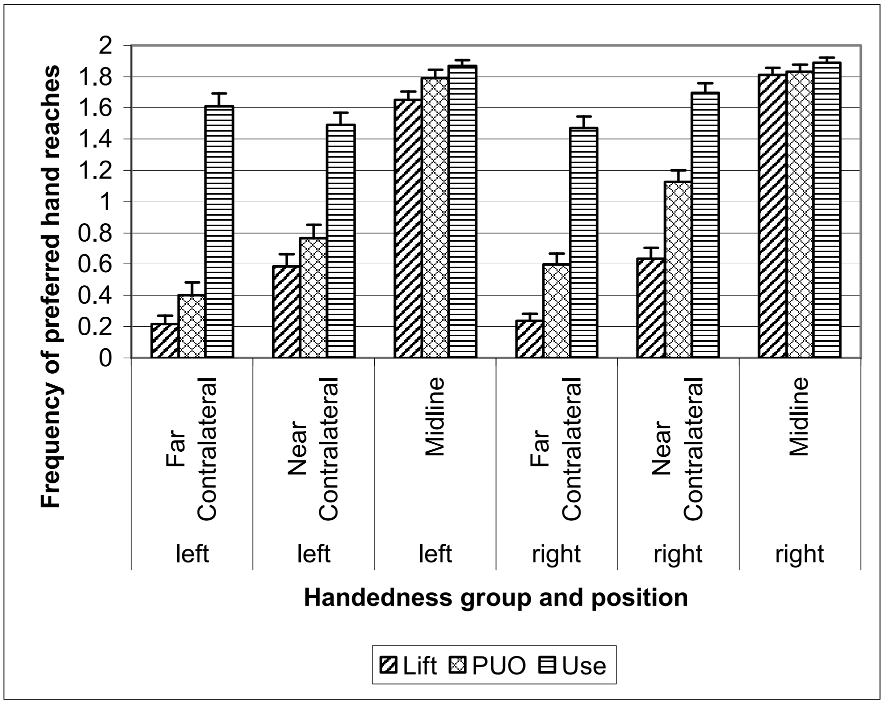
The significant interaction of task by position for left-handed participants is shown in this figure. The task effect was significant for all three positions. At the Near and Far Right positions, each task was significantly different, and the frequency of preferred hand reaches increased from the Lift to PUO to Use tasks. At the Midline position, significantly fewer preferred hand reaches were performed for the Lift task than the PUO and Use tasks, which did not differ.

Figure 10: The number of switches (Use - PUO) performed by each left-handed participant.



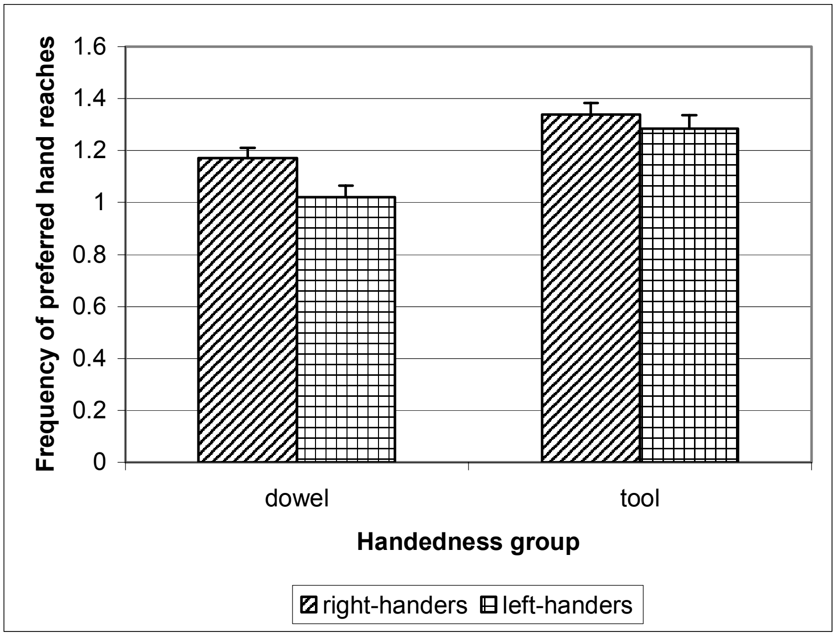
The number of switches (the frequency of preferred hand reaches for the Use task minus the frequency of preferred hand reaches for the PUO task) is shown in this figure. In contrast to the right-handed participants, only one left-handed participant did not perform any switches. Left-handed participants made an average of 5.0 switches each.

Figure 11: The three-way interaction of handedness group by task by position.



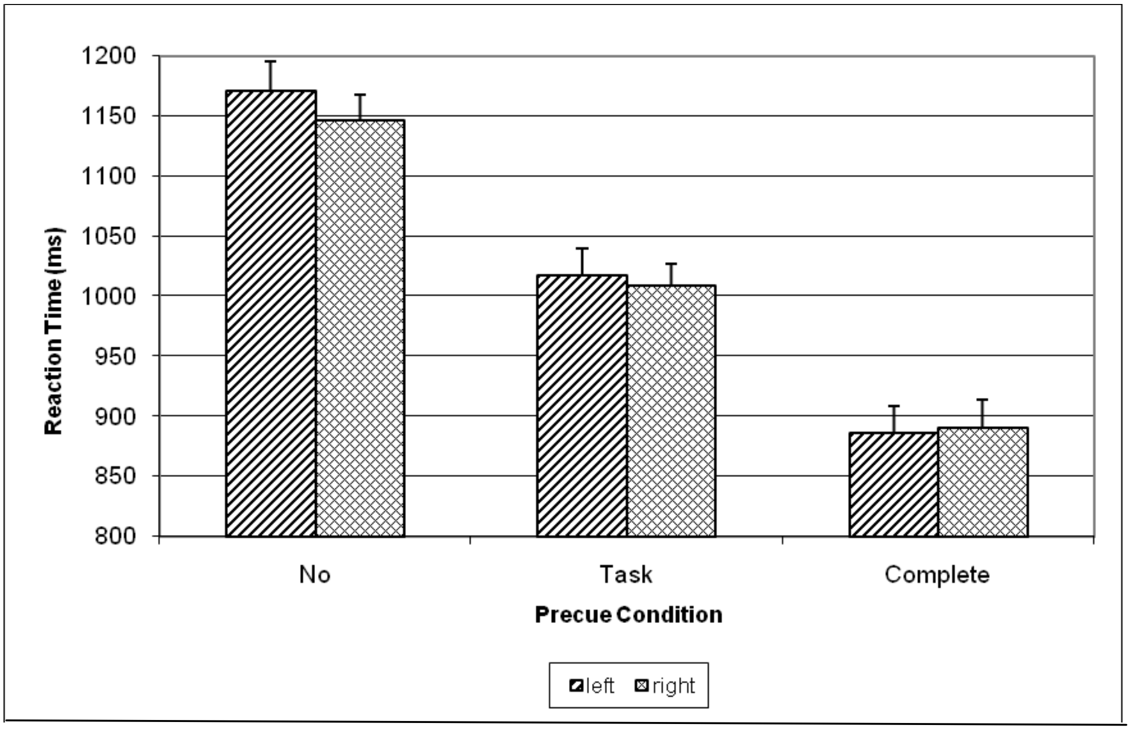
This figure illustrates the significant three-way interaction of handedness group by task by position (for the Midline and Near and Far Contralateral positions). For both right- and left-handed participants, the task by position interaction was significant. For both handedness groups, all three tasks were significantly different from each other at the Near and Far Contralateral positions. Differences between the groups emerged at the Midline position. For right-handers, significantly more preferred hand reaches were made for the Use task than the Lift task, and the PUO task did not differ from either the Lift or Use tasks. For left-handers, at the Midline position the frequency of preferred hand use was equal for the PUO and Use tasks, which was significantly greater than for the Lift task.

Figure 12: The handedness group by object interaction.



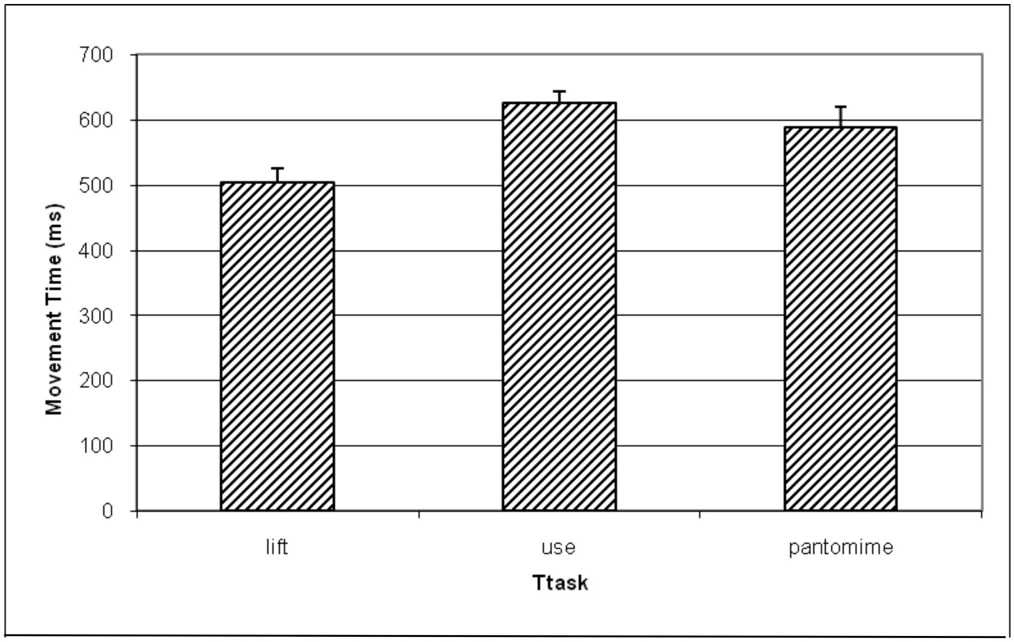
This figure shows the significant interaction of handedness group by object. Right-handed participants made significantly more preferred hand reaches to the dowel than did left-handed participants. However the handedness groups did not differ in terms of the frequency of their preferred hand reaches to the tool.

Figure 13: The interaction of precue condition by hand for reaction time.



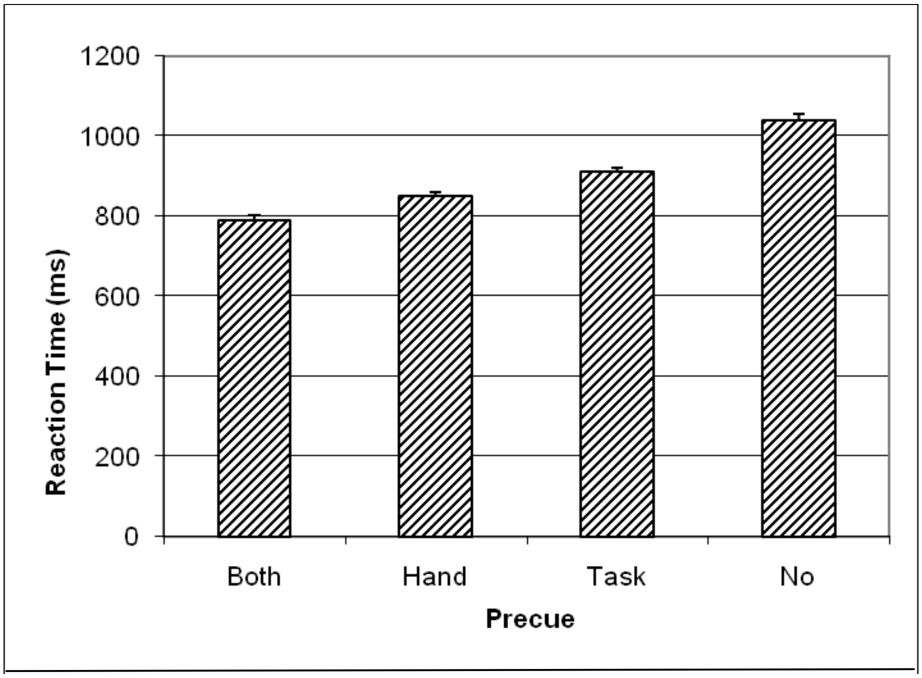
This figure shows the significant interaction of precue condition by hand for reaction time. For the Task and Both precue conditions there was no difference between the hands in terms of reaction time. Only for the No precue condition did the right hand initiate the movement faster than the left hand.

Figure 14: The main effect of task for movement time.



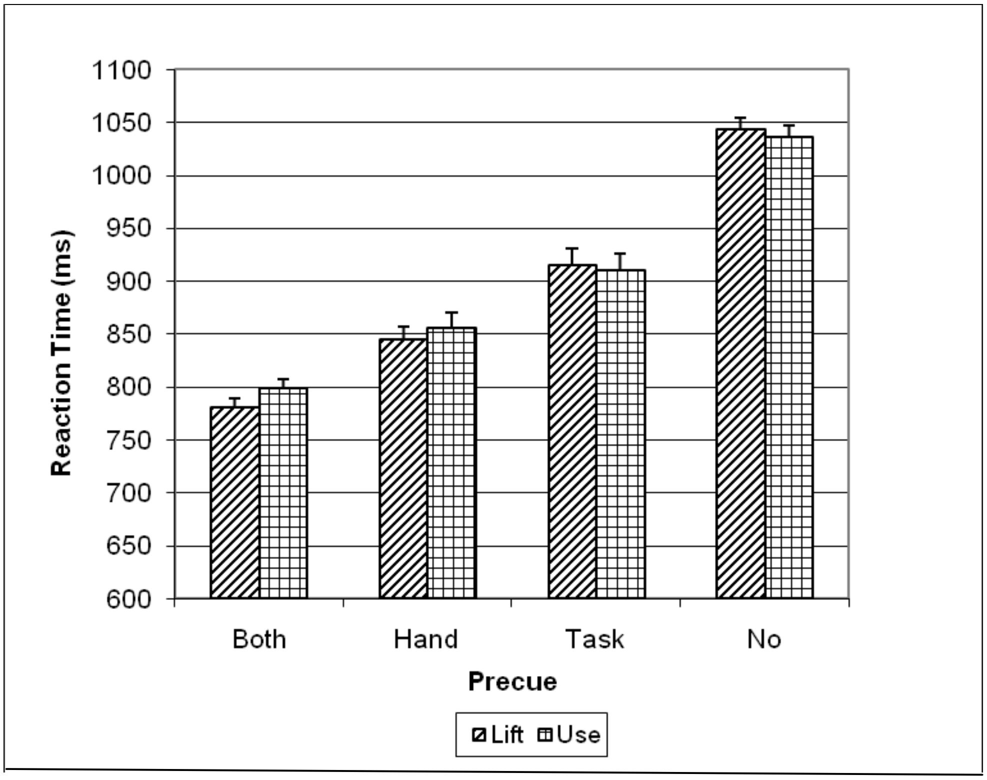
The significant main effect of task on movement time is illustrated in this figure. Movement time was significantly faster for the Lift task than the Use and Pantomime tasks, which did not differ.

Figure 15: The main effect of precue condition on reaction time.



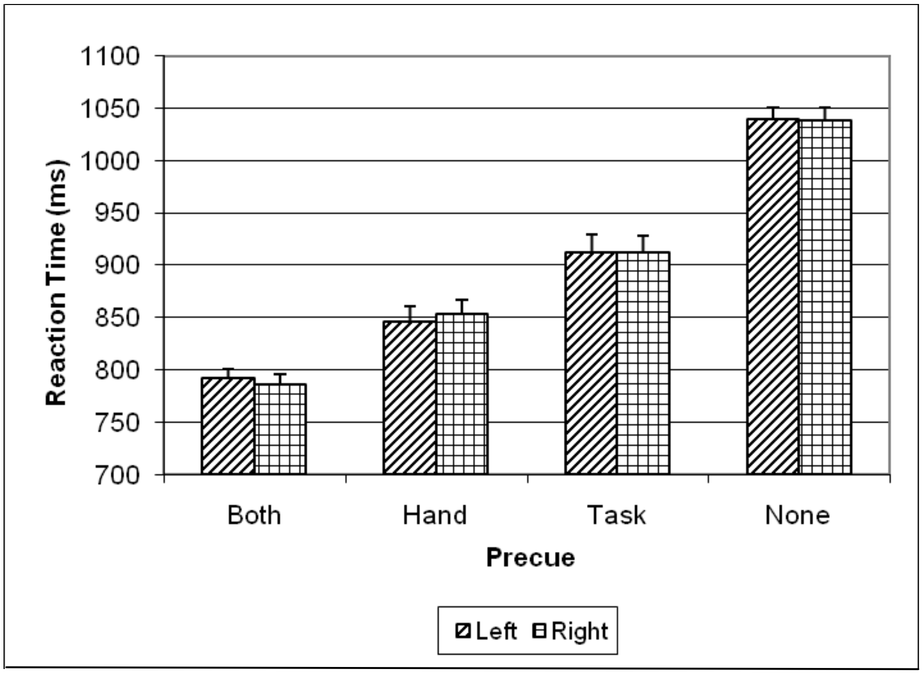
The significant main effect of precue condition on reaction time is shown in this figure. Post-hoc analyses revealed that each precue condition differed significantly from each other. Reaction time therefore increased as the amount of advance information decreased. The reaction time for the Hand precue condition was significantly faster than for the Task precue condition. This suggests that having advance knowledge of the hand that is to be used to perform the movement is more useful in planning the movement than is advance knowledge of the task that is to be performed.

Figure 16: The interaction of precue condition by task for reaction time.



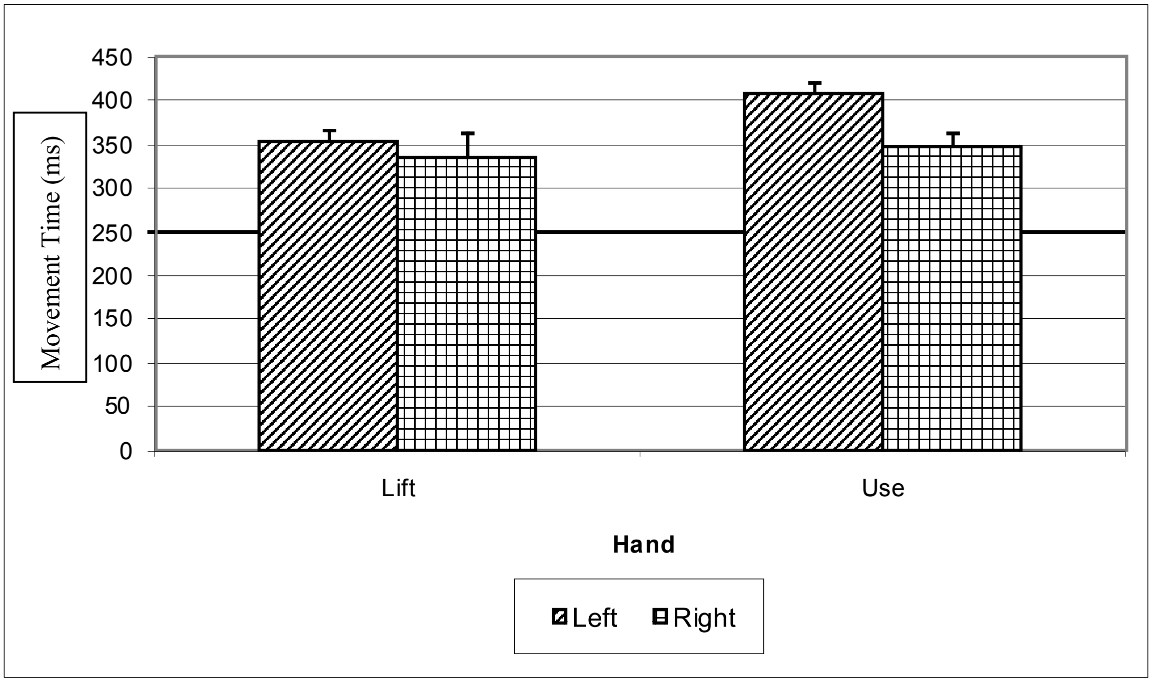
This figure illustrates the significant interaction of precue condition by task for reaction time. For the Both and Hand precue conditions, the Lift task was initiated significantly faster than the Use task. There was no difference between the Lift and Use tasks for the Task and No precue conditions.

Figure 17: The interaction of precue condition by hand for reaction time.



The figure shows the interaction of precue by task for reaction time. This interaction was not significant, indicating the absence of a right-hand advantage for reaction time. Post-hoc analyses indicated that this was the case for all four precue conditions.

Figure 18: The interaction of task and hand for movement time.



The figure shows the significant interaction of task by hand for movement time. For both tasks, movement time was significantly faster for the right hand than the left hand. However, this difference between the hands was greater for the Use task, suggesting that the right hand advantage for movement time increased as the skill demands of the task increased.

Appendices

Appendix 1: WATERLOO HANDEDNESS QUESTIONNAIRE

Please indicate your hand preference for the following activities by circling the appropriate response. If you always (ie. 95% or more of the time) use one hand to perform the described activity, circle RA or LA (for right always or left always). If you usually (ie. about 75% of the time) use one hand, circle RU or LU, as appropriate. If you use both hands equally often, circle EQ.

1. Which hand would you use to spin a top?	LA LU EQ RU RA
2. With which hand would you hold a paintbrush to paint a wall?	LA LU EQ RU RA
3. Which hand would you use to pick up a book?	LA LU EQ RU RA
4. With which hand would you use a spoon to eat soup?	LA LU EQ RU RA
5. Which hand would you use to flip pancakes?	LA LU EQ RU RA
6. Which hand would you use to pick up a piece of paper?	LA LU EQ RU RA
7. Which hand would you use to draw a picture?	LA LU EQ RU RA
8. Which hand would you use to insert and turn a key in a lock?	LA LU EQ RU RA
9. Which hand would you use to insert a plug into an electrical outlet?	LA LU EQ RU RA
10. Which hand would you use to throw a ball?	LA LU EQ RU RA
11. In which hand would you hold a needle while sewing?	LA LU EQ RU RA
12. Which hand would you use to turn on a light switch?	LA LU EQ RU RA
13. With which hand would you use the eraser at the end of a pencil?	LA LU EQ RU RA
14. Which hand would you use to saw a piece of wood with a hand saw?	LA LU EQ RU RA
15. Which hand would you use to open a drawer?	LA LU EQ RU RA
16. Which hand would you turn a doorknob with?	LA LU EQ RU RA
17. Which hand would you use to hammer a nail?	LA LU EQ RU RA
18. With which hand would you use a pair of tweezers?	LA LU EQ RU RA
19. Which hand do you use for writing?	LA LU EQ RU RA
20. Which hand would you turn the dial of a combination lock with?	LA LU EQ RU RA

21. Is there any reason (e.g. injury) why you have changed your hand preference for any of the above activities? YES NO (circle one) Explain.

22. Have you ever been given special training or encouragement to use a particular hand for certain activities? YES NO (circle one) Explain.

Appendix 2: Table of Non-Significant Main Effects and Interactions for Experiment 1 (as well as the significant interactions that do not involve the handedness group variable from the analysis comparing left- versus right-handers).

Main Effect / Interaction	*F* term	*F* Value	*p* Value	Observed Power
Left-Handers				
Object x Task x Position	4, 236	1.47	0.21	0.45
Left- and Right-Handers Compared				
Group x Object x Task x Position	4, 560	0.42	0.79	0.15
Group	1, 140	3.12	0.08	0.42
Group x Object x Task	2, 280	0.38	0.68	0.11
Group x Object x Position	2, 280	1.11	0.33	0.25
Object	1, 140	84.16	< 0.001	0.38
Position	2, 280	442.74	< 0.001	1.00
Task	2, 280	146.72	< 0.001	1.00
Object x Task	2, 280	12.90	< 0.001	0.99
Object x Position	2, 280	23.40	<0.001	1.00
Task x Position	4, 560	113.92	< 0.001	1.00
Object x Task x Position	4, 560	3.71	< 0.05	0.89

Appendix 3: Results of the Analyses Using 5 Positions for Experiment 1

Main Effect / Interaction	*F* term	*F* Value	*p* Value	η^2
Right-Handers				
Object	1, 81	41.10	< 0.001	0.34
Task	2, 162	143.81	< 0.001	0.64
Position	4, 324	316.39	< 0.001	0.80
Object x Task	2, 162	9.70	< 0.001	0.11
Object x Position	4, 324	17.72	< 0.001	0.18
Task x Position	8, 648	81.93	< 0.001	0.50
Object x Task x Position	8, 648	3.65	< 0.001	0.04
Left-Handers				
Object	1, 59	46.35	< 0.001	0.44
Task	2, 118	142.37	< 0.001	0.71
Position	4, 236	248.96	< 0.001	0.81
Object x Task	2, 118	4.30	<0.05	0.07
Object x Position	4, 236	15.61	< 0.001	0.21
Task x Position	8, 472	87.40	< 0.001	0.60
Object x Task x Position	8, 472	2.06	<0.05	0.03

Appendix 4: Table of Non-Significant Main Effects and Interactions for Experiment 2

Main Effect / Interaction	*F* term	*F* Value	*p* Value	Observed Power
Reaction Time				
Hand	1, 23	2.37	0.14	0.31
Task x Hand	2, 46	1.32	0.28	0.27
Precue x Task x Hand	4, 92	0.62	0.65	0.20
Movement Time				
Precue x Task x Hand	4, 92	1.07	0.38	0.32
Precue	2, 46	1.90	0.16	0.37
Precue x Task	4, 92	0.89	0.47	0.27
Precue x Hand	2, 46	2.10	0.13	0.41
Task x Hand	2, 46	0.40	0.67	0.11

Appendix 5: Table of Non-Significant Main Effects and Interactions for Experiment 3

Main Effect / Interaction	*F* term	*F* Value	*p* Value	Observed Power
Reaction Time				
Precue x Task x Hand	3, 123	0.98	0.40	0.26
Hand	1, 41	0.05	0.94	0.05
Task	1, 41	2.12	0.15	0.30
Task x Hand	1, 41	0.67	0.47	0.16
Precue x Hand	3, 123	0.91	0.44	0.25
Movement Time				
Precue x Hand x Task	3, 123	0.004	1.00	0.05
Precue	3, 123	0.78	0.51	0.21
Precue x Hand	3, 123	0.15	0.93	0.08
Precue x Task	3, 123	0.69	0.56	0.19
Replacement Time				
Precue x Task x Hand	3,123	0.44	0.72	0.14
Precue	3, 123	0.10	0.96	0.07
Hand	1, 41	0.72	0.40	0.13
Precue x Task	3, 123	0.75	0.52	0.21
Precue x Hand	3, 123	0.53	0.66	0.16
Task x Hand	1, 41	0.64	0.43	0.14