The Origins of Manual Asymmetries: What is Revealed by Pushing the Limits of Task Difficulty

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Abstract

Researchers have postulated a variety of explanations for the superiority in performance of one hand over the other, many which suggest that task complexity plays an important role. However, contradictory evidence of the role of task demands has been found recently by Van Horn and McManus (1994) who have shown that difference between the hands remains constant across tasks of increasing difficulty. The purpose of the experiments reported here was to investigate the difference in performance between the hands by examining a wider range of task demands than had been previously examined. Six experiments are reported where the two hands were compared on the Annett pegboard, a Fitts' reciprocal tapping task, and the Grooved Pegboard (a standard test used in neuropsychological assessment). The difficulty of each task was varied using Fitts' Law (Fitts, 1954). It was shown that one-dimensional changes to task demands, specifically peg size, do not affect the magnitude of the performance difference between the hands. These findings replicate those of van Horn and McManus (1994). However, it was also found that an increase in the right-hand advantage occurred when multiple dimensions of task demands are examined simultaneously. The reason for this increase in the difference between the hands in perhaps due to the experimental context and/or practice effects. In all probability, the differences in performance of the two hands reflect the organization of the underlying neural control structures.

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Dedication

Dedicated to the memory of my father. Dr. Philip Bryden. May he be proud.

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centre is represented as a dark grey oval. Pathways of control are drawn in as arrows.

INTRODUCTION

A uniquely human characteristic is the performance of most tasks with one hand rather than the other. For most people the hand they prefer to use is their right hand. Not only do people prefer to use one hand rather than the other, but they also, usually, perform tasks faster and more accurately with this hand. Recently, it has been shown that when the demands of a task are increased the difference in the performance time between the hands remains constant (van Horn & McManus, 1994). These findings contradict the current theories accounting for manual asymmetries, which postulate that the preferred-hand advantage is greater for more difficult or more highly skilled tasks, because the preferred-hand system is more efficient either in utilizing visual feedback (Flowers, 1975) or in controlling motor output (Annett, Annett, Hudson, & Turner, 1979). The implication of van Horn and McManus's findings is that the difference between the hands is a function of some constant factor such as the time it takes motor commands to reach the control system in the hemisphere controlling the left hand.

The purpose of the work described here is to expand the work of van Horn and McManus (1994) by examining hand performance across a number of tasks which vary in difficulty. Most importantly, the current work quantified the difficulty of each task by using Fitts' Law, thus enabling a wide-range of task difficulty to be examined. A review of the previous research on handedness and manual asymmetries will be presented next.

1. What is Handedness? Performance versus Preference

Handedness is perhaps the most studied human asymmetry (M.P. Bryden. 1982). Approximately ninety percent of the population shows a preference for the right hand (Annett. 1985; Hecaen & Ajuriaguerra. 1964). with the other ten percent preferring the left hand. Individuals not only choose to use their preferred hand for most unimanual motor tasks, but they are also more proficient with their preferred hand across a wide range of tasks. These tasks include finger tapping (Peters. 1980). peg moving (Annett. 1976). and throwing at targets (Watson & Kimura, 1989). The incidence of right handedness appears to be somewhat dependent upon the culture or country examined (M.P. Bryden. Ardilla. & Ardilla, 1993; McManus & M.P. Bryden, 1993). For instance, it has been shown that the incidence of left handedness is lower in certain cultures. including India (Singh & M.P. Bryden, 1994), Japan (Ida & M.P. Bryden. 1996) and the Tucano, an aboriginal people of the Amazon watershed of Columbia (M.P. Bryden, Ardilla, & Ardilla, 1993). As well, it appears that the incidence of left handedness may be changing over time. Turn of the century estimates of left handedness are in the range of 4% to 7% (Chamberlain. 1928; Rife, 1940) while data collected more recently suggest that the incidence is closer to 12% (McManus. 1997). Handedness surveys have also found that the incidence of left-handedness appears to be larger in males than in females (Hecaen & Ajuriaguerra, 1964. M.P. Bryden, 1982).

The measurement of hand preference has been a source of disagreement among researchers. Many investigators have tended to use crude behavioural measures to indicate handedness, such as asking participants with which hand they prefer to write. Luria (cf. 1965) even suggested that a person is a latent left-hander if the left arm is uppermost when the arms are folded in front of the body. Other researchers have classified handedness using more quantitative measures such as questionnaires or surveys (M.P. Bryden, 1977; Oldfield, 1971). Hand preference questionnaires usually take the form of asking participants which hand they prefer to use to complete a number of tasks, such as writing, holding a hammer when nailing, holding a toothbrush, and turning on a light switch. In the past, some researchers have only asked participants to identify the hand they prefer to use. Other researchers though, (Annett, 1976; Oldfield, 1971) have recognized that there is not only a direction to handedness (i.e., right or left-handed) but there are also different degrees of handedness (i.e., strongly right-handed versus ambidextrous). To assess the degree of handedness, questionnaires have been constructed that ask participants to specify whether they "always" or "usually" use their right or left hands to perform the task in question.

One of the problems with preference measures is their inherent subjectivity, as in any self-report measure. Not only is the meaning of the questions posed open to the reader's interpretation, but also the individual must imagine or recall what they would do in a given circumstance in order to complete the questionnaire accurately. Performance measures, in comparison, are not susceptible to these problems and thus present an objective alternative to preference measures. Such measures compare the relative performance of the two hands on a given task (Annett, 1985; 1992; Peters & Durding, 1979). Tasks examined have compared the performance of the hands on their relative strength (Provins & Magliaro, 1989) and on their relative speed (Annett, 1985; Flowers, 1975). Because relative strength is dependent upon factors other than handedness (e.g., age, experience, and practice), comparing the hands on a test of relative speed is currently a more common practice. Researchers have compared the performance of the hands on peg moving (Annett, 1967), finger tapping (Peters, 1980), dot tapping (Tapley & M.P. Bryden, 1985) and manual aiming (Roy & Elliott, 1986). Performance measures such as relative speed tend to yield two normal distributions (Annett, 1976), such that on average the right hand is slightly, but significantly faster than the left hand.

Generally, there appears to be a strong relationship between self-reported hand preference and performance. For instance, Annett (1976), and Peters and Durding (1978) have shown a strong correlation between preference and performance on peg moving and finger tapping respectively. More recently, Peters (1998) performed a thorough examination of the relationship between hand performance and hand preference. Participants completed various forms of handedness questionnaires and performed a number of unimanual tasks, including the Annett peg-moving task, the Grooved pegboard task, a finger tapping task, a movement sequencing task, and two O'Connor dexterity tasks (finger and tweezers). Peters (1998) found the correlation coefficients to be strongly significant between the entire set of preferences and performances, thus showing further evidence for the relationship between preference and performance. Thus, individuals with stronger hand preferences display more disparate performance abilities between their two hands, than those with inconsistent hand preference.

Summarizing then, hand performance measures offer a sound method of evaluating manual asymmetries. Measures of movement time will be used in this thesis, since performance measures are not only more objective than preference measures, but such tasks also allow task demands to be varied systematically. As well, the two measures, preference and performance, show a strong concordance (Peters, 1998).

2. Handedness, Brain Organization, and Motor Control

The human brain is structured in such a way that there are two hemispheres joined by the corpus callosum. It is well known that the motor cortex of one hemisphere controls the movements of the limbs on the opposite side of the body (Kolb & Whishaw, 1996). Thus, the movements of the right hand are controlled by the left hemisphere, while movements of the left hand are controlled by the right hemisphere. Historically, it was thought that the two hemispheres were simply mirror images of each other (Springer & Deutsch, 1993), but in the last century, research has shown that each hemisphere is specialized for different functions. Generally, it is thought that in right-handed individuals the left hemisphere plays a greater role in language processes and the control of complex voluntary movement, while, the right hemisphere has been shown to have a greater role in the control of visuospatial processing (Kolb & Whishaw, 1996).

Brain Organization and Language

Evidence that the left hemisphere plays a special role in controlling language has come from both clinical populations and from studies of normal individuals. At the turn of the century, it was recognized that the left hemisphere played a special role in language processing (cf. Broca, 1868; as cited in Kimura, 1992). This was evidenced by the fact that one patient, Tan, who had suffered unilateral left hemisphere damage to the anterior portion of the temporal lobe, showed severe language deficits in the production of speech. Later examination of other patients corroborated these findings. Since the seminal work of Broca, modern techniques have firmly established the left hemisphere as being specialized for speech. For instance, Wada and Rasmussen (1960) developed a technique to determine, unequivocally, the hemisphere specialized for language. Sodium amytal, an anesthetic, was injected into the carotid artery of patients undergoing elective surgery for the management of epilepsy. If injected into the speech hemisphere, sodium amytal arrests speech for several minutes. Using this technique it was determined that 96% of right-handers have speech lateralized to the left hemisphere, while only 70% of left-handers have left hemisphere speech (Rasmussen & Milner, 1977). Current theories of handedness have still not completely explained why the pattern of asymmetry is different in left and right-handers.

Around the same time as Wada and Rasmussen's research using sodium amytal, Kimura (1961) showed that the dichotic listening procedure could be used as a noninvasive method of assessing language lateralization in normal individuals. She presented pairs of spoken digits simultaneously, one word to each ear, through headphones. Participants were required to recall as many digits as possible, in any order. Individuals recalled more of the digits that had been presented to the right ear than the left ear. Kimura proposed that the right ear had direct access to the speech hemisphere, because the ipsilateral pathways were suppressed during dichotic presentation, thus accounting for the right-ear advantage. Thus, Kimura provided further evidence indicating that the left hemisphere was specialized for speech.

Summarizing, numerous techniques have allowed researchers to conclude that the left hemisphere is specialized for the control of speech. In right-handers, speech is nearly always located in the left hemisphere. Left-handers, on the other hand, have speech lateralized to the left hemisphere in about 70% of the cases (Rasmussen & Milner, 1977).

Brain Organization and Motor Control

Evidence that the left hemisphere plays a special role in controlling movement has come mainly from studies of patients with unilateral brain damage. Liepmann (1908; as cited in De Renzi, 1989) compared patients with right hemisphere damage to those with left hemisphere damage. He found that approximately 50% of the patients with left hemisphere damage showed an impaired execution of gestures. Liepmann concluded that the left hemisphere controlled the "organization of motor activity of either side of the brain" (De Renzi, 1989, pg. 247). Liepmann further argued that left hemisphere specialization for praxis was closely related to right hand preference. He suggested that both praxis and handedness depended upon learned movement engrams stored in the left hemisphere. The movement engrams would be immediately available to the motor cortex guiding the right limb, but would only be available to guide the left limb through callosal transmission to the right-hemisphere motor cortex. Consequently, the right hand is not only the hand of preference, but is also faster, and more accurate than the left hand. However, recently De Renzi (1989) argued that Liepmann's hypothesis explains apraxia better than it explains hand preference, as it is not clear why the transfer of motor engrams should entail such degradation as to account for the performance decrements of the left hand.

With the advent of neuroimaging techniques researchers have new insight into the working brain, and have been able to determine that the motor commands for movements originate in the left-hemisphere. Studies have shown increases in regional cerebral blood flow (rCBF) in the left-hemisphere motor, supplementary motor, and premotor cortex when movements are made with the right hand (Kawashima, Yamada, Kinomura, Yamaguchi, Matui, Yoshioka, & Fukuda, 1993). In contrast, when the left arm is moved there are not only increases in blood flow to the motor cortex of the right hemisphere but there are also increases in rCBF to the motor association cortices, including both pre-motor and supplementary motor cortices, in the left hemisphere (Kawashima et al., 1993). Researchers have concluded that increases of rCBF in the motor cortex are related to the production of movements, while increases in rCBF in the supplementary and premotor cortex of the left hemisphere are thought to be related to the programming and sequencing of movements (Kolb & Whishaw, 1996).

What is the Left Hemisphere Specialized for?

At the turn of this century, Liepmann (1908; as cited in De Renzi, 1989) argued that aphasia and apraxia were related, and that both were manifestations of the loss of the same ability. Leipmann proposed that both apraxia and aphasia, which follow left hemisphere damage, could be explained if the left hemisphere was specialized in the control of voluntary movement. By this logic aphasia is not a disorder of language production per se, but rather a motor disorder of the articulatory apparatus. An extension of Leipmann's idea was proposed by Kimura (1992) who argued on the basis of years of research evaluating patients suffering from left hemisphere damage that the left hemisphere is specialized for the selection and programming of both oral and manual musculature. She found that the problems observed in both aphasia and apraxia were manifestations of an inability to program the appropriate musculature to perform the task, whether it was a manual task or an oral task. Efron (1990), on the other hand, has maintained that the left hemisphere may be important for the detection of temporal order. More specifically, the "left hemisphere might be specialized for temporal sequencing, or in other words, organizing behaviour and/or information over time" (Kolb & Whishaw, 1996, pg. 205).

In summary, the majority of right and left-handers have both speech and motor control lateralized to the left hemisphere. The left hemisphere appears to be specialized for the selection of both oral and manual musculature (Kimura, 1992), or the sequencing of movements in time (Efron, 1990).

3. Performance Measures: The Right-Hand Advantage

The performance of the preferred hand is generally found to be faster and more skilled than that of the non-preferred hand, especially for tasks that require highly practiced elements (Peters, 1996). For instance, it has been argued that the right-hand system is superior at manipulation (Bradshaw & Rogers, 1993), has superior dexterity (Flowers, 1975), is better at sequencing movements (Watson & Kimura, 1989), and shows greater movement accuracy and faster movement speed (Todor & Cisneros, 1985). However, the reason for this superiority in performance of the preferred hand is a matter of debate. Three explanations have been considered: the visual feedback hypothesis (Flowers, 1975), the motor output hypothesis (Annett, Annett, Hudson & Turner, 1979; Elliott & Chua (1996), and the preferential experience theory (Provins, 1997). Advocates of the visual feedback hypothesis argue that "humans typically show a right-hand superiority in tasks that entail high accuracy demands with fine corrective movements, frequently, but perhaps not necessarily, under visual control" (Bradshaw & Rogers, 1993, p. 197). Others including Annett et al. (1979) and Elliott and Chua (1996) have suggested that the right-hand advantage is due to the abilities of the left hemisphere in precisely controlling motor output. Proponents of the preferential experience theory, in comparison, argue that the superiority of the right hand can be accounted for by the differential amounts of practice each hand receives during a lifetime. Currently, the evidence is limited for any one theory, predominately because the data are contradictory.

Feedback Processing

Until quite recently, most researchers contended that the preferred-hand advantage in right-handers for motor tasks reflected an advantage of the left-hemisphere in processing and utilizing response-based feedback. The first researcher to suggest that the essential difference between the hands was in the utilization of feedback was Woodworth in 1899. He compared the two hands in a task where participants had to perform a series of horizontal sliding movements, where their goal was to produce a movement with the same spatial endpoint as the previous movement. Participants performed the task with both hands, under conditions where vision was either available or not. As well, participants had to time their movements to match the beat of a metronome, creating a variety of speed conditions. The results showed greater differences in accuracy between the hands as the speed of the movement increased, only when vision was available. Woodworth concluded that hand differences were due to a superiority of the right hand in utilizing response-based feedback.

Nearly a century later Flowers (1975) also came to the conclusion that the seat of superiority of the right hand was in the utilization of feedback. However, Flowers specified that the type of feedback was visual in nature. He compared the performance of the hands of right and left-handers on both a simple and a complex task. The simple task was a rhythmical tapping task, while the complex task was a manual aiming task. Flowers argued that the simple task was essentially ballistic in nature because participants were unable to monitor visually, or to make visual corrections during the movements, while the manual aiming task required participants to make visual corrections. and was closed-loop in nature. The results showed that there was a negligible difference in performance between the hands for the simple. ballistic task. while large hand differences were found in movement time and accuracy measurements for the complex task. Based on these findings. Flowers concluded that the "essential dexterity difference" between the hands was "in the sensory or feedback control of the movement rather than in the motor function per se" (Flowers. 1975. p. 39).

Many researchers found Flower's (1975) idea both appealing and compelling. prompting a number of investigations of the visual feedback explanation for the preferred-hand advantage. Evidence supporting a visual feedback explanation was found by Roy (1983) who manipulated the instructions given to participants. When right-handed participants were told to be accurate in their movements. a small advantage for the preferred hand was observed. However. when speed was stressed. this advantage increased dramatically. Roy (1983) suggested that the speeded condition required the more efficient use of visual feedback. thus supporting the idea that the origin of the right-hand advantage is in its better. faster use of visual feedback. Further evidence for visual feedback advantages comes from work conducted by Todor and Cisneros (1985) who attempted to identify which phase of a movement is responsible for hand differences in an aiming task. Kinematic analysis revealed that the longer movement times of the non-preferred hand were mainly a result of increased time spent after peak velocity. where visual feedback is thought to be most important.

However. other research has provided evidence that the visual feedback explanation cannot account entirely for the performance differences between the hands. For example. Todor and Doane (1978) contrasted the performance of both hands for right and left-handed participants on a Fitts' (1954) reciprocal tapping task. By manipulating the size of the target and the movement amplitude, the amount of visual feedback needed to perform the task was also manipulated. The authors proposed that the more difficult condition required a greater amount of visual feedback than the simple condition. It was found that the preferred hand did not perform significantly better in the condition requiring greater visual feedback. Therefore, the experiment did not provide support for the contention that the origin of the right-hand advantage is derived from its superior ability to process visual feedback. However, it was not until the work of Roy and Elliott (1986) that visual feedback was manipulated directly. Here, participants were asked to perform a manual aiming task under conditions of full or no vision. Although accuracy was decreased in the no vision conditions, the difference in performance between the two hands was not affected by the presence or absence of vision. Further work conducted by Carson, Chua, Elliott, and Goodman (1990) has replicated these findings.

Therefore, the proposition that differential performance of the hand/hemisphere systems is due to differences in using and/or processing visual feedback has equivocal experimental support. Researchers have offered the alternative that the right-hand system may be more proficient in its ability to utilize kinesthetic feedback (Roy, Kalbfleisch, & Elliott, 1994). That there was still a right-hand advantage regardless of whether vision was available or not in the work of Roy and Elliott (1986) can be explained by this notion of more efficient use of kinesthetic feedback. However, this proposition has not yet been tested explicitly.

Movement Output Specification

Because visual feedback theories were unable to account for many experimental results, investigators began to propose alternate theories of the origin of the right-hand advantage to explain the inconsistencies in the data. Annett, Annett, Hudson and Turner (1979) examined the performance of the hands on a peg-moving task, which requires participants to move ten pegs from their home position to an empty row of holes, one at a time, as quickly as possible. It was found that the preferred-hand advantage was greater under conditions where the tolerance (difference between the hole and peg size) was small. After filming participants performing the task, they showed that the increased movement time of the non-preferred hand was primarily due to missing the hole more often and therefore requiring more corrective movements. The authors felt that visual feedback monitoring could not be used as an explanation for the increased number of corrective movements because the hands did not differ in the amount of time taken to insert a peg. Therefore, Annett et al. suggested that the motor output of the non-preferred hand was noisier than that of the preferred hand. They concluded that the left hand/right hemisphere system was more variable in its execution of the movement.

On the basis of the findings that refute a visual feedback theory, Roy and Elliott (1986, 1989) and Carson et al. (1990) have also suggested that the right-hand system is less variable in generating the forces necessary for a particular movement. However, recent work by these investigators (Carson, Elliott, Goodman, Thyer, Chua & Roy, 1993) has failed to find any evidence supporting this theory. Different weights were added to the limbs and the performance of the right and left hands was compared. It was reasoned that if the left-hand were more variable in specifying muscular forces, then the disadvantage of this system should increase under added mass. Note that moving more mass would require greater force, and thus greater force variability, resulting in greater endpoint variability (Schmidt, Zelaznik, & Frank, 1978; Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979). However, the performance of the hands was not affected differentially by the added mass. Thus, the differences between the hands cannot be accounted for by a force-variability explanation. Kinematic analyses have shown the differences in performance tend to appear in the later portions of the movement, during the error-correcting phase, leading current theories to suggest that the right hand is more precise in producing the muscular forces required to "modify the terminal trajectory to achieve an exact endpoint" (Elliott & Chua, 1996, p. 155).

Preferential Experience and Learning

A third hypothesis purports that preferential experience or practice can entirely account for the superiority of the preferred hand. Here, it is suggested that the acquisition of motor skills is specific to the particular task learned, and that the advantage of the preferred hand is a result of the long periods of learning or experience that are needed for the acquisition and perfection of the skill (Provins, 1997). An equally plausible account would be that the preferred hand may be more efficient in acquiring skills through practice.

In the literature, there appears to be some support for the preferential experience or learning hypotheses, despite the fact that it is difficult to isolate the contribution of practice in the simple unimanual tasks usually examined. For example, Peters (1976) practiced finger tapping daily, performing a total of 13,000 trials with each hand. At the beginning of the experiment, Peters reported that the preferred hand was 6.5% faster than the non-preferred hand, however, by the end of the training period both hands were equivalent in tapping speed. Likewise, Annett, Hudson, and Turner (1974) examined the cumulative effects of practice on a peg-moving task in three subjects for 130 trials. Participants were found to improve with both hands, but the difference between the hands was unchanged in two participants, and reduced but by no means eliminated in one individual. P. J. Bryden and Allard (1998) also report the effects of practice in a peg-moving task for a single subject. Five trials per day were recorded. While the left hand improved dramatically over the course of observation to the point where its performance surpassed the original level of the right hand, there was still a significant difference between the two hands at the end of the training period. The variability in the performance of the left hand was also found to diminish with practice. These studies suggest that practice can indeed influence the performance of the hands, but that the underlying asymmetry, in most cases, is still observable.

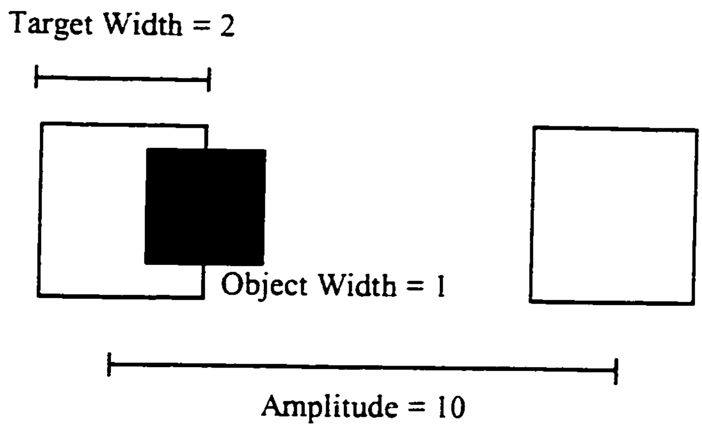
Provins (1997) has argued, however, that the such studies where the experience of the two hands is not equal for the individual components of the task do not necessarily give a realistic indication of the influence of normal usage and experience. For this reason, Provins and Glencross (1968) opted to examine the performance of the two hands in a typing task with both expert and novice typists, thus enabling the authors to obtain a more realistic estimate of the effects of long-term practice on manual asymmetries. They found few or no performance differences between the hands for the expert typists, but highly significant performance differences favouring the right hand for the novices. Interestingly, both groups showed strong right-hand advantages in a handwriting task. Provins (1997) suggests that such studies provide solid evidence that "the differences between sides in motor proficiency and preference are relatively specific to each task and that this specificity is closely related to the amount of training received by each side on each task" (pg 189).

In summary, there are three competing explanations for the right-hand advantage: feedback processing, motor output, and experience or learning. While there is supporting evidence for each hypothesis, as of yet no one theory can account for the findings.

4. Fitts' Law and Manual Asymmetries

Previous researchers have compared the performance of the two hands across different tasks varying in difficulty (Flowers, 1975; Provins & Magliaro, 1989). However, much of the research on manual asymmetries and task complexity has not varied the difficulty of the movement in measurable terms. Research in the movement sciences has provided a relatively straightforward way of quantifying the difficulty of a task. In 1954, Paul Fitts, using a number of simple tasks including a peg transfer task, a tapping task, and a disc-placing task, demonstrated that movement time increased linearly when the index of difficulty for a particular task also increased. He defined index of difficulty (ID) as log base two of two times the movement amplitude over the width of the target being captured (ID = $\log_2$(2*amplitude/target width). For tasks such as peg moving, where pegs must be inserted into holes, Fitts divided the movement amplitude by the tolerance of the target, with tolerance defined as the difference between the size of the target and the size of the object being positioned in the target. Figure 1 illustrates how index of difficulty is calculated. Since the formulation of this equation, Fitts' Law has been replicated for a large variety of tasks, including discrete aiming, moving objects to insert them into holes, moving a cursor on a screen and throwing darts (Shumway-Cook & Woollacott, 1995).

Figure 1. The calculation of index of difficulty, according to Fitts' Law (1954).



Tolerance = (Target-Object Width) = 1

ID = log2 (2*Amplitude/Tolerance)

ID = log2 (2*10/1)

ID = 4.32

Various explanations have been put forth to account for the increase in movement time as a function of task difficulty revealed by Fitts. For example, Crossman and Goodeve (1983), Keele (1968) and Beggs and Howarth (1972) have all proposed that the increase in movement time was due to the need to make corrections based on visual feedback. In contrast, Schmidt, et al (1978) and Schmidt, et al (1979) have suggested that the variability in muscular impulses may lead to an increase in movement time with more difficult movements (Schmidt, 1988).

Clearly, the use of Fitts' index of difficulty is an effective way of quantifying the difficulty of a movement task. However, only a few studies in the literature have explicitly applied Fitts' Law to their investigations of manual asymmetries and task complexity (Annett et al., 1979; Todor & Cisneros, 1985). First, Todor and Cisneros (1985) examined the performance of both hands across varying indices of difficulty (IDs were 5, 6 and 7 according to their calculations), using a Fitts' reciprocal tapping task. As index of difficulty increased, Todor and Cisneros report that the relative difference between the two hands increased. However, Todor and Cisneros calculated ID using only target width, and so did not take into account the size of the implement. Calculating tolerance was important in this study because in one condition the size of the implement was actually larger than the size of the target. Recalculating the indices of difficulty using tolerance instead of target width shows that Todor and Cisneros' values of 5, 6 and 7 bits were actually 5.7, 8.9 and an inverted Fitts' condition (where the object is larger than the target), respectively. The inverted Fitts' condition can be likened to slapping one's hand on a smaller object, and thus would be easy to perform. While the authors report an index of difficulty by hand interaction for movement time, recalculation of the index of difficulty using tolerance means this interaction no longer represents an increasing between-hand difference across increasing task difficulty. Rather. the difference between the hands is now significantly larger for the easiest condition examined. The findings of Todor and Cisneros are therefore ambiguous.

A second study which investigated the performance of the two hands across task difficulty, and manipulated difficulty using Fitts' Law. was performed by Annett. Annett. Hudson and Turner (1979). The authors investigated a range of IDs from approximately 4.0 to 8.0 bits. using tolerance in their calculation of difficulty. They found that differences between the hands became greater as the hole to peg ratio decreased. that is. as the difficulty of the task increased. After filming participants performing the task Annett et al. found that the difference in movement time between the two hands was not attributable to insertion time differences. nor were there differences in the speed of the two hands. Rather. Annett et al. noted that the non-preferred hand simply made more errors than the preferred hand. They concluded that the essential difference between the hands was due to the non-preferred hand simply being noisier in its output.

A more recent attempt to manipulate the difficulty of a task was performed by van Horn and McManus (1994). The authors manipulated characteristics of the Annett pegboard (1967). the Bishop square tracing task (Bishop. 1980). and the Tapley-Bryden dot-marking task (Tapley & M.P. Bryden. 1985). to alter the difficulty of each of these tasks. To clarify. the Annett pegboard requires participants to move pegs. the Bishop squaring tracing task requires a line to be drawn between two lines in the shape of a square. and the Tapley-Bryden task requires individuals to mark the inside of a series of small circles. For the Annett pegboard task. van Horn and McManus (1994) manipulated the movement amplitude, the distance between the holes themselves, the diameter of the pegs, and the shape of the pegs, although Fitts' Law was not used to quantify task difficulty. Main effects were found for all manipulations of the Annett pegboard, such that increasing the task difficulty produced longer movement times. Yet none of these changes interacted significantly with the hand used to perform the task, indicating that the difference between the hands remained constant. The authors then proceeded to manipulate the difficulty of the Bishop square-tracing task and the Tapley-Bryden dot-marking task. In the Bishop square-tracing task the size of square, and the distance between the two lines was manipulated, while the size and distance between the circles was manipulated in the Tapley-Bryden task. Again, none of the difficulty manipulations affected the magnitude of the between-hand difference. Thus, as the demands of the task increased, the movement time of both hands increased, but the difference between the hands remained constant.

Thus, previous research examining the performance of the two hands as a function of index of difficulty has produced a myriad of contradictory results. The reason behind this confusion lies in the differing methodologies adopted by the different researchers. First, and perhaps of greatest importance are the inconsistencies in the quantification of task demands across the studies. Note that while both Annett et al. and Todor and Cisneros quantified task difficulty using Fitts' Law, Annett et al. applied the concept of tolerance to their calculations, while Todor and Cisneros did not. Secondly, the tasks examined differed greatly amongst the studies and included writing-type tasks, peg-moving tasks, and reciprocal tapping tasks. Thirdly, comparing the studies of Annett, et al. and van Horn and McManus (1994) shows that procedural differences may have contributed to the disparate findings. For instance, the study conducted by Annett et al. was a between-subjects design on the factor of ID, where only a small sample size was examined, but for each condition five trials were performed for each hand. Also of note in the Annett et al. study was the fact that participants were required to stand while they performed the task. While this may seem to be a negligible methodological distinction, recent work has shown that manipulations of posture in a pegboard task (standing versus sitting) affect the degree of the performance difference between the hands (Westwood, E. A. Roy, P. J. Bryden, M. P. Bryden, and P. Roy, 1997) such that the performance difference may increase when the task is performed while standing as opposed to sitting. In contrast, van Horn and McManus (1994) examined a very large sample of the population, including both left and right-handers, but only measured two trials per condition. Participants were also seated in the van Horn and McManus study. Clearly, the methodology and procedure of their study differed in many ways from the Annett et al. study and perhaps can account for the different findings between the two studies.

Thus, not only do the previous studies examining task demands and hand performance report differing results but the studies themselves have been conducted in very different ways. Clearly, the issue of how the hands perform relative to each other as a function of task demands must be resolved before any theory of the origin of the right-hand advantage can be advanced. Thus, the issue of whether the performance difference between the hands increases or remains constant as a function of task demands must be determined.

5. The Present Investigation

The Purpose

The first objective of the present investigation was to determine whether the findings of van Horn and McManus (1994) could be replicated. As well, previous work was extended by examining the motor performance of the two hands on a number of tasks, across a wider range of task difficulty than had previously been investigated. The goal of this work was to reach an understanding of how the two hands perform relative to each other across task difficulty, and also to elaborate on why the performance capabilities of the two hands differ.

The Task

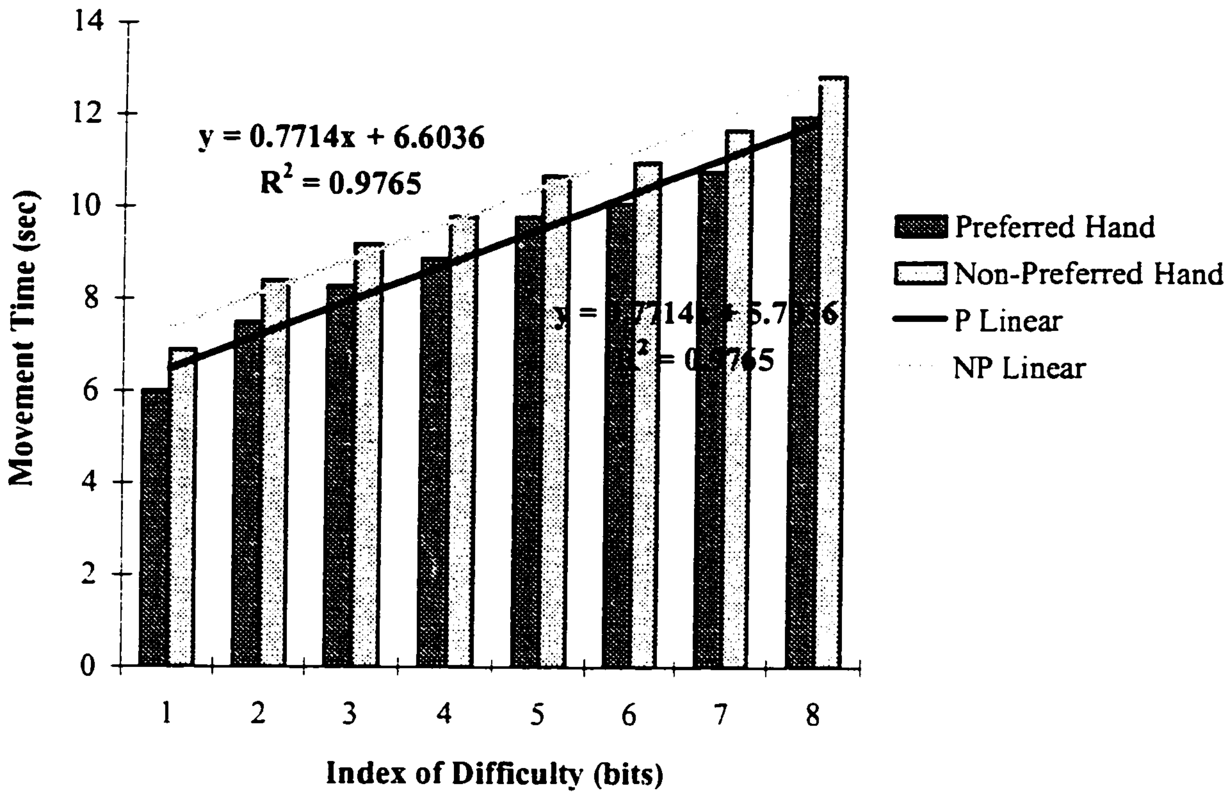
The tasks examined in the present series of studies involve tasks similar to those examined by Fitts (1954). These tasks include the reciprocal tapping task and the peg-moving task reported by Fitts (1954), where the factors of target size, object size and movement amplitude can be manipulated. In the reciprocal tapping task participants tap back and forth between targets. Likewise, in the peg-moving task participants are asked to move ten pegs, one at a time, to a row of empty holes. Typically, in performing such tasks, participants are told to move as quickly as possible, while the time taken to complete the task is measured. Participants are constrained by the need to be accurate, especially in the peg-moving task, as trials where a peg was dropped were repeated. In other words, participants must take the time to perform the movement correctly. Thus, accuracy is not explicitly measured in these tasks, but rather incorporated into the total movement time.

The Expectations

First, it was hypothesized that for all tasks examined there would be a difference in movement time as a function of both the hand factor and the index of difficulty factor. The preferred hand should complete the tasks significantly faster than the non-preferred hand. As well, there should be a significant main effect of index of difficulty, such that movement time will increase linearly with increasing task difficulty, regardless of the hand performing the task. Consequently, as predicted by Fitts' Law, a significant linear relationship should be observed between movement time and index of difficulty for the overall movement time, as well as for the movement times for each hand.

At issue, however, is what will happen when both hand and difficulty factors are considered together. Previous literature would suggest that two possible findings might occur with respect to the interaction between the hand factor and the index of difficulty factor. First, based on the findings of van Horn and McManus (1994) the movement time difference between the hands should remain constant across increasing task difficulty. More simply, this would mean that the preferred hand would perform better than the non-preferred hand by a constant time difference, regardless of task difficulty and the interaction between the factors of hand and index of difficulty (or tolerance) would not be significant. Figure 2 shows the hypothetical situation of a constant between-hand difference as a function of index of difficulty. Hypothetical movement times for each hand can be seen, as well as the associated linear function for each hand across task difficulty. Here, it can be seen that both hands seem to be performing the task in like manner, with the exception that the preferred hand is a constant amount faster than the non-preferred hand.

Figure 2. Hypothetical situation of a constant between-hand difference as a function of index of difficulty: no hand by ID interaction, and no significant differences between the slopes for each hand.

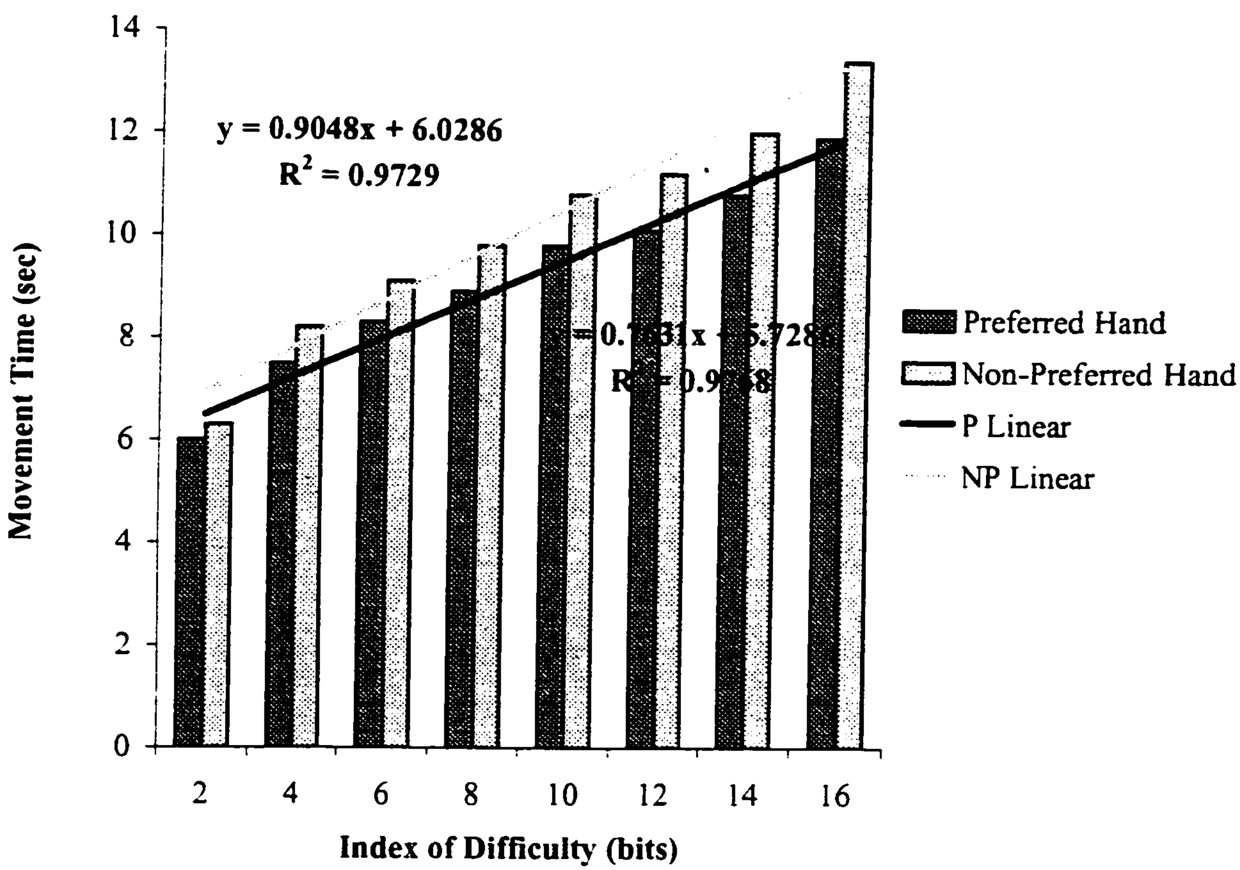


Based on the results reported by Flowers (1975), Annett et al (1979) and Todor and Cisneros (1985), the possible alternative finding of the present investigation is that the movement time differences between the hands could increase or diverge with increasing difficulty. Figure 3 depicts the situation where large differences between the hands are found for very difficult tasks, and negligible differences between the hands are seen for very simple tasks. More specifically, one would hypothesize that the preferred hand would not be as adversely affected by increasing task difficulty as the non-preferred hand. This effect would result in a significant interaction between hand and index of difficulty or tolerance, and in addition, the slopes of the Fitts' Law linear functions for each hand would diverge significantly.

EXPERIMENT 1

The purpose of the first experiment was to ascertain whether the results of van Horn and McManus (1994) were reliable for tasks which differ on index of difficulty. As it was important to replicate the results on one of the tasks used by van Horn and McManus, the Annett pegboard was used. Therefore, index of difficulty, as quantified by Fitts' Law, was manipulated in this first experiment and the performance of the two hands across each level of task difficulty was observed. Based on the findings of van Horn and McManus, it was hypothesized that the movement time difference between the hands would remain constant across increasing levels of task difficulty. As well, it was expected that there would be no interaction between the factors of hand and index of difficulty.

Figure 3. Hypothetical situation of an increasing between-hand difference as a function of index of difficulty: significant hand by ID interaction, and significant differences between the slopes for each hand.



Method

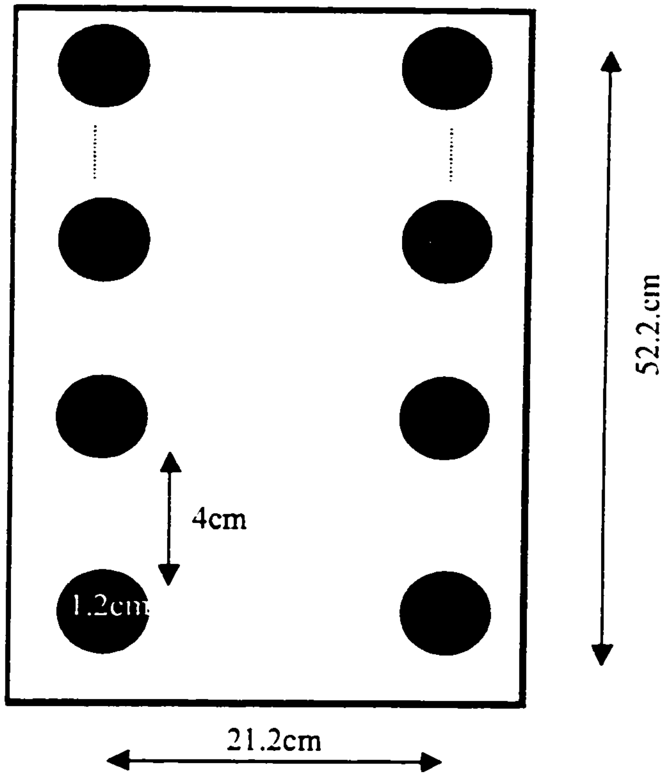
Participants

One hundred and fifty-one first-year undergraduate students participated in the experiment, as part of a laboratory assignment for an introductory Kinesiology course at the University of Waterloo. One hundred and thirty-five right-handers (45 males and 90 females) and sixteen left-handers (6 males and 10 females) participated in the experiment. Handedness was assessed simply by asking students with which hand they preferred to write. Because of the large sample size differences between the two handedness groups, only the results of the right-handers will be reported.

Apparatus

The task was performed on a variation of the Annett pegboard (Annett, 1967). A schematic diagram of the Annett pegboard is shown in Figure 4. The board was 30.6cm by 52.2cm with two rows of 10 evenly spaced holes drilled along each length of the board, each hole with a diameter of 1.27cm. The distance between the holes along each length was 4cm. The distance between the two rows of holes was 21.2cm. Participants were tested using the pegboard under four different conditions in which the size of the pegs was manipulated. Four sizes of pegs were examined including 1.25cm, 1.1cm, 0.97cm, and 0.63cm (approximately 1/2, 7/16, 3/8, and 5/16 inches). The most difficult peg to position was the 1.25cm peg which was approximately the same size as the holes, while the smallest peg (0.63cm) was 62% of the diameter of the peg hole and required the least precision. Using Fitts' Law index of difficulty calculation, and using tolerance (Fitts, 1954) the four ID values investigated corresponded to 6.0, 7.1, 8.0 and 11.0 bits of information.

Figure 4. Schematic diagram of the Annett pegboard used in experiment one.



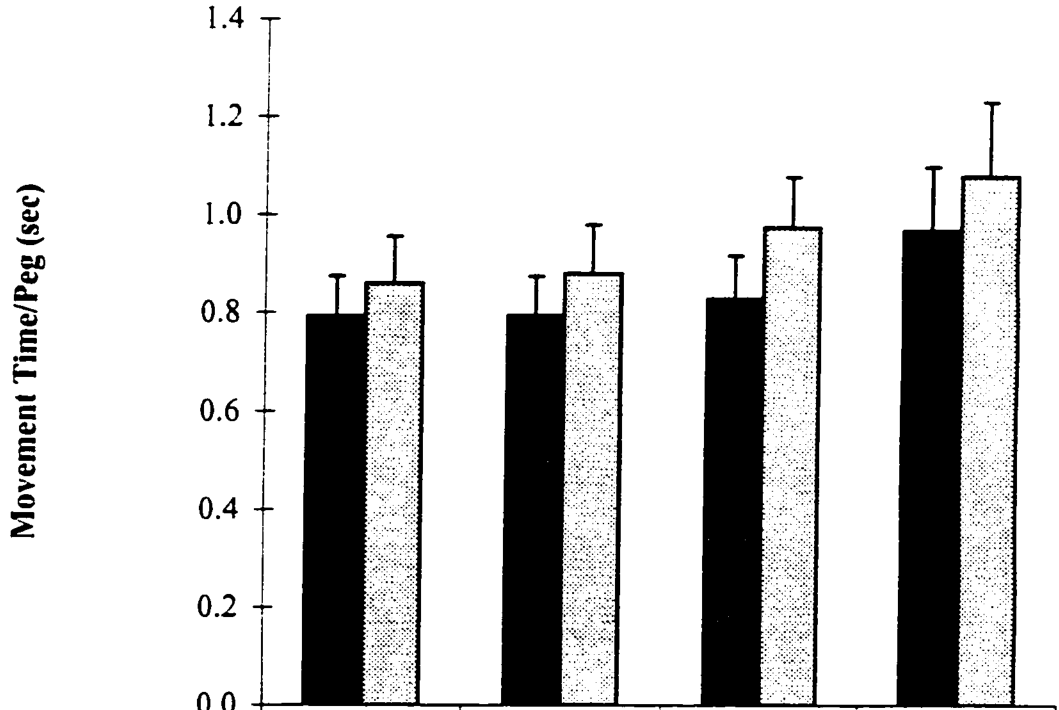
Procedure

Testing was performed in laboratory sections, with no more than twenty participants in each group. Different experimenters conducted the different sections. Participants were seated with the pegboard in front of them such that the filled row of pegs was farthest from them. The task was to move as many pegs as possible, from the filled row to the empty row, in ten seconds, while minimizing the number of errors they made. Participants began the task by placing the peg in the corner opposite to the hand they were using. For each index of difficulty participants performed the task once with each hand. The total number of pegs moved in ten seconds was observed and recorded following each trial. Movement time per peg was then calculated by dividing 10 seconds by the number of pegs moved in that time.

Results

All movement times were coded with respect to the participant's preferred hand. A two (hand) by four (index of difficulty) analysis of variance revealed main effects for hand ($F_{(1,134)}$=35.83, p=0.0001), and for index of difficulty ($F_{(3,402)}$=27.93, p=0.0001). The ANOVA table is presented in Appendix A, Table 1. The performance of the preferred hand (0.848 seconds/peg) was faster overall than the non-preferred hand (0.957 seconds/peg). In addition, movement times were found to increase as index of difficulty (or peg size) increased. Tukey's post hoc analysis revealed significant differences between all indices of difficulty except the easiest two levels (IDs of 6.0 and 7.1). Of particular interest is the lack of an interaction between index of difficulty and hand, thus supporting van Horn and McManus (1994). Figure 5 presents the overall movement times

Figure 5. Total movement times, including stardard deviations, for preferred and non-preferred hands as a function of index of difficulty for Experiment 1.



	6	7.1	7.9	11
■ Preferred Hand	0.79	0.79	0.83	0.97
□ Non-Preferred Hand	0.86	0.88	0.98	1.08

Index of Difficulty (bits)

for each hand, as a function of index of difficulty. A linear regression of movement time on index of difficulty, collapsed across all factors, revealed a significant linear relationship (R^2=0.9671, p=0.0167), as predicted by Fitt's Law. Figure 6 shows the linear regression equation of total movement time as a function of difficulty.

Next, a linear regression was performed to examine the relationship between movement time and index of difficulty, for each of the hands separately, to test Fitts' Law. When the data were collapsed across participants, the preferred hand showed a significant linear relationship between movement time and index of difficulty (R^2=0.9448, p=0.028, where the slope of the function was equal to 0.04). The non-preferred hand also exhibited a significant linear function (R^2=0.9327, p=0.0342, where the slope of the function was equal to 0.045). Figure 7 depicts the linear functions for the preferred and non-preferred hands across index of difficulty.

Discussion

The analysis revealed no interaction between index of difficulty and the hand with which the task was performed. Hence, the current experiment showed a constant between-hand difference in performance times across increasing task difficulty. The results of this experiment, therefore, replicate the findings of van Horn and McManus (1994).

The question remains, then, of why the differences between the hands was constant over varying degrees of difficulty in the present study, when the studies by Annett et al. (1979) and Todor and Cisneros (1985) both report an interaction between hand performance and task difficulty. The range of levels of difficulty examined in the current

Figure 6. Linear regression equation for overall movement time as a function of index of difficulty for Experiment 1.

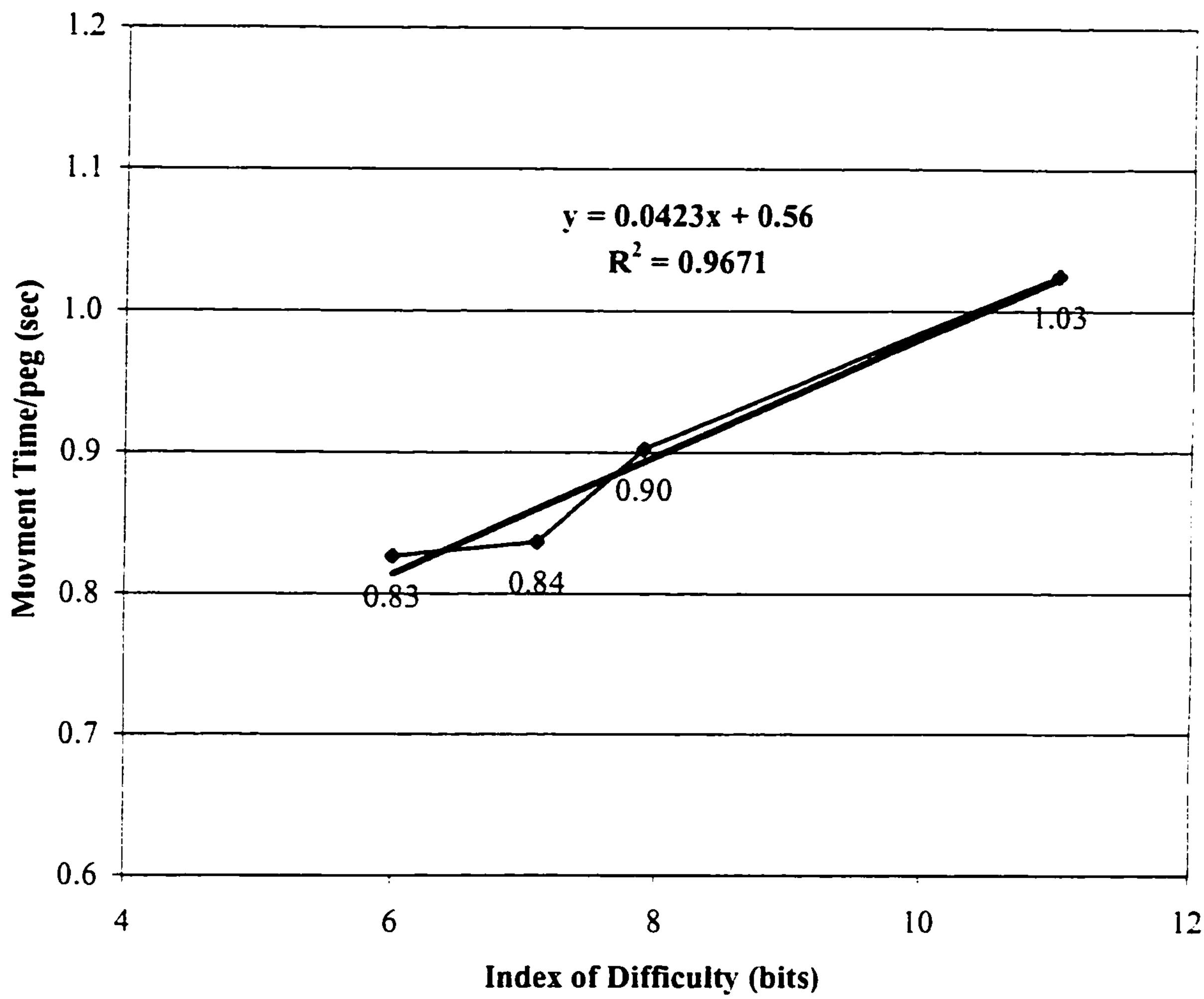
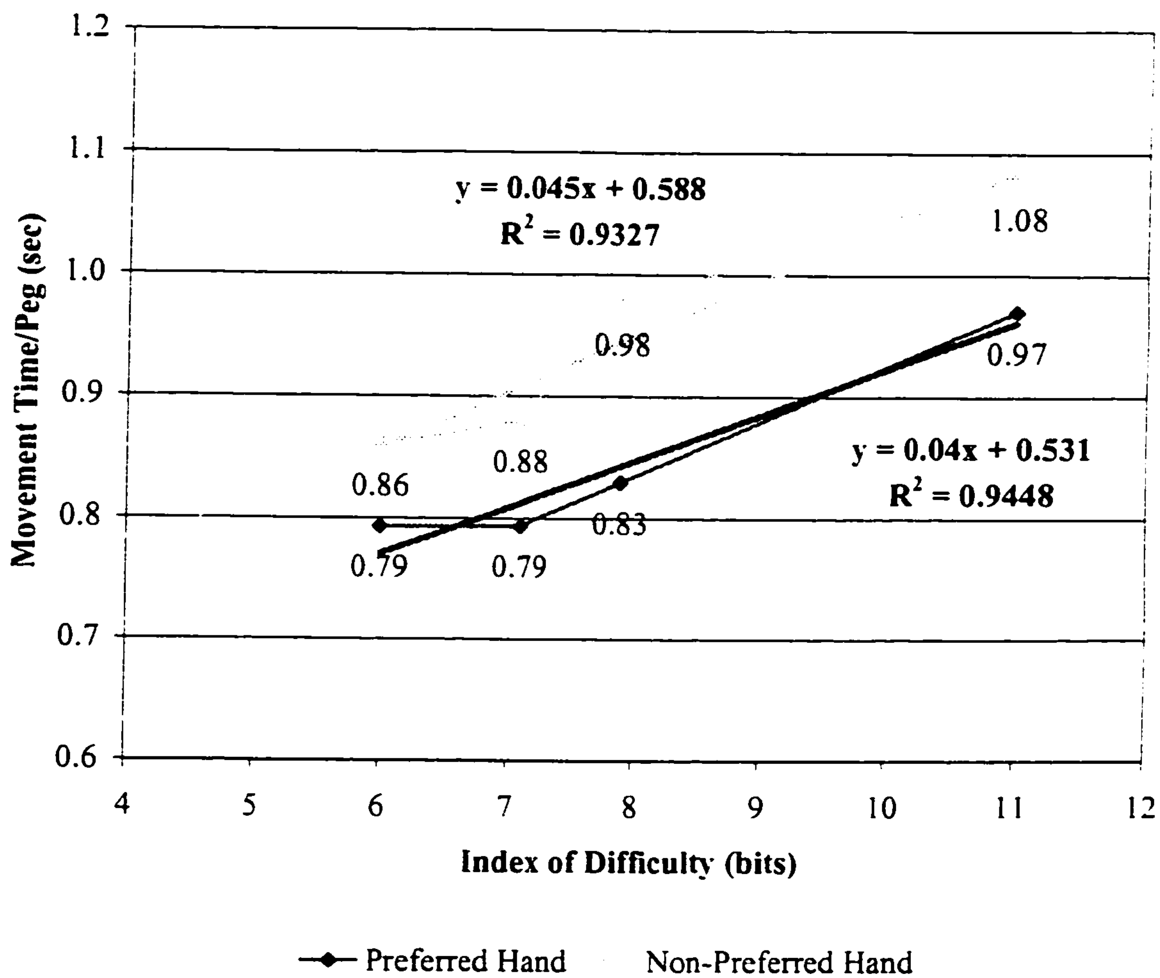


Figure 7. Linear regression equations of movement time as a function of index of difficulty for preferred and non-preferred hands for Experiment 1.



experiment was larger (6.0 to 11.0 bits) than those investigated by Annett et al. (4.0 to 8.0 bits) and Todor and Cisneros (5, 6, and 7 bits), and the number of participants was much larger than in the previous work. Thus, the current study had more power to detect an interaction if one existed, and therefore the results of the current study are likely representative of the true situation. Task and methodology discrepancies between the Annett et al. (1979) study and the present study might also help to explain the differences in results. Annett et al. required participants to stand in front of the pegboard, while our study and that of van Horn and McManus (1994) required participants to be seated while performing the peg-moving task. As discussed earlier, a standing posture may amplify the performance differences between the hands (Westwood et al., 1997). As well, methodological differences in the manner in which index of difficulty was calculated may also account for the discrepancies in findings between the current study and that of Todor and Cisneros. On the other hand, the differences between the two hands as a function of task difficulty are in the predicted direction: there is a steeper slope for the non-preferred hand.

Thus, before concluding that the differences between the hands remains constant across task difficulty, the performance of the two hands should be compared on a number of tasks, across a still wider range of indices. It would be advantageous to examine the effects of both target and movement amplitude, as well as object size, as the present study manipulated only the size of object. It could also be argued that the task itself was too simple to elicit large performance differences between the hands. Steenhuis and M.P. Bryden (1989) have argued that individuals choose their preferred hand more often for tasks requiring greater manual skill. It has been suggested by these authors that the relatively small performance differences found on the Annett pegboard are a result of the low degree of manual skill it requires. Thus, the performance differences of the two hands should be examined not only across a wide range of task difficulties, but also across different tasks.

EXPERIMENT 2

The purpose of the next experiment was twofold; first, to replicate the results of van Horn and McManus (1994) and the previous experiment using a different task, and second, to manipulate both target size and movement amplitude, which had not been done in the previous study, as well as object size. Here, a variation of the Fitts' reciprocal tapping task was used which required participants to tap on targets of various sizes using a hand-held stylus. Approximately the same absolute range of indices of difficulty was examined as in the previous experiment, but here the IDs were lower (2.0 to 6.0 bits). Based on the results of the previous study, it was hypothesized that there would be no interaction between hand and task difficulty, and that the slopes of the linear functions for the two hands would not differ significantly.

Method

Participants

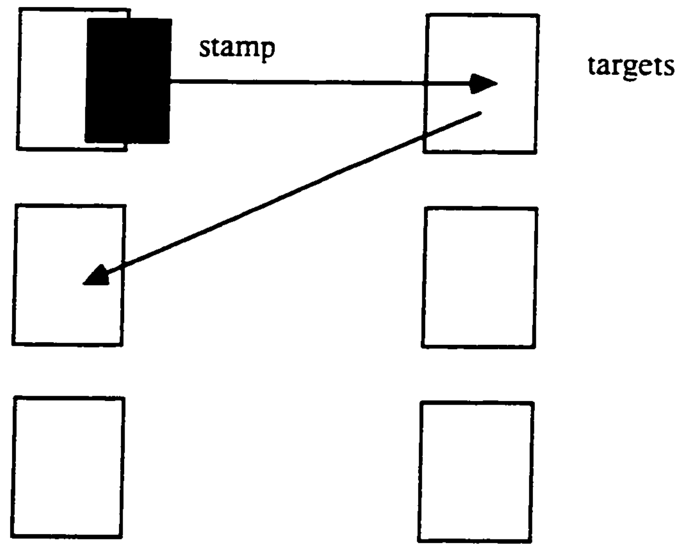
One hundred and ninety-nine first-year undergraduate students participated in the experiment, as part of a laboratory assignment for an introductory Kinesiology course. One hundred and eighty right-handers (121 females and 59 males) and nineteen left-handers

(10 females and 9 males) participated. Participants were initially classified as either right- or left-handed based on their self-professed hand preference. However, the Waterloo Handedness Questionnaire - Revised (Boucher, M.P. Bryden, & Roy, 1997) had been administered at an earlier date and the questionnaire data were used to establish the handedness of the participants correctly. Only the results of the right-handers will be discussed here. It should be noted that the analysis of the left-handers did reveal the same pattern of results as the right-handers.

Apparatus

The task was performed using a variation of the Fitts' (1954) reciprocal tapping task where participants were required to tap on targets of various sizes using a hand-held stamp (see Figure 8 for a diagram of set-up). This task differed from the traditional Fitts' tapping task in that participants were not tapping back and forth between two targets, but rather tapped down two rows of targets. The targets were drawn on pieces of paper, and participants used an inked stamp to tap on each of the targets in the series. Two different stamp sizes were used (2.5cm by 1.5cm and 5.5cm by 2.5cm). For each stamp size, three different target sizes were used, but the effective tolerance remained the same across stamp size (0cm, 1.25cm, and 1.875cm tolerances). Three different amplitudes were also examined (5cm, 10cm, and 20cm). Different participants were allocated to each stamp/amplitude combination (i.e., six groups). For each of the three movement amplitudes, three different indices of difficulty were investigated (5cm amplitude resulted in 2, 3 and 4 bits, 10cm amplitude resulted in 3, 4 and 5 bits, and 20cm amplitude resulted in 4, 5, and 6 bits). Therefore, a total of five indices of difficulty were examined for each stamp size (2, 3, 4, 5, and 6 bits), where index of difficulty was both a between and within-

Figure 8. Schematic diagram of the the Fitts' reciprocal tapping task used in experiment two.



subject factor. For this reason, index of difficulty was not used as factor in the overall analysis. Summarizing, the between-subjects factors were stamp size and movement amplitude, and the within-subject factor was tolerance. Each participant performed the task six times, once for each condition.

Procedure

Testing was performed in sections, with no more than twenty participants in each group. The participant's task was to tap on as many targets as possible, in ten seconds, using the hand held stamp, while minimizing the number of errors they made (i.e., tapping outside the target boundaries). Participants stood and made the movements towards and away from their body. Ten seconds per condition were counted down with a stopwatch. After the signal to stop tapping was issued, the total number of taps was tabulated and recorded. Movement time per stamp placement was then calculated by dividing 10 seconds by the number of targets correctly stamped in that time.

Results

Separate analyses for each stamp size were performed, as the groups were comprised of different participants. For each stamp size a three (tolerances) by two (hands) by three (amplitudes) analysis of variance was performed, using movement time per tap (sec) as the dependent variable, and where amplitude was a between-subjects factor. The ANOVA table for the large stamp is presented in Appendix A, Table 2. Significant main effects were found for hand ($F_{(1,31)}$=158.79, p=0.0001), tolerance ($F_{(2,62)}$=13.24, p=0.0001), and movement amplitude ($F_{(2,51)}$=10.77, p=0.0001) for movements made with the large stamp. Duncan's post hoc analysis revealed that the preferred hand (0.2124sec/tap) was significantly faster than the non-preferred hand (0.2422sec/tap). As well, the 0cm tolerance condition (0.236sec/tap) resulted in significantly longer movement time than either of the 1.87cm or 1.25cm tolerance conditions (0.22sec/tap and 0.225 sec/tap, respectively). Duncan's post hoc analysis also revealed that the 8cm movement amplitude (0.255sec/taps) resulted in significantly longer movement times than either the 4cm or the 2cm movement amplitude (0.218sec/tap and 0.207sec/tap, respectively). No significant interactions were found. Figure 9 portrays the total movement times as a function of movement amplitude and tolerance conditions for the large stamp condition.

Similarly, with the small stamp size significant main effects were found for hand ($\underline{F}_{(1,31)}$=87.64, $\underline{p}$=0.0001), tolerance ($\underline{F}_{(2,62)}$=54.11, $\underline{p}$=0.0001), and movement amplitude ($\underline{F}_{(2,51)}$=16.58, $\underline{p}$=0.0001) (see Appendix A, Table 3). Once again, Duncan's post hoc analysis revealed that the preferred hand (0.251sec/tap) was significantly faster than the non-preferred hand (0.293sec/tap). As well, all three tolerance conditions were significantly different from each other. The 0cm tolerance condition (0.300sec/tap) resulted in the longest movement time, then the 1.25cm tolerance condition (0.272sec/tap), and finally the 1.87cm tolerance condition (0.244sec/tap) with the shortest movement times. According to Duncan's post hoc analysis the 8cm movement amplitude (.316sec/tap) resulted in significantly longer movement times than either the 4cm or the 2cm movement amplitudes (0.259sec/tap and 0.236sec/tap, respectively). Once again, no significant interactions were found. Figure 10 shows the total movement times as a function of movement amplitude and tolerance conditions for the small stamp condition.

Next, a series of linear regressions examining the relationship between movement time and index of difficulty were performed for each stamp size as a test of Fitts' Law.

Figure 9. Total movement times as a function of movement amplitude and tolerance for the large stamp in Experiment 2.

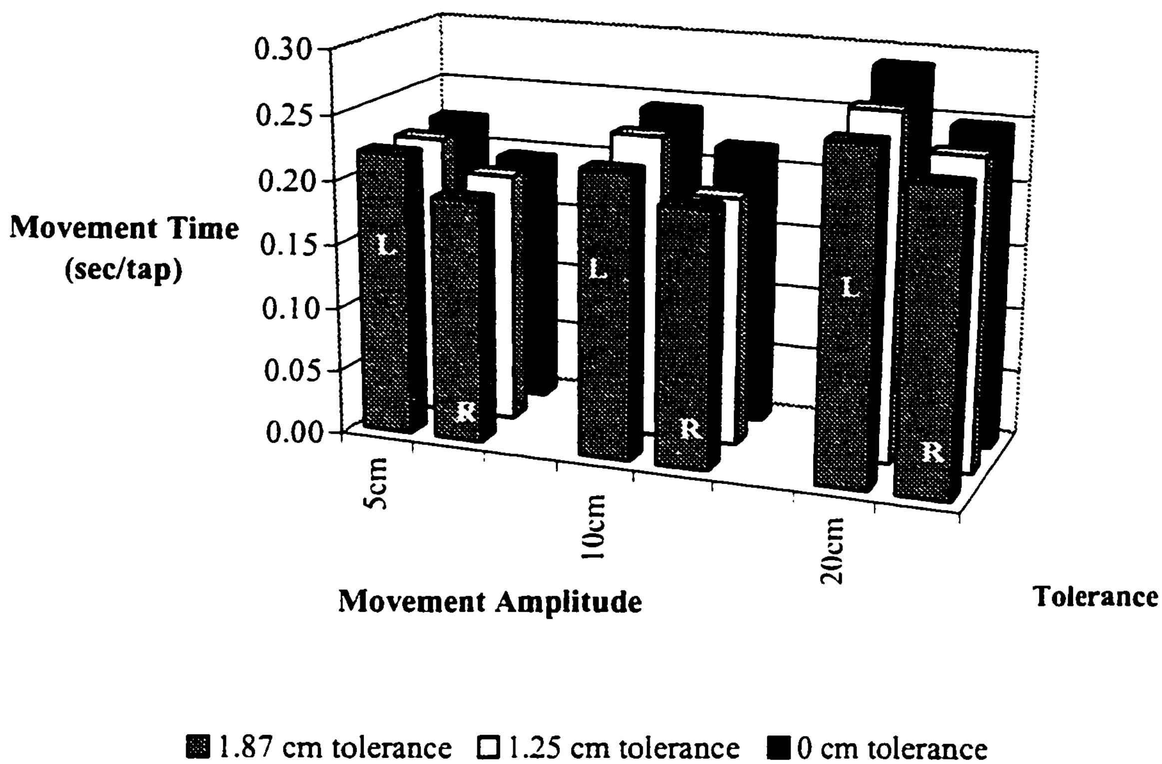
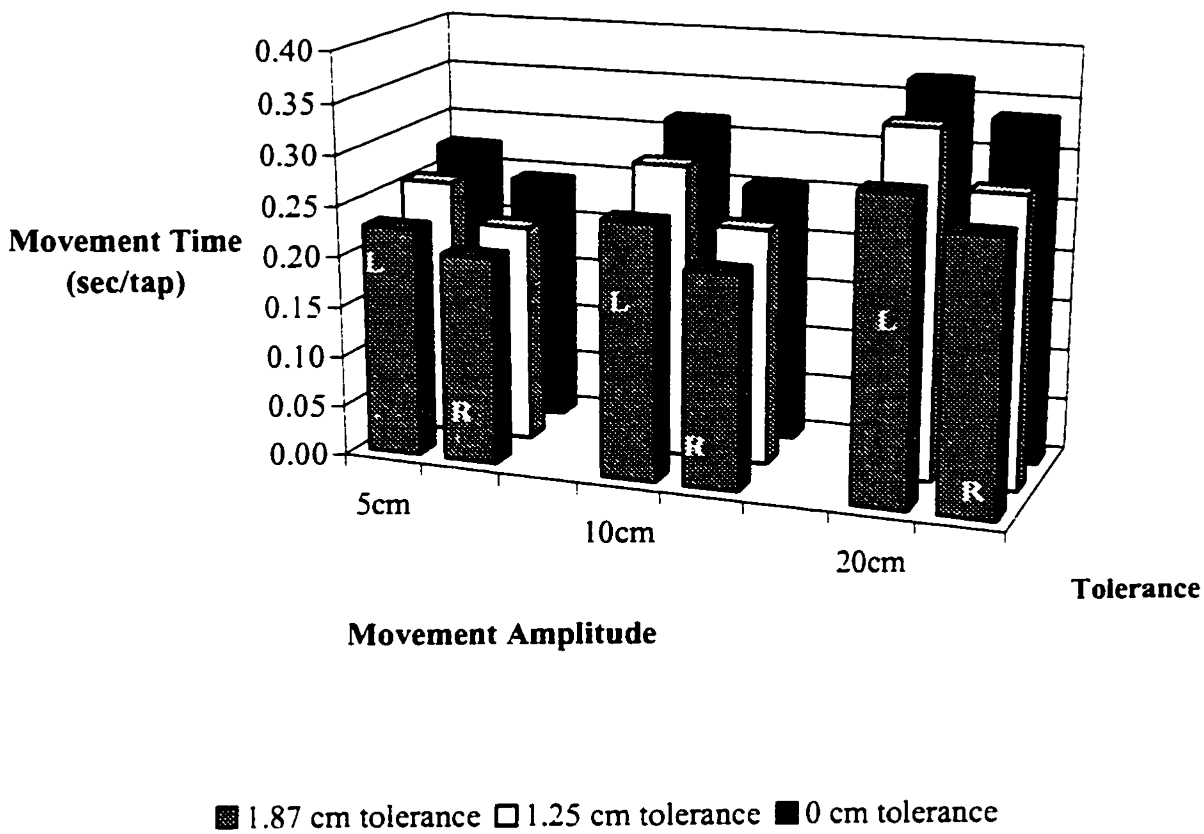


Figure 10. Total movement times as a function of movement amplitude and tolerance for the small stamp in Experiment 2.



Recall, because movement amplitude was a between-subjects variable that the same participants did not perform the task at all five indices of difficulty, rather each participant performed only three indices. In addition, the number of participants who performed each ID fluctuated. However, the analyses were necessary to demonstrate Fitts' Law. First, a linear regression of total movement time on index of difficulty was calculated for the large stamp size. A significant linear relationship was revealed (R^2=0.9601, p=0.0034, slope=0.0254), as predicted by Fitts' Law. The total movement times and the associated linear equation as a function of index of difficulty are presented in Figure 11 for the large stamp size. Examining this relationship for each hand shows that both the preferred (R^2=0.957, p=0.0038) and the non-preferred hand (R^2=0.9053, p=0.0127) have strong, significant relationships between index of difficulty and movement time. The linear functions of the preferred and non-preferred hands for the large stamp are shown in Figure 12.

Next, a linear regression of total movement time on index of difficulty was calculated for the small stamp size. A significant linear relationship was found (R^2=0.8646, p=0.0001, slope=0.0337), as predicted by Fitts' Law. The total movement times and the associated linear equation as a function of index of difficulty are presented in Figure 13. For the small stamp, both the preferred (R^2=0.9134, p=0.011) and the non-preferred hand (R^2=0.9926, p=0.0003) showed strong, significant relationships between index of difficulty and movement time. The linear functions of the preferred and non-preferred hands for the small stamp are shown in Figure 14.

Finally, linear regressions were performed for each hand, collapsed across all factors including stamp size. A significant linear relationship between movement time

Figure 11. Linear regression equation of movement time as a function of index of difficulty for the large stamp, in Experiment 2.

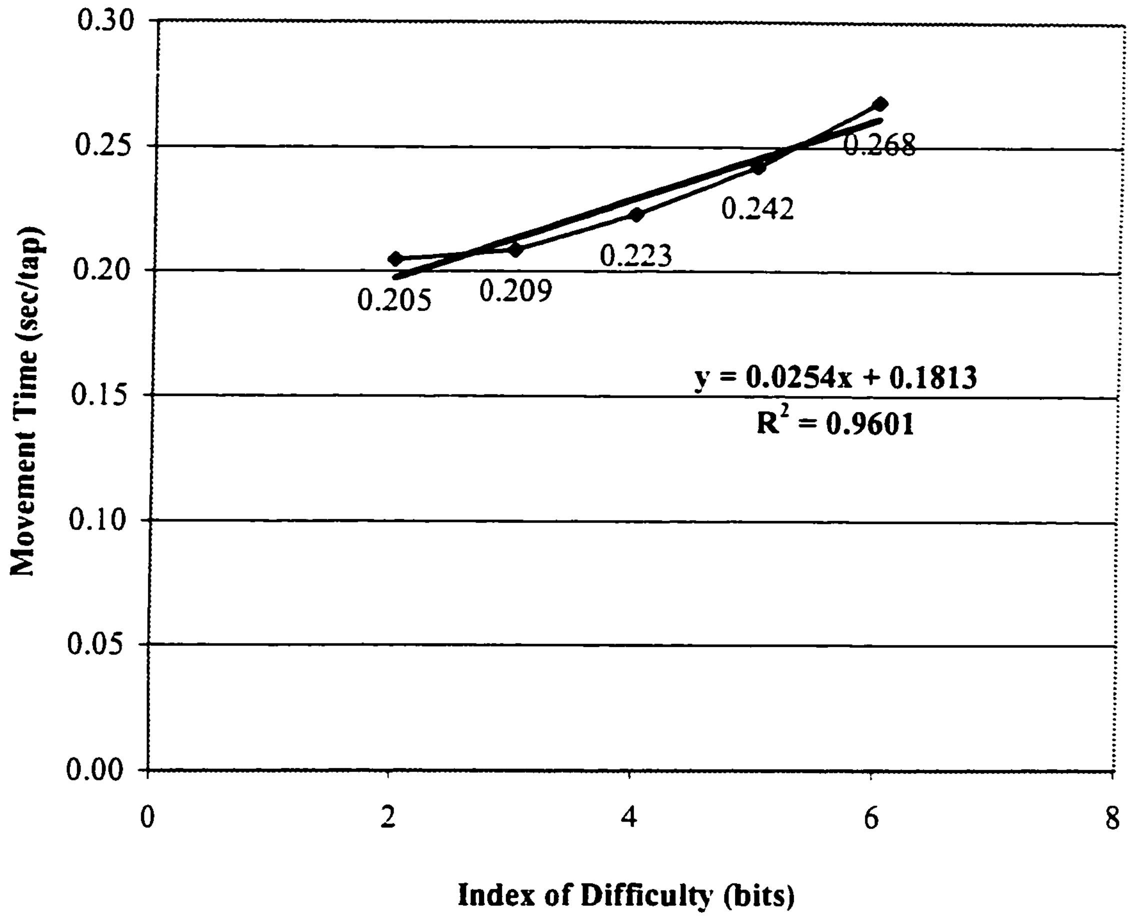


Figure 12. Linear regression equations of movement time as a function of index of difficulty for preferred and non-preferred hands for the large stamp in Experiment 2.

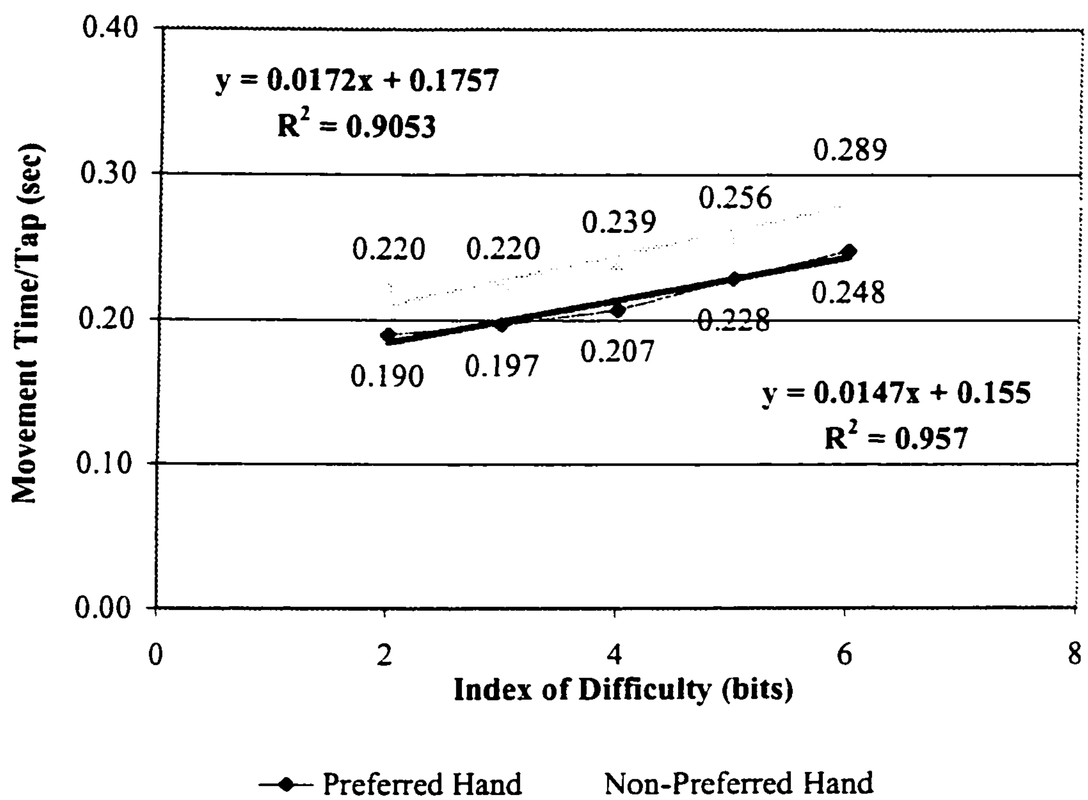


Figure 13. Linear regression equation of movement time as a function of index of difficulty for the small stamp, in Experiment 2.

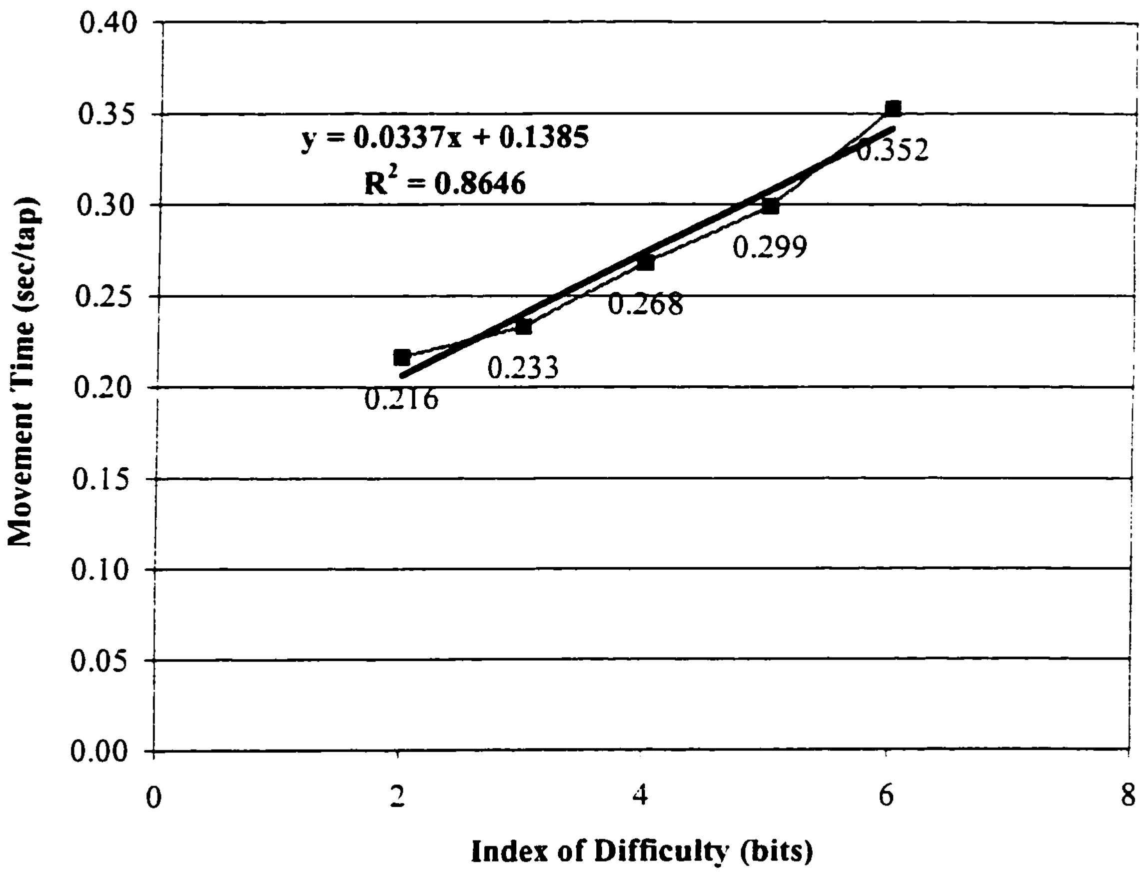
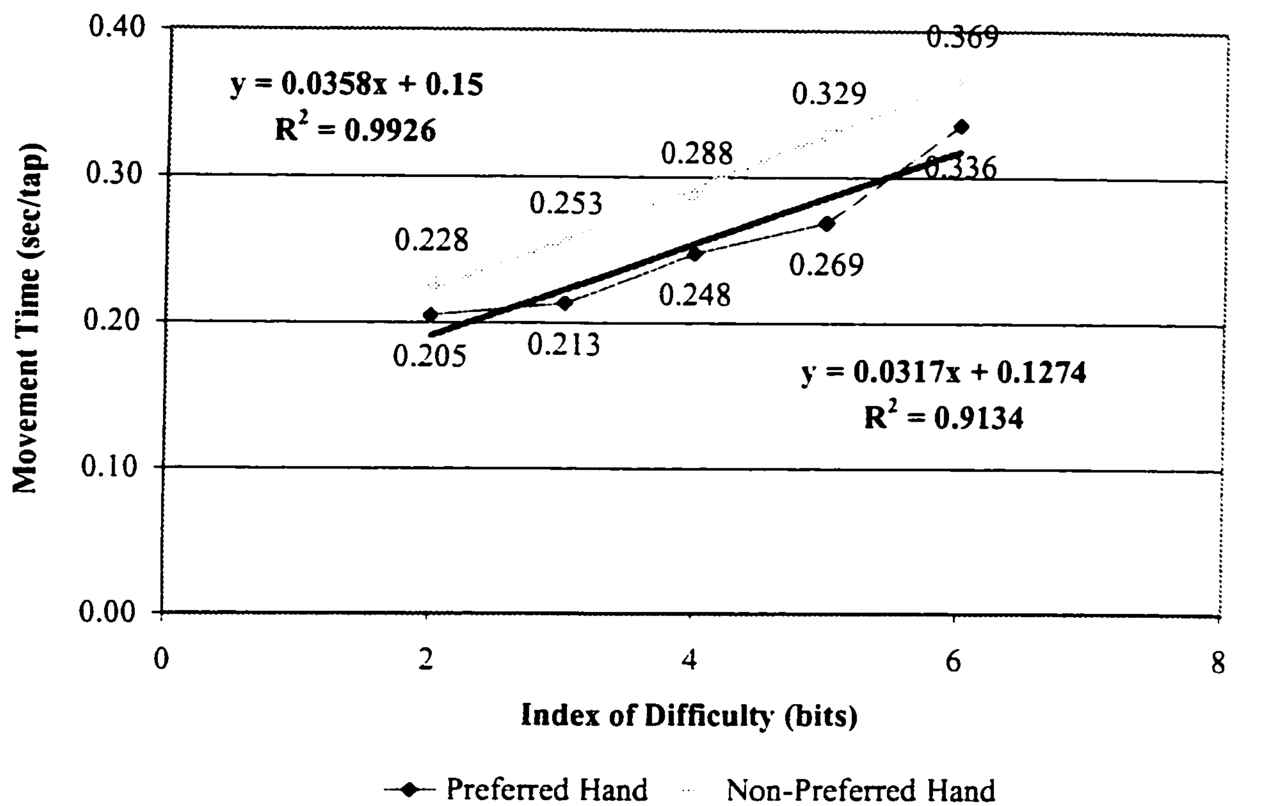


Figure 14. Linear regression equations of movement time as a function of index of difficulty for preferred and non-preferred hands for the small stamp in Experiment 2.



and index of difficulty was found for both the preferred (R^2=0.9342, p=0.0073, slope=0.024) and the non-preferred hands (R^2=0.9767, p=0.0015, slope=0.027). Figure 15 depicts the relationship between movement time and index of difficulty collapsed across all factors for the preferred and non-preferred hands.

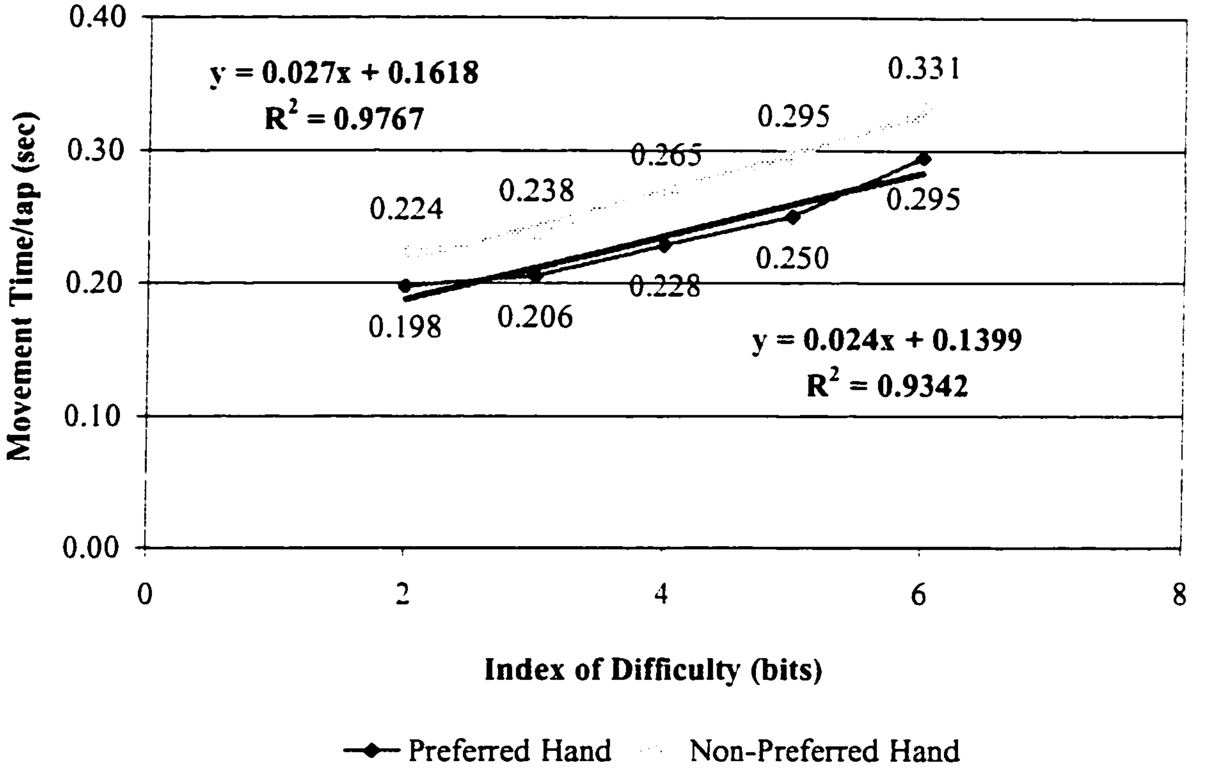
Discussion

Experiment 2 found that the hand by ID interaction was non-significant, confirming once more that the performance difference between the hands is invariant across index of difficulty. The results of van Horn and McManus (1994) were again replicated.

Unlike Experiment 1 however, both the tolerance and the amplitude of the movement were manipulated in this experiment. Experiment 2 examined the same range, but lower values of task difficulty as the IDs examined ranged from 2.0 to 6.0 bits, while in the previous experiment the IDs ranged from 6.0 to 11.0 bits. It appears then, that the findings of experiment 1 cannot be a result of the manipulation of the tolerance component of task difficulty, because the same results were found in Experiment 2. Moreover, it has been shown that there is a constant between-hand difference across a high ID range (Experiment 1) as well as across a lower ID range (Experiment 2). Therefore, it is difficult to argue that the constant between-hand difference is an artifact of examining a limited range of indices of difficulty.

As noted earlier, the present study manipulated both tolerance and movement amplitude, thus presenting the opportunity to investigate the effects of these factors on hand performance. Lengthening the movement amplitude has been said to increase the

Figure 15. Linear regression equations of movement time as a function of index of difficulty for preferred and non-preferred hands, collapsed across stamp size in Experiment 2.



amount of pre-programming necessary (Todor & Cisneros, 1985) and increase the strength of the initial impulse (Schmidt et al., 1978; 1979) necessary to produce the movement. The movement amplitude manipulation did not affect the two hands differentially, evidenced by the lack of an interaction between hand and amplitude. According to these results, the between-hand difference cannot be attributed to differential processing times needed for movement programming, or in the strength of the initial impulse. Contrary to previous reports (Todor & Doane, 1978) movement amplitude does not influence the magnitude of the preferred-hand advantage.

There was also no differential effect of tolerance on the movement times of the preferred and non-preferred hands, as shown by the lack of an interaction between hand performance and tolerance. Current theories suggest that decreasing the size of the target relative to the object size increases the amount of visual feedback required to perform the movement (Crossman and Goodeve, 1983). Researchers have also suggested that the differences in movement time between the two hands can be accounted for by more efficient visual feedback processing of the right hand/left hemisphere system (Flowers, 1975). However, considering that the hands did not perform differentially across tolerance conditions, the visual feedback hypothesis does not adequately explain the performance differences between the hands.

In summary, the present experiment determined that the performance difference between the hands remains constant across the lower end of task difficulty as quantified by Fitts' Law. Furthermore, this study determined that the performance of the two hands was not differentially affected by the two components of task difficulty: tolerance and movement amplitude. This suggests that neither movement programming nor visual feedback theories can entirely account for the movement time differences between the hands.

EXPERIMENT 3

The results of the first two experiments corroborate the findings of van Horn and McManus (1994) in that the difference in performance between the preferred and non-preferred hands remained constant across a range of task difficulty. In contrast, some researchers have concluded that the performance difference between the hands is most evident during the target acquisition (Todor & Cisneros, 1985). The Grooved pegboard was chosen for the next experiment, because it requires a high level of manual dexterity during the final phase of the movement. The added difficulty in the Grooved pegboard is that it places increased constraints upon the positioning element of the task. By comparing the time required to position all twenty-five pegs to the time taken to remove the pegs, the limits of task difficulty can thereby be pushed beyond those already investigated. Based on the finding of a constant between-hand difference across task difficulty in the previous two experiments, it was again hypothesized that there would be no interaction between the hand used to perform the task and task difficulty. More specifically, it was thought that the absolute difference between the hands would be the same for both placing and removing the pegs.

Method

Participants

Fifty-one undergraduate students at the University of Waterloo participated in this experiment on a volunteer basis. Forty-five right-handers (29 females and 16 males) and six left-handers (3 females and 3 males) participated as part of a larger investigation of hand performance across various tasks. All participants completed the Waterloo Handedness Questionnaire Revised (Boucher, M.P. Bryden & Roy, 1997) prior to experimentation, which was used to verify the direction of hand preference.

Apparatus

Task demands were manipulated by having participants complete two phases of the Grooved Pegboard: one phase consisting of placing the pegs in their holes (Place), and another of removing the pegs and placing them in a large receptacle (Remove). The pegs were key-shaped, as were the holes. Thus, the Place phase of the task had high spatial precision demands, because correctly orienting the small pegs in their respective holes was challenging. In contrast, the Remove phase placed significantly fewer demands on spatial precision since the receptacle size was large (diameter = 12cm), allowing participants to accomplish the task by simply tossing the pegs towards the receptacle. It is important to note that an orientation component (i.e., twisting of the pegs) was required in the Place phase but not in the Remove phase. Applying Fitts' equation for calculating index of difficulty using tolerance and assuming an equal average movement amplitude between the two tasks, the Place phase had an ID of 13 bits, while the Remove phase had an ID of 1.5 bits of information. The shape of the peg was not taken into consideration in the calculation.

Procedure

Participants were seated at a table with the Grooved pegboard in front of them, oriented so that the receptacle was closest to them. Each participant was required to complete both phases of the Grooved pegboard. They were asked to perform the task as quickly as possible, while limiting the number of errors they made. Participants alternated between tasks, always beginning with the Place phase, and completed two trials of each phase. Starting hand was counterbalanced across participants. The time taken to complete each task was measured using a stopwatch, and then recorded.

Results

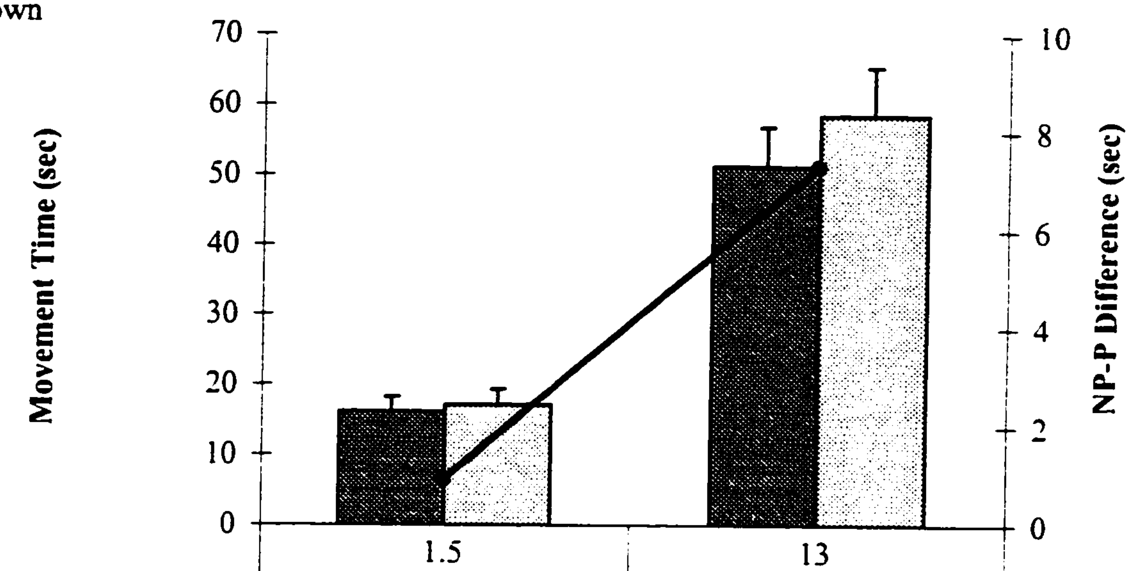
In order to take into account the fact that the Place phase necessarily took longer than the Remove phase, the movement times for each phase were first converted to a logarithmic score. Note, however, the true movement times are presented in both text and figures to aid in comprehension. Only the analysis for the right-handers is included here, due to the discrepancy in sample size between the two groups. It should be noted that there were no differences between the groups. A two (hand) by two (phases) repeated measures analysis of variance was conducted. The ANOVA table is presented in Appendix A, Table 4. Main effects of hand ($F_{(1,44)}$=3643.34, p=0.0001) and phase ($F_{(1,44)}$= 61.25, p=0.0001) were found. The preferred hand (33.69 seconds) was, on average, faster than the non-preferred hand (37.83 seconds). In addition, the Place phase (54.86 seconds) took significantly longer to complete than the Remove phase (16.66 seconds). A significant interaction between hand and phase ($F_{(1,44)}$= 62.93, p=0.0001) was also found, indicating that the performance difference between the hands changed as a function of the phase.

Here, there was a small, but significant difference between the hands for the Remove phase (preferred=16.19, non-preferred=17.13), and a large difference between the hands existed for the Place phase (preferred=51.2, non-preferred=58.52). Figure 16 shows the movement times of the preferred and non-preferred hands for both phases of the Grooved pegboard, according to index of difficulty. Depicted as well in Figure 16 is the absolute difference between the hands.

Discussion

Experiment 3 revealed that the performance difference between the hands was larger and more consistent for the Place phase, while there was a relatively small difference between the hands for the Remove phase. The findings suggest that task difficulty does influence the performance of the two hands differentially. Observe that Experiment 3 examined only two tasks, with widely disparate indices of difficulty. In fact, the index of difficulty varied so greatly in this study that the goal of the task may have also varied. One explanation for the significant interaction is that the results are indicative of what would occur if a wide range of tasks were examined, from the very easy to the very difficult, in the same individuals. If this were the case, the constant between-hand difference reported in Experiment 1 and 2 could be due to having examined only a narrow window of performance across task difficulty. In order to investigate fully the effects of task difficulty on hand performance, it is clear that a wider range of task difficulties, from the very simple to the very complex, should to be examined in the same

Figure 16. Movement times, including stardard deviations, for preferred and non-preferred hands for the Grooved pegboard. The absolute difference in performance between the hands is also shown



	1.5	13
Preferred Hand	16.19	51.21
Non-Preferred Hand	17.13	58.52
NP-P difference	0.943	7.309

Index of Difficulty (bits)

participants. Experiments 5 and 6 further investigate the performance of the two hands as a function of task difficulty, and use a wide range of indices.

Note, however, that Experiment 3 also incorporated an additional component into the peg-moving task. Participants were required to twist the pegs into their proper orientation in the Place phase of the task, but there was no orientation component in the Remove phase. Therefore, the greater differences in the Place phase cannot necessarily be attributed to its greater index of difficulty. Perhaps the orientation component required the processing abilities of the left hemisphere, which has been shown to be superior in the sequencing or organization of movements (Kimura, 1992). This would explain the greater preferred-hand advantage for the Place phase. Based on these arguments, the next step was to determine if the orientation requirement places greater demands on the participants than the normal, straight orientation, when index of difficulty is held constant. In this manner, it could be determined whether the orientation factor produces a greater performance difference between the hands. Experiment 4 was performed to examine the effects of orientation on manual asymmetries.

EXPERIMENT 4

In order to examine the effects of orientation on hand performance a new pegboard was designed which required participants to twist the pegs in order to orient them properly in their respective holes. This "orientation" pegboard was then compared to the standard Annett pegboard. Index of difficulty was kept constant across the two pegboards. Based on the findings of the previous experiment it was hypothesized that a greater preferred-hand advantage would be evident for the orientation pegboard than the standard Annett pegboard.

Method

Participants

Fifty-one undergraduate students participated in the present experiment to earn bonus marks toward their course work in Kinesiology at the University of Waterloo. Forty-five right-handers (29 females and 16 males) and six left-handers (3 females and 3 males participated as part of a larger investigation of hand performance across various tasks. All participants completed the Waterloo Handedness Questionnaire Revised (Boucher, M.P. Bryden & Roy, 1997) prior to experimentation, which was used to verify the direction of hand preference.

Apparatus

The Annett pegboard described in Experiment 1 was used in this experiment, along with a new variation of the Annett pegboard which required participants to twist the pegs in order to orient them in their respective holes. The new pegboard had the same measurements as the Annett pegboard, as well as the same number of holes and pegs; hence, both pegboards were associated with the same indices of difficulty. However, both the holes and pegs of the new pegboard had a keyhole shape, which made it necessary to twist the wrist to position the peg. This keyhole shape was achieved by attaching two wooden dowels together (diameters 1.3cm and 0.9cm). One row on the orientation pegboard had all the holes in the same orientation, while the holes were in 10 different orientations in the second row. A schematic diagram of the orientation pegboard is presented in Figure 17.

Procedure

The participant's task was to move as many pegs as possible, in ten seconds, while minimizing the number of errors they made. For the orientation pegboard, participants moved the pegs into the row where hole orientation differed for each insertion. Each participant completed both the standard Annett pegboard and the orientation pegboard, while seated, with both their preferred hand and their non-preferred hand for two trials. Starting hand was counterbalanced across participants. The time to complete the task was measured using a stopwatch and then recorded.

Results

Initially, the data were grouped according to the handedness preference of the participants, and movement times were then coded with respect to the preferred hand. Only the analysis for the right-handers is included here, due to the discrepancy in sample size between the two groups. A two (hand) by two (orientation present or absent) repeated measures analysis of variance was conducted. The ANOVA table is presented in Appendix A, Table 5. Main effects of hand ($F_{(1,44)}=199.89$, $p=0.0001$) and orientation ($F_{(1,44)}=81.76$, $p=0.0001$) were found. The preferred hand (11.45 seconds) took less time to complete the task than did the non-preferred hand (12.51 seconds). The orientation pegboard (13.63 seconds) produced significantly longer movement times than did the normal Annett pegboard (10.33 seconds). A hand by orientation interaction was also revealed ($F_{(1,44)}=8.97$, $p=0.004$), where the overall, mean preferred-hand advantage was

Figure 17. Schematic diagram of orientation pegboard used in experiment four.

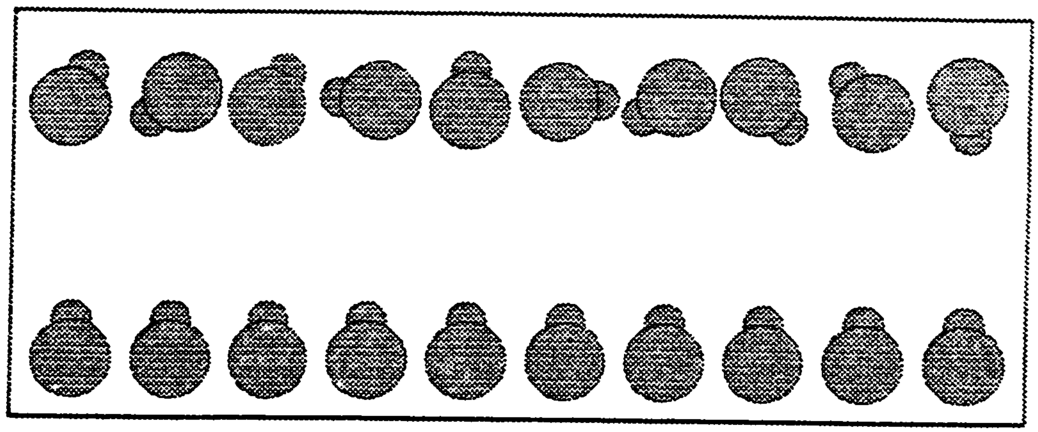
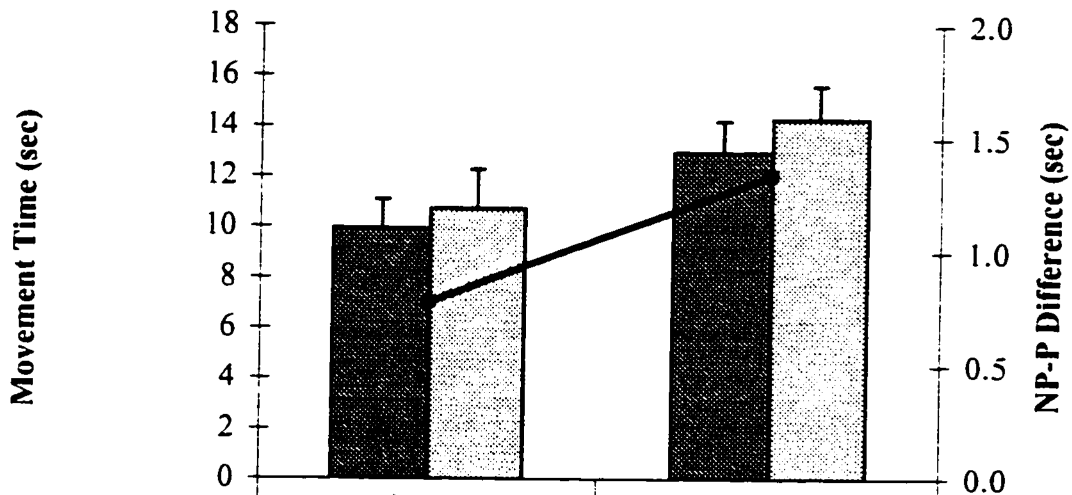


Figure 18. Movement times, including stardard deviations, for preferred and non-preferred hands for the Annett pegboard and orientation pegboard in Experiment 4. The absolute difference in performance between the hands is also shown.



	Annett	Orientation
Preferred Hand	9.94	12.96
Non-Preferred Hand	10.72	14.30
NP-P difference	0.78	1.34

Pegboard

significantly larger for the orientation pegboard (1.34 seconds) than for the Annett pegboard (0.78 seconds). Figure 18 presents the movement times for the preferred and non-preferred hands as a function of index of difficulty. The absolute difference in performance time between the hands is also indicated in the figure.

Discussion

The results of Experiment 4 indicate that adding an orientation component to the pegboard task significantly affected the magnitude of the performance difference between the two hands, as evidenced by the significant interaction. Greater differences between the hands for tasks with an orientation component may result from greater involvement of the left hemisphere in programming such a movement. Given the results of the current experiment the effects described in Experiment 3 may be due to difference in the orientation requirement between the two phases of the Grooved pegboard. It appears from this experiment that the orientation of the target influences the magnitude of manual asymmetries in a manner not observed when only task difficulty is manipulated. The next two experiments will return to the issue of the performance of the two hands across task difficulty in order to ascertain whether task difficulty interacts with hand performance (as seen in Experiment 3) or not (as seen in experiments one and two) given a large range of difficulty and the same participants performing all conditions.

EXPERIMENT 5

It was shown in Experiment 3 that the performance difference between the hands increased for the Place phase of the Grooved pegboard as compared to the Remove phase. As discussed, the Place phase not only represented a high degree of difficulty, as defined by Fitts' Law, but it also required the peg placement to be oriented precisely. The remove phase in comparison represented a very low degree of difficulty, and there was no orientation component necessary to achieve the goal of the task. Experiment 4 was therefore performed in order to ascertain whether task difficulty or orientation was the contributing factor to the increase in the performance difference between the hands. Here it was shown that end-point orientation results in an increased preferred-hand advantage. However, it is still necessary to determine whether a wide range of task difficulties also influences the extent of the preferred-hand advantage. In order to examine this possibility, the methodology employed in Experiment 3 with the Grooved pegboard was adapted for use with the Annett pegboard. Specifically, participants either positioned pegs into holes in the Annett pegboard, or removed them from their holes and placed them into a large receptacle. The task had no orientation component. In this manner, both the low and high ends of task difficulty could be examined simultaneously, in the same task.

Method

Participants

Thirty-two right-handed (7 males and 25 females) undergraduate students from the University of Waterloo participated in the present experiment on a volunteer basis. All participants completed the Waterloo Handedness Questionnaire Revised (Boucher, M.P. Bryden & Roy, 1997) following the task, which was then used to determine the direction of hand preference.

Apparatus

Task demands were manipulated by having participants complete two phases on the Annett pegboard. The Place phase required participants to pick up pegs from a large receptacle and position them one at a time into the closest row of holes. The Remove phase required participants to remove the pegs from the row and place them back into the large receptacle. Thus, the task was very similar to the one used in Experiment 3, but the Annett pegboard was used instead of the Grooved pegboard, thus no orientation component was present in this task. The large receptacle was approximately 14cm in diameter, and the diameter of the holes in the pegboard was 1.27cm. Four sizes of pegs were used (1.25cm, 1.1cm, 0.59cm, 0.33cm). Using Fitts' equation for calculating index of difficulty and assuming an equal average movement amplitude between the two tasks (17.2cm), the Place phase had IDs of 11, 6.9, 5.7, and 5.2 bits, while the Remove phase had IDs of 1.43, 1.4, 1.36, and 1.33 bits.

Procedure

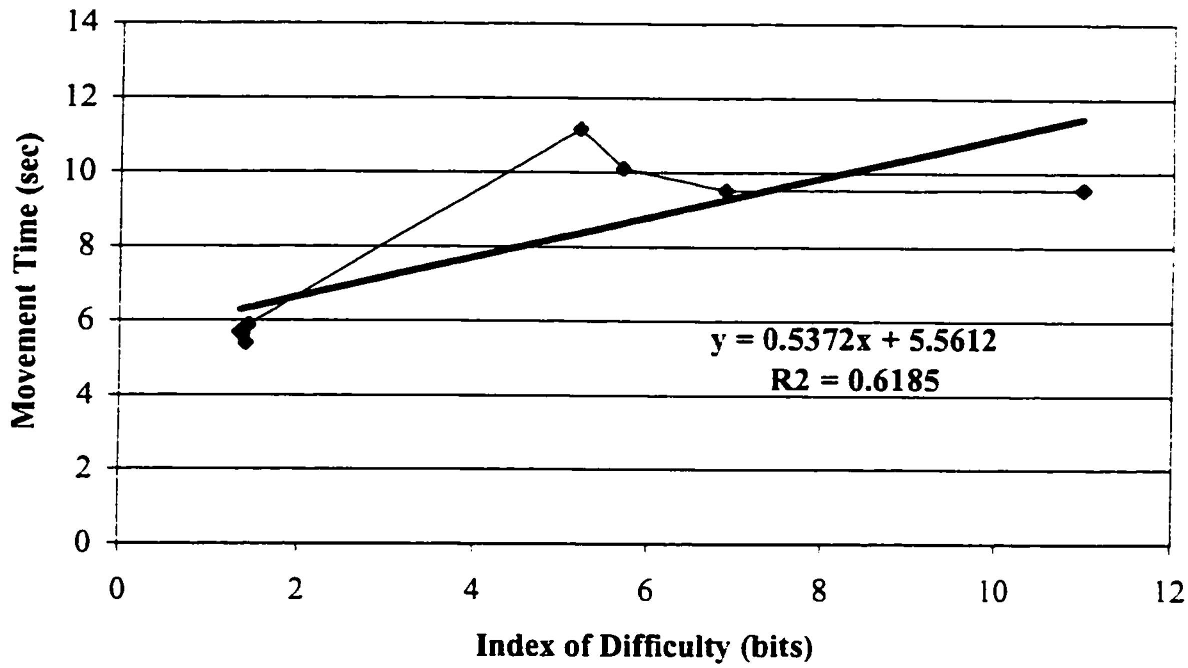
Participants were seated at a table with the Annett pegboard in front of them, oriented so that the receptacle was closest to the participant. For the Place phase, participants were asked to pick up the pegs, one at a time, from the receptacle, and place them into the closest row of holes, starting with the hole in contralateral space. For the Remove phase, participants were asked to take the pegs out of the row of holes, one at a time starting in contralateral space, and place them in the large receptacle.

Each participant was required to complete both phases. They were asked to perform the task as quickly as possible, while limiting the number of errors they made. Participants alternated between tasks, always beginning with the Place phase, and completed three trials with each peg, for each hand. Starting hand was counterbalanced across participants. The time taken to complete each task was measured using a stopwatch, and then recorded.

Results

In order to take into account the fact that the Place phase necessarily took longer than the Remove phase, the movement times for each phase were first converted to a logarithmic score. Note, however, the true movement times are presented in both text and figures to aid in comprehension. Initially, a two (hand) by eight (index of difficulty) repeated measures analysis of variance was conducted using the logarithmic total movement times for each hand as the dependent variable. Note that the index of difficulty factor includes both the peg size factor and the phase factor. The ANOVA table is presented in Appendix A, Table 6. Here, main effects of hand ($F_{(1,31)}$=69.66, p=0.0001) and index of difficulty ($F_{(7,217)}$=906.06, p=0.0001) were found. Overall, the preferred hand (7.59 seconds) was significantly faster than the non-preferred hand (8.14 seconds). While there was a significant effect of task difficulty, movement time did not increase with increasing difficulty in the typical pattern of Fitts' Law, as evidenced by the relatively poor linear relationship between overall movement time and index of difficulty (R^2=0.6185, p=0.0206), which can be seen in Figure 19. The low R^2 suggests that index of difficulty may not be an appropriate measure when more than one component of Fitts' Law is manipulated. A

Figure 19. Linear regression equation for overall movement time as a function of index of difficulty in Experiment 5.

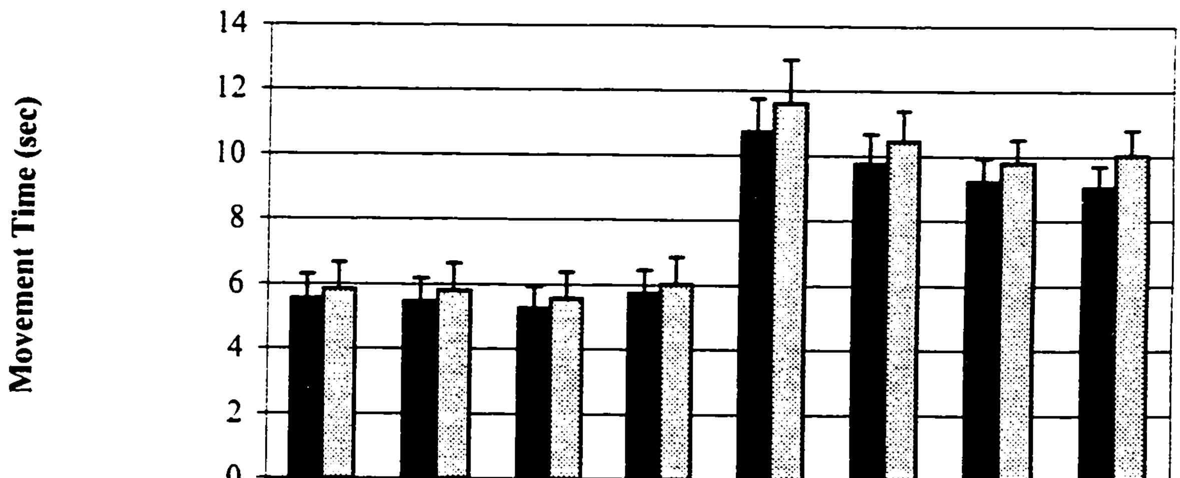


significant interaction between hand and index of difficulty was also revealed ($F_{(7,217)}$=2.30, p=0.028). Duncan's post hoc analysis illustrated a relatively confusing pattern of results, which made interpretation difficult. Large, significant differences between the hands were observed at the high end of task difficulty, and smaller differences between the hands were seen at the lower end of task difficulty. Recall that the indices at the high end of task difficulty represent the Place phase, while the indices at the low end represent the Remove phase. Figure 20 illustrates the overall true movement times for each hand, as a function of index of difficulty.

Next, a two (phase) by four (peg size) by two (hand) repeated measures analysis of variance (see Appendix A, Table 7) was conducted in order to investigate the effects of each of the components of task difficulty on hand performance, using the logarithmic movement times. Main effects of hand ($F_{(1,31)}$=69.66, p=0.0001) and peg size ($F_{(1,31)}$=43.1, p=0.0001) and phase ($F_{(1,31)}$=2005.2, p=0.0001) were found. The hand effect was in the expected direction, as shown in the previous analysis. Duncan's post hoc analysis revealed that the Place phase (10.08 seconds) took significantly longer than the Remove phase (5.64 seconds), as expected. Overall, movements using the smallest peg were significantly slower (8.43 seconds) than movements made with the other three pegs. Similarly, movements with the largest peg were significantly faster (7.45 seconds) than movements using the other pegs.

A significant interaction between phase and peg size ($F_{(3,93)}$=51.86, p=0.0001) was also found. Duncan's post hoc analysis demonstrated that overall movement times for the Place phase were affected by peg size, but this was not the case for the Remove phase. Figure 21 portrays total movement times as a function of peg size and phase. The analysis

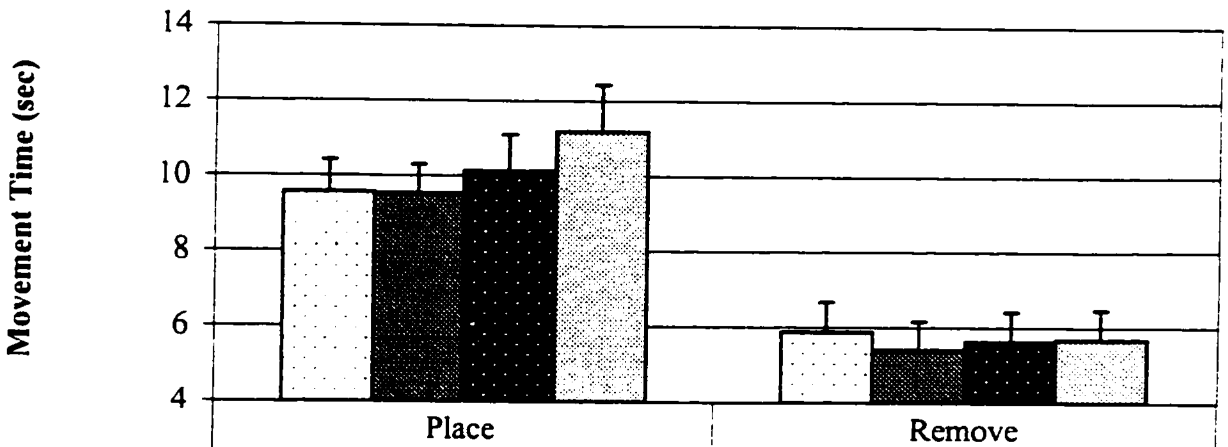
Figure 20. Movement times, including stardard deviations, as a function of index of difficulty for preferred and non-preferred hands in Experiment 5.



	1.33	1.36	1.4	1.43	5.2	5.7	6.9	11
■ Preferred Hand	5.53	5.45	5.25	5.73	10.74	9.768	9.218	9.05
▢ Non-Preferred Hand	5.84	5.789	5.55	6.02	11.606	10.455	9.801	10.035

Index of Difficulty (bits)

Figure 21. Movement times, including stardard deviations, as a function of phase and peg size in Experiment 5.



	Place	Remove
Large	9.54	5.88
Medium	9.51	5.4
Small	10.11	5.62
Smallest	11.17	5.68

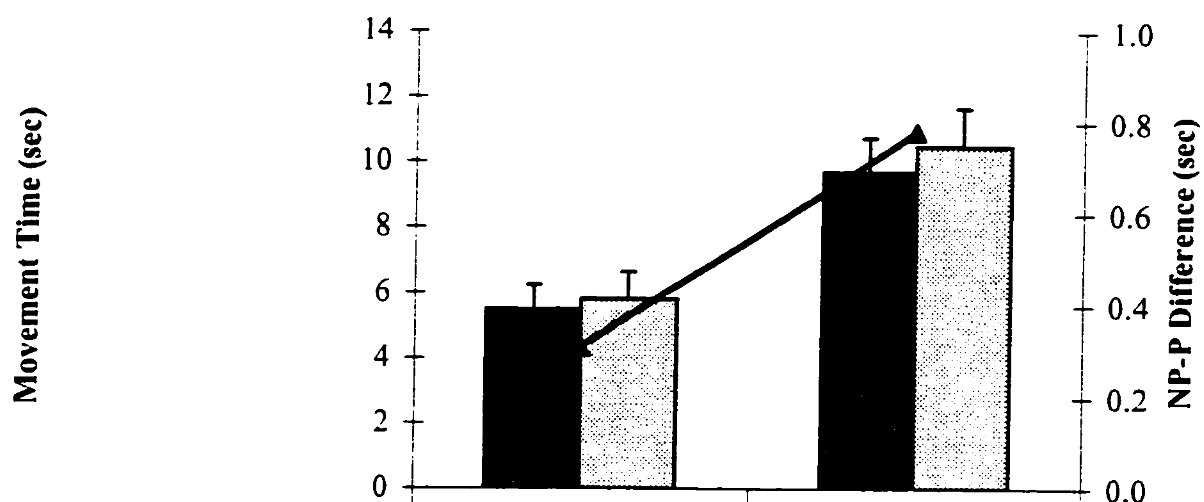
also indicated a significant interaction between phase and hand performance ($F_{(1,31)}$=6.02, p=0.02). Duncan's post hoc analysis showed significant differences between the hands for both phases of the task. Of particular interest is the fact that the performance difference between the hands decreased in magnitude for the Remove phase as compared to the Place phase, as can be seen in Figure 22 which illustrates the total movement times for each hand as a function of the phase completed.

Discussion

A significant interaction between index of difficulty and hand performance was found in Experiment 5, suggesting that the preferred-hand advantage increases as a function of task difficulty, even when there is no demand for orientation precision. Note, however, in Figure 20 the random pattern of movement times as a function of index of difficulty, suggesting that ID may not be an appropriate descriptor of difficulty in this particular situation. As well, the indices of difficulty examined here were either very high or very low (i.e., no medium indices), and therefore it could be argued that the clustering of IDs increased the chances of observing between-hand differences. Clearly, hand performance should be investigated across a number of different IDs, where a continuum of performance can be better observed.

Another problem with the interpretation that the performance difference between the hands increases as a function of index of difficulty based on the current experiment is that the continuum of IDs examined actually represents two different tasks. Recall that the Remove phase represented IDs at the low end of the continuum, while the Place phase represented IDs at the high end of the continuum. The Remove phase consisted of

Figure 22. Movement times, including stardard deviations. for preferred and non-preferred hands as a function of phase in Experiment 5.



	Remove	Place
Preferred Hand	5.494	9.695
Non-Preferred Hand	5.803	10.475
NP-P Difference	0.309	0.780

participants pulling pegs out of their holes and dropping them into a large receptacle. The Place phase, in contrast, required participants to pick pegs out of the large receptacle and position them into their respective holes. Clearly, the two phases represent two different movements, and thus it may be inappropriate to compare the two as a function of index of difficulty.

The second analysis was performed to examine the effects of the different phases and peg sizes on the performance of the two hands. The most important finding in this analysis was the significantly larger differences between the hands for the Place phase (between-hand difference was 0.779 seconds) in comparison to performance on the Remove phase (between-hand difference was 0.31 seconds). Note that the between-hand difference for the Place phase is consistent with, and of the same magnitude as previous between-hand differences reported here and in earlier studies (van Horn & McManus, 1994). Conversely, the difference between the hands observed for the Remove phase is of much smaller magnitude than previously reported, here or in other studies. The large increase in the performance difference between the hands as a function of phase may be a result of the types of movements involved in the two phases. Precise, carefully controlled positioning movements were required in the Place phase, while the movements required for the Remove phase did not need to be as controlled in order to maintain speed and accuracy. Movements that need to be carefully controlled with respect to the timing and sequencing of distal musculature, such as those in the Place phase, are presumably controlled by the left hemisphere. In which case, the right-hand advantage would be due to the quicker access that the motor centre of the right hand has to the sequencer in the left hemisphere. It should also be pointed out at this time that in contrast to the phase manipulation, the peg size manipulation did not interact with hand performance. This shows that a manipulation of ID that includes different movements, as in the Phase manipulation, has different consequences for the performance difference between the hands than changes in index of difficulty achieved by manipulating the peg size.

The results of this experiment suggest that the difference between the hands is significant, but relatively small, when the goal of the task is unconstrained or the movement is simple, as in the Remove phase. In contrast, there is a significantly larger between-hand difference when the goal of the task is tightly constrained, suggesting that such tasks may require the generative abilities of the left-hemisphere.

EXPERIMENT 6

Experiment 5 showed that increasing the index of difficulty augmented the performance difference between the hands. However, not only did the manipulation of interest change across the conditions investigated, but so did the movement performed to attain the goal accurately. Recall that in order to examine a wide range of difficulties a Remove task was compared to a Place task. Ultimately, one cannot conclude that index of difficulty, as defined by Fitts' Law, affects the performance of the two hand differentially until a wide range of IDs have been investigated in the same task. Therefore, in Experiment 6, in contrast to previous studies, both the size of the peg and the size of the hole were manipulated in a version of the Annett pegboard, in order to create a range of IDs.

Method

Participants

Thirty right-handed (12 males and 18 females) undergraduate students at the University of Waterloo performed the present experiment in order to obtain course credit in an introductory Kinesiology course at the University of Waterloo. All participants completed the Waterloo Handedness Questionnaire - Long Form (M.P. Bryden, 1977) following completion of the experiment, in order to assess the direction of hand preference.

Apparatus

Four different versions of the Annett pegboard were used in the present experiment, each with different sized holes. All four boards were 30.6cm by 52.2cm with two rows of 10 evenly spaced holes drilled along the length of the board (4cm apart). The distance between the two rows of holes was 21.2cm. Four hole sizes were investigated (1.27cm, 1.18cm, 1.0cm, and 0.9cm). Seven different sized pegs were used (1.25cm, 1.1cm, 0.94cm, 0.81cm, 0.59cm, 0.45cm, and 0.33cm). For each pegboard, however, only four different sizes of pegs were used, where the most difficult peg for each pegboard was close to the same size as the hole. The other peg sizes used were the next consecutively smaller pegs. Thus, for the 1.27cm hole (pegboard 1), the four peg sizes used were 1.25cm, 1.1cm, 0.94cm, and 0.81cm resulting in IDs of 11, 8, 7, and 6.5 respectively. Peg sizes 1.1cm, 0.94cm, 0.81cm, and 0.59cm were used for Pegboard 2 (1.18cm hole), resulting in IDs of 9.7, 7.3, 6.8, and 6.1 respectively. For the 1.0cm hole (pegboard 3), the peg sizes investigated were 0.94cm, 0.81cm, 0.59cm and 0.45cm, resulting in IDs of 9.5, 7.8, 6.7, and 6.3 respectively. Finally, peg sizes 0.81cm, 0.59cm, 0.45cm, and 0.33cm were examined for pegboard 4 (0.9cm hole), resulting in IDs of 8.9, 7.1, 6.6, and 6.2 respectively.

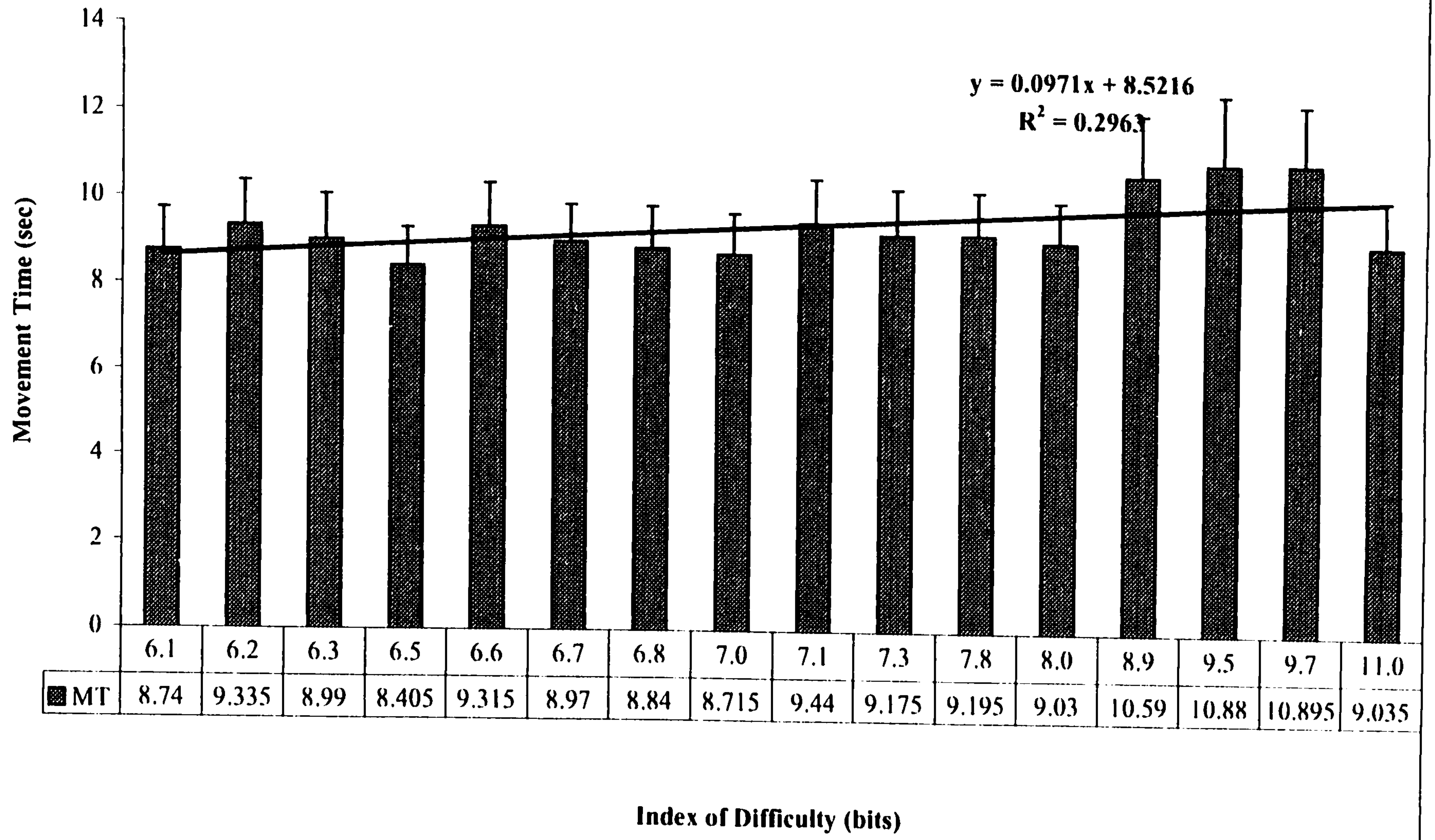
Procedure

The participant's task in the present experiment was to move ten pegs from the home position on the Annett pegboard to their respective positions in the second row as quickly as possible while seated, as described in Experiment 1. One of two presentation orders (randomly presented peg sizes, blocked order of pegboards) was assigned to each participant. Each participant performed three trials of all sixteen peg size/pegboard combinations with each hand. The time taken to move ten pegs was recorded using a stopwatch (from first peg touch, to last peg release).

Results

First, a hand by difficulty (sixteen indices) repeated measures analysis of variance was conducted. The ANOVA table is presented in Appendix A, Table 8. A main effect of hand ($F_{(1,29)}$=179.35, p=0.0001) was found in the anticipated direction where the preferred hand (8.88 seconds) was significantly faster than the non-preferred hand (9.82 seconds). A main effect of index of difficulty ($F_{(15,435)}$=69.15, p=0.0001) was also found, but here the typical pattern of Fitts' Law was not observed (see Figure 23 which depicts the total movement time as a function of index of difficulty). This was evidenced through the significant but poor linear relationship between movement time and index of difficulty (R^2=0.2963, p=0.0293). Again, the low R^2 appears to be a result of manipulating both components that compose tolerance simultaneously. There was also a significant hand by ID interaction ($F_{(15,435)}$=3.03, p=0.0001). Duncan's post hoc analysis of the interaction

Figure 23. Linear regression equation of overall movement time, including stardard deviations, as a function on index of difficulty in Experiment 6.



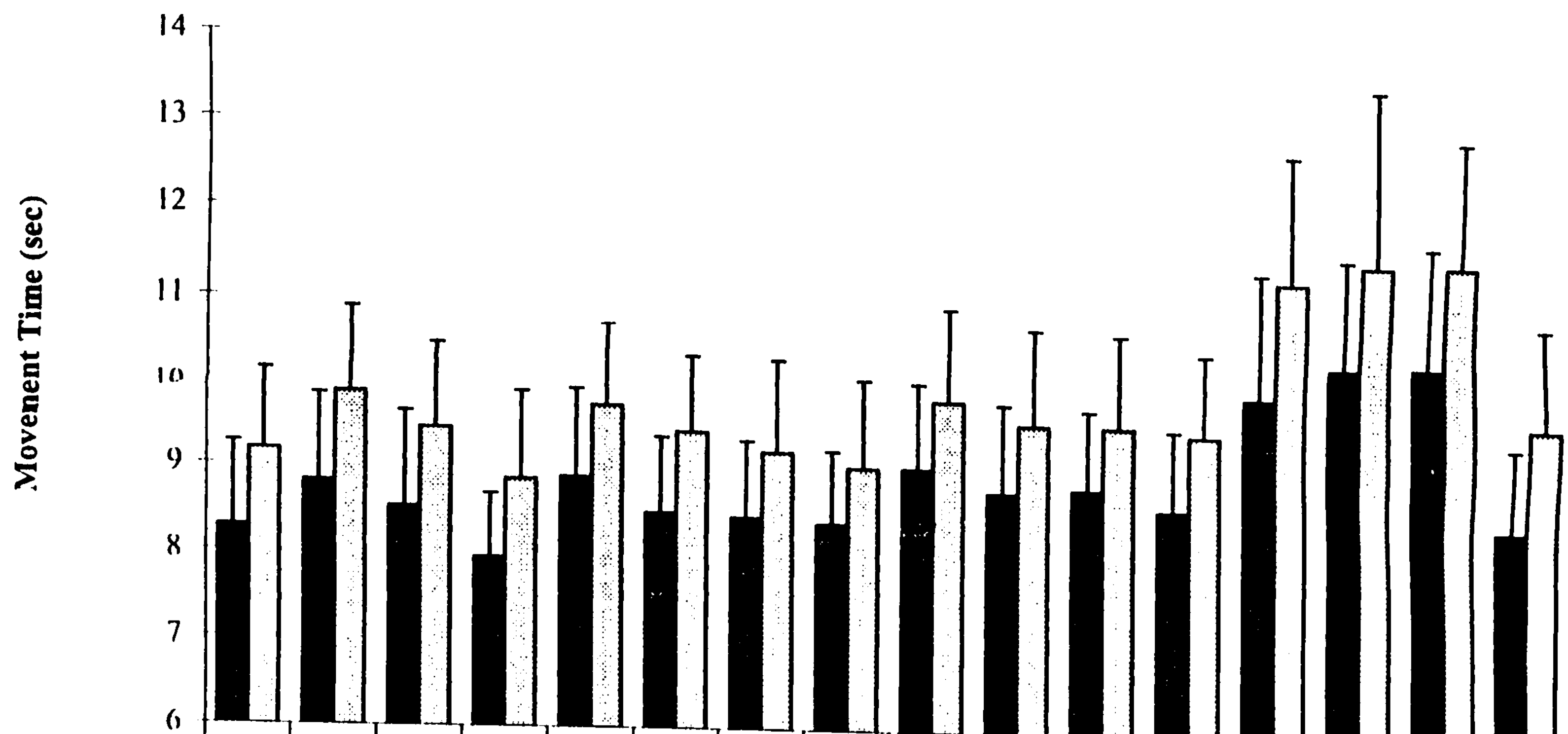
	6.1	6.2	6.3	6.5	6.6	6.7	6.8	7.0	7.1	7.3	7.8	8.0	8.9	9.5	9.7	11.0
MT	8.74	9.335	8.99	8.405	9.315	8.97	8.84	8.715	9.44	9.175	9.195	9.03	10.59	10.88	10.895	9.035

revealed a confusing pattern of significant differences, as can be seen in Figure 24 which depicts the movement times for each hand as a function of index of difficulty. Observe the random pattern of performance across the Fitts' measure of task difficulty.

The pattern of results observed in Figure 24 suggests that the measure of tolerance as an index of difficulty may be meaningless when both peg and hole size are manipulated. Therefore, a second analysis was performed which examined the effects of peg size on hand performance for each of the pegboards by partitioning tolerance into its two components, hole and peg size. Thus, a four (peg sizes) by two (hands) repeated measures analysis of variance was conducted for each hole size (pegboard). The ANOVA tables are presented in Appendix A, Table 9, 10, 11, and 12.

Pegboard 1 Significant main effects were found for hand ($F_{(1,29)}$=144.87, p=0.0001) and peg size ($F_{(3,87)}$=25.89, p=0.0001). The preferred hand (8.33 seconds) was faster overall than the non-preferred hand (9.26 seconds). Duncan's post hoc analysis revealed no significant difference in movement time between the 1.25cm (9.035 seconds) and 1.1cm (9.037 seconds) pegs. These two pegs had the longest movement times. The smallest peg (8.41 seconds) was significantly different from all other peg sizes and had the shortest movement times. A significant interaction was also found ($F_{(3,87)}$=4.42, p=0.0061). Duncan's post hoc analysis displayed a pattern of results where the performance of the non-preferred hand was significantly slower for the two largest pegs (9.63 seconds for the 1.25cm peg, and 9.47 seconds for the 1.1cm peg), as compared to the performance of either hand for all other peg sizes. The movement times for the preferred hand for the two largest pegs were 8.43 and 8.59 seconds respectively. Figure 25 demonstrates the performance differences between the hands as a function of peg size. Here, it can be seen

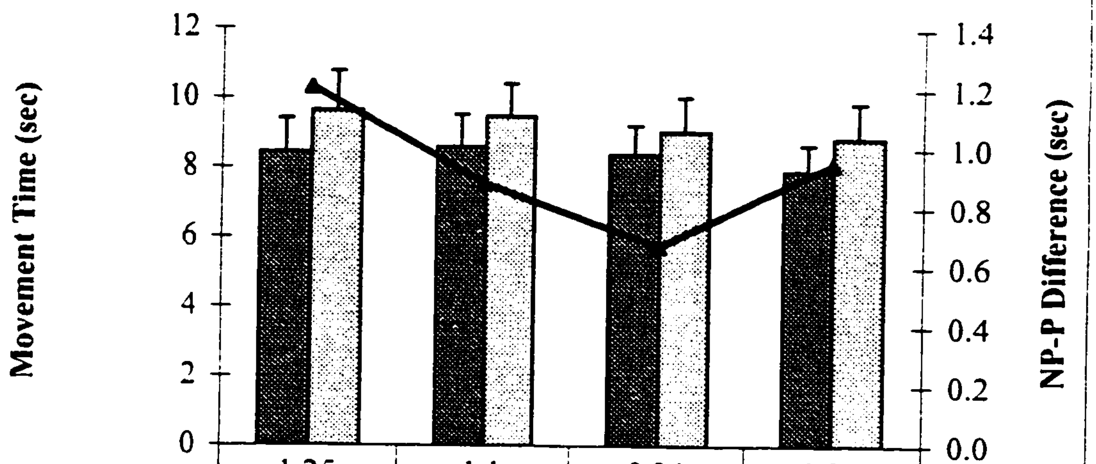
Figure 24. Movement times, including stardard deviations, for preferred and non-preferred hands as a function of index of difficulty for Experiment 6



	6.1	6.2	6.3	6.5	6.6	6.7	6.8	7.0	7.1	7.3	7.8	8.0	8.9	9.5	9.7	11.0
Preferred Hand	8.29	8.82	8.53	7.94	8.9	8.50	8.46	8.38	9.05	8.77	8.82	8.59	9.93	10.29	10.31	8.43
Non-Preferred Hand	9.19	9.85	9.45	8.87	9.73	9.44	9.22	9.05	9.83	9.58	9.57	9.47	11.25	11.47	11.48	9.64

Index of Difficulty (bits)

Figure 25. NP-P difference and movement times, including stardard deviations, for preferred and non-preferred hands as a function of peg size for 1.27 cm holes for Experiment 6.



	1.25	1.1	0.94	0.81
Preferred Hand	8.432	8.596	8.380	7.930
Non-Preferred Hand	9.636	9.478	9.052	8.879
NP-P Difference	1.204	0.882	0.672	0.949

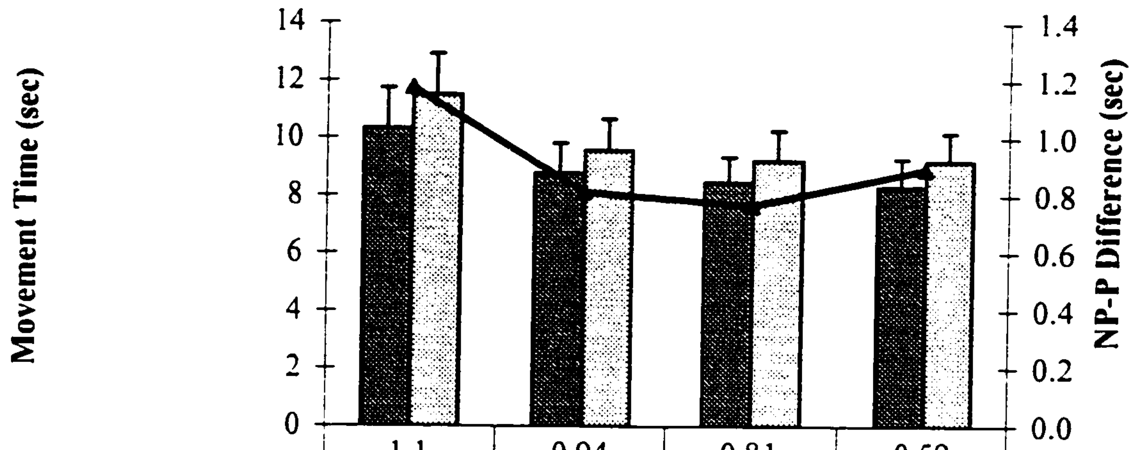
Peg Size (cm)

that the absolute difference between the hands for the largest peg size is 1.2 seconds, while the differences are smaller for the other pegs (where the performance differences are below one second).

Pegboard 2 The analysis found significant main effects for hand ($F_{(1,29)}$=99.9, p=0.0001) and peg size ($F_{(3,87)}$=124.06, p=0.0001). The preferred hand (8.96 seconds) was faster overall than the non-preferred hand (9.87 seconds). The slow movement times for the 1.1cm (10.89 seconds) and 0.94cm (9.18seconds) pegs were observed to be significantly different from each other as well as the other two pegs. The two smaller pegs (0.81cm and 0.59cm) were not significantly different from each other, and were associated with faster movement times (8.83 seconds and 8.74 seconds, respectively). A significant interaction was also found ($F_{(3,87)}$=3.5, p=0.0018). Once again, Duncan's post hoc analysis revealed a pattern of results where the largest difference between the hands (1.17 seconds) was shown for the largest peg (1.1cm). Figure 26 presents the movement times for the preferred and non-preferred hands as a function of peg size.

Pegboard 3 As expected, significant main effects were found for hand ($F_{(1,29)}$=138.92, p=0.0001) and peg size ($F_{(3,87)}$=101.01, p=0.0001). The preferred hand (9.04 seconds) was faster overall than the non-preferred hand (9.98 seconds). Duncan's post hoc analysis showed that the movement time for largest peg size (0.94cm) was significantly longer (10.88 seconds) than the movement times for all other peg sizes. A significant interaction was also found ($F_{(3,87)}$=3.89, p=0.0117), where the largest difference (1.18 seconds) between the hands was observed for the largest peg. Figure 27 presents the movement times for the preferred and non-preferred hands as a function of peg size.

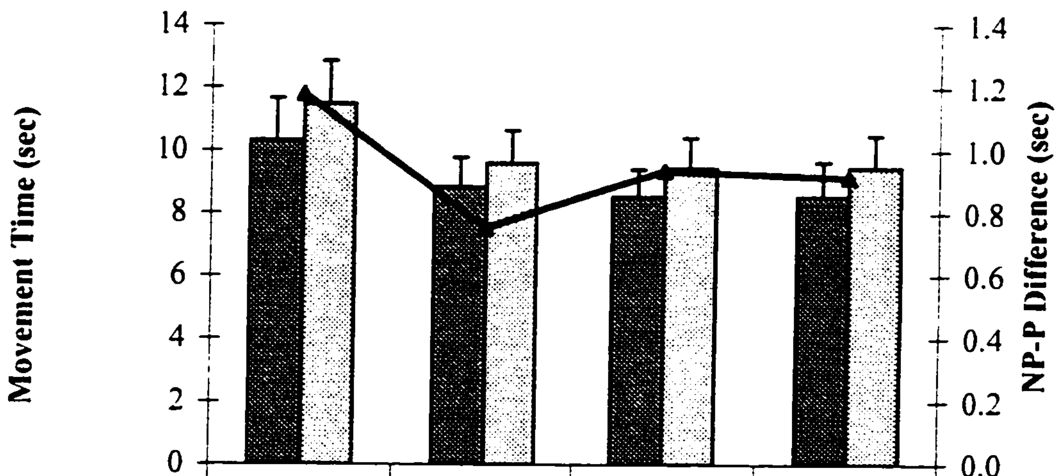
Figure 26. NP-P difference and movement times, including stardard deviations, for preferred and non-preferred hands as a function of peg size for 1.18 cm hole for Experiment 6.



	1.1	0.94	0.81	0.59
Preferred Hand	10.308	8.772	8.456	8.299
Non-Preferred Hand	11.482	9.584	9.221	9.193
NP-P Difference	1.174	0.812	0.765	0.894

Peg Size (cm)

Figure 27. NP-P difference and movement times, including stardard deviations, for preferred and non-preferred hands as a function of peg size for 1.0 cm holes for Experiment 6.



	0.94	0.81	0.59	0.45
Preferred Hand	10.293	8.821	8.510	8.539
Non-Preferred Hand	11.473	9.574	9.445	9.453
NP-P Difference	1.180	0.753	0.935	0.914

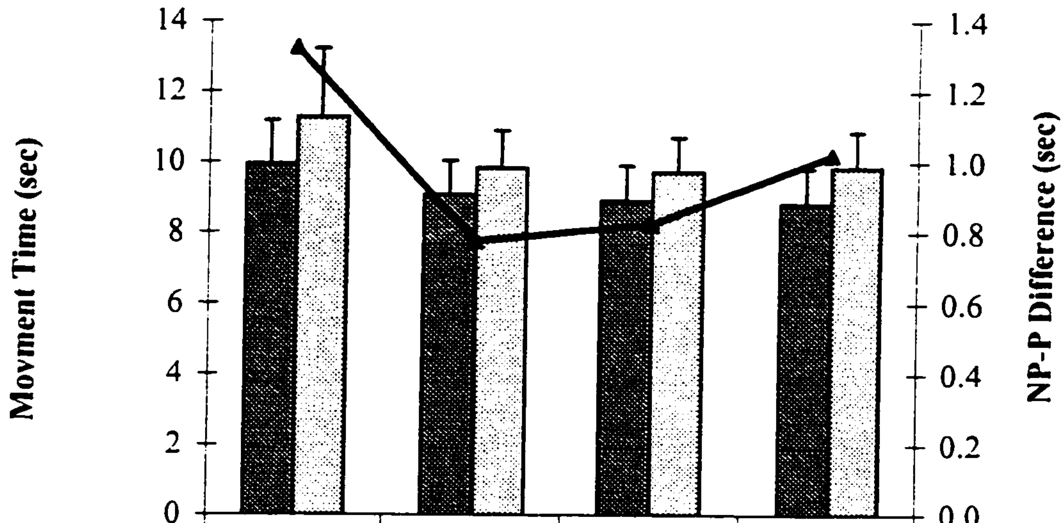
Peg Size (cm)

Pegboard 4 The analysis found significant main effects hand ($F_{(1,29)}$=86.11, p=0.0001) and peg size ($F_{(3,87)}$=63.17, p=0.0001). The preferred hand (9.18 seconds) was faster overall than the non-preferred hand (10.17 seconds). Duncan's post hoc analysis showed the movement time for largest peg size (0.81cm) was significantly longer (10.59 seconds) than the movement times for all other peg sizes. Once again, a significant interaction was also found ($F_{(3,87)}$=4.32, p=0.007), where the largest differences (1.33 seconds) between the hands were shown for the largest peg (1.33 seconds) using Duncan's post hoc analysis (see Figure 28 for the movement times as a function of hand and peg size).

Discussion

The significant interaction between index of difficulty and hand performance for movement time found in Experiment 6 appears to suggest that the performance advantage of the preferred hand increased with increasing task difficulty, as defined by Fitts' Law. As can be seen in Figure 24, however, the pattern of performance of the two hands as a function of task difficulty do not strongly conform to Fitts' Law. These findings suggest that in the context of pegboards the concept of index of difficulty, and perhaps specifically the concept of tolerance, may not be as applicable as thought earlier, especially when both peg size and hole size are manipulated in the same task. Thus, the relationship between the preferred-hand advantage and index of difficulty is a function of the components of task difficulty, each of which may influence the expression of the advantage in a different manner. For this reason, separate hand by peg size analyses were conducted for each size

Figure 28. NP-P difference and movement times, including stardard deviations, for preferred and non-preferred hands as a function of peg size for 0.9 cm holes for Experiment 6.



	0.81	0.59	0.45	0.33
Preferred Hand	9.927	9.058	8.907	8.829
Non-Preferred Hand	11.252	9.834	9.732	9.851
NP-P Difference	1.325	0.776	0.825	1.022

Peg Size (cm)

of hole. Peg size was found to affect hand performance significantly for all hole sizes, with the peg size by hand interactions being due to longer movement times for the non-preferred hand with the largest peg size, as compared to the preferred hand. The difference between the hands for the largest peg size was greater than one second (on average approximately 1.2 seconds), while the between-hand differences for the other, smaller pegs was less than one second (approximately 0.85 seconds on average). The smallest peg sizes also resulted in large performance differences between the hands (averaging a close to one second difference). Recall that peg size here is relative to hole size, because the largest peg size inserted into any one hole could not be larger than the hole itself. Therefore, the significant peg size by hand interactions found for each hole size indicate that as the peg to hole size ratio increases the preferred-hand advantage also increases. As a point of interest, the peg to hole size ratio is not a better predictor of movement time than tolerance, when the ratio is used instead of tolerance in the calculation of index of difficulty. Note also that these findings are in direct disagreement with the results of Experiment 1, which showed no interaction between hand and index of difficulty.

There are several plausible accounts for why the relative peg size affects the performance of the two hands differentially. Recall that Annett et al. (1979) reported a similar finding as shown here when only hole size was manipulated in the Annett pegboard. Annett et al. (1979) proposed, on the basis of a frame by frame film analysis, that there were no differences between the hands in terms of speed or insertion time but rather the non-preferred hand simply made more errors (approximately 50% more than the preferred hand). Such an explanation accounts for the findings in the present study of an increased preferred-hand advantage where the ratio of peg to hole size was close to one (largest peg size for each pegboard). It is also important to note that in the current study the difference between the hole size and peg size was much smaller than in the original Annett et al. study, which may have increased the chances of the non-preferred hand making "errors". By this explanation the increased performance differences between the hands are due to the "noisier" output of the non-preferred hand, presumably at the level of the motor centre in the right hemisphere, and that this "noise" is more costly when the task constraints are very high (i.e., when the peg was relatively close in size to that of the hole). However, if control noise is the only explanation for the increased preferred-hand advantage then the amount of error for the non-preferred hand should increase in a systematic manner as the peg size approaches the size of the hole. Thus, the fact that the ID by movement time R^2 value was depressed in the current study might be considered curious. As well, because it is the motor centre of the non-preferred hand that is believed to be the cause of the greater "noise", Annett's theory predicts that the performance decrement should be observed primarily for the non-preferred hand. In Experiment 6, however, the performance of the preferred hand also appears to be greatly affected in the condition where peg size was almost equivalent to the hole size. To illustrate, the movement time of the non-preferred hand increased by almost two seconds when the peg size was almost equivalent to the hole size, in comparison to increases in movement time of around 300 milliseconds for the other peg sizes. The movement time of the preferred hand increased by approximately one and half seconds when the peg size was almost equivalent to the hole size. As well, there was a trend for an increased preferred-hand advantage for the smallest pegs, which Annett's theory of control noise cannot explain. Therefore, the noise of the non-preferred hand cannot completely account for the pattern of results found here.

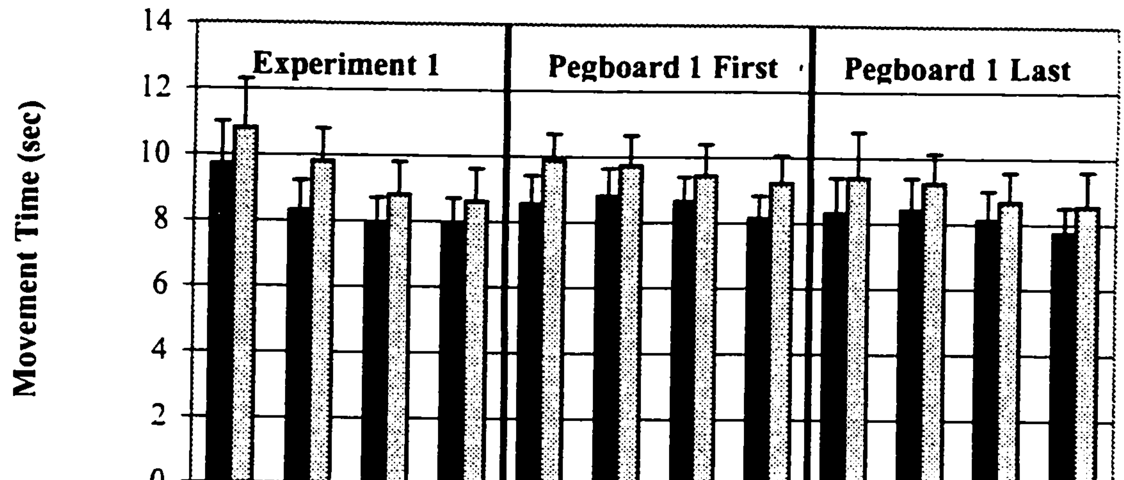
The experience of the preferred hand in manipulating objects may explain the increased between-hand difference for the extremes in relative peg size. The preferred hand has had far greater experience with objects of different sizes, since that hand is more often chosen to perform tasks where motor dexterity is required. Closer examination of the performance of the two hands across trials reveals that there is a trend for the non-preferred hand to improve at a slightly faster rate than the preferred hand (trials effects were not significant). Given sufficient practice the differences between the hands as a function of both task difficulty and peg size might vanish. Finally, one could return to the argument that conditions where there are relatively small differences in size between the peg and hole require greater visual feedback, and that the effects observed for the large peg size were the result of the right hand/left hemisphere system being better at utilizing such feedback. Ultimately, however, the visual feedback theory has relatively little support in the literature. Equally, in the current study, such a proposition does not account for the observed non-significant trend for the between-hand difference to increase slightly for smaller pegs (see Figure 28).

One question which has not yet been addressed is why the results of the current study are different from the results of Experiment 1. Note that pegboard 1 in the current experiment was virtually the same as the pegboard examined in Experiment 1. For the current study the pegboards were blocked in two different presentations orders: one where pegboard 1 was presented first, and one where pegboard 1 was presented last. In order to estimate the effect of practice on hand performance, peg size by hand analyses were conducted for pegboard one in each of the two order positions. It was found that when pegboard 1 was presented first there was no interaction between peg size and hand

($F_{(3,42)}$=2.12, p=0.1122), but when pegboard 1 was presented last the interaction between peg size and hand approached significance ($F_{(3,42)}$=2.31, p=0.08). Thus, the performance difference between the hands remains constant across different peg sizes when it is the participants' first experience with the pegboard. After some experience with the task, however, the performance difference between the hands begins to diverge when the peg size is closer to the size of the hole. These results hint at an account for the discrepant findings between Experiment 1 and 6, and suggest that practice has a role in the extent of the preferred-hand advantage. Figure 29 compares the results from Experiment 1 and the two orders of pegboard 1 as a function of peg size. Further work is required to examine the effect of order on manual asymmetries.

There were also a number of methodological and procedural differences between the current study and experiment 1, which may provide further insight into the discrepant results between the studies. A greater number of trials was examined in Experiment 6 than either in Experiment 1 or 2, or the study conducted by Van Horn and McManus. This suggests that the lack of significant interactions with hand performance in these latter studies might have been due to a high level of within-subject variability because of the few trials collected. Another major difference between Experiments 1 and 6 is the amount of practice that participants have with each peg size in Experiment 6. The largest and smallest pegs in absolute size were used in 6.25% of trials for one hand, while the 0.81cm peg was used in 25% of trials for one hand. As well, in Experiment 1 movement time was measured as the number of pegs that could be moving in ten seconds, while in Experiment 6 the movement time was the time taken to move ten pegs. Thus, in a single trial, participants may have moved more pegs in Experiment 1.

Figure 29. Comparison of similar pegboards in Experiments 1 and 6, showing effects of order for movement time (including stardard deviations).



	1.25	1.1	0.97	0.63	1.25	1.1	0.94	0.81	1.25	1.1	0.94	0.81
■ Preferred Hand	9.7	8.3	7.9	7.9	8.5	8.8	8.6	8.1	8.3	8.4	8.1	7.7
□ Non-Preferred Hand	10.8	9.8	8.8	8.6	9.9	9.7	9.4	9.2	9.4	9.2	8.7	8.5

Peg Size (cm)

Perhaps more important, however, is the range of peg sizes and holes that was examined in the current study. Experiments that have observed an interaction between difficulty and hand performance for peg-moving tasks have required participants to move the same peg to holes of different sizes (Annett et al., 1979), while those which have not observed an interaction between these two factors have required participants to move the different pegs to holes of the same size (van Horn & McManus, 1994; Experiment 1). Worth noting is that these experiments assumed that all of the manipulations would affect task difficulty in the same manner. The present study made no such assumptions, and instead both peg size and hole size were manipulated with seven different peg sizes and four different hole sizes. Moreover, every participants performed all combinations of the task, in one experimental testing setting. In other words, participants were aware of the variety and extent of the task. Instructions given prior to testing elaborated on the different combinations of peg and hole size. It is possible, therefore, that only with a large variety of pegs and holes is there an increase in the performance advantage of the preferred hand. This would suggest that the context of the task is important in the degree of lateralization of control. This notion will be considered in further detail in the general discussion.

In summary, Experiment 6 revealed that the concept of index of difficulty was not closely related to movement time when both hole and peg size were manipulated within a peg-moving task. It was found when each pegboard was examined separately, that the size of the peg relative to the size of the hole affected the performance of the two hands differently. In particular, greater differences between the hands were found when the peg size was very close in size to the hole. It was suggested that the effects observed in Experiment 6 may be in part due to the context in which the experiment was performed.

and in part due to practice, creating a situation that necessitates or increases the dependence on left hemisphere control.

GENERAL DISCUSSION

Previous research conducted by van Horn and McManus (1994) demonstrated that the magnitude of the performance difference between the hands for movement time does not increase when the demands of the task are increased. More explicitly, it was found that the preferred hand showed no greater advantage for more challenging tasks than for simple tasks. As discussed earlier, the results of van Horn and McManus (1994) are contradictory to previous experiments (Annett et al., 1979; Todor & Cisneros, 1985) which show that the advantage of the right hand increases as the difficulty of a task increases. The purpose of the present investigation was to examine the performance difference between the hands more rigorously, by studying the motor performance of the two hands on a number of tasks across a wider range of task difficulty than had previously been investigated. The goal of this work is to reach an understanding of how the two hands perform relative to each other across task difficulty and to elaborate on why the two hands differ in performance capabilities.

1. Summary of the Experiments

The purpose of Experiment 1 was to replicate the experiment conducted by van Horn and McManus (1994). Here, the finding of a constant difference between the hands across increasing difficulty was confirmed using the Annett pegboard. Considering the simplicity of the Annett pegboard and that only the size of the peg was manipulated in this experiment, a second experiment was conducted. A version of the Fitts' reciprocal tapping task was used that manipulated not only the object size and target size, but also the movement amplitude. No significant interactions with hand performance were found for either the large or small stamp sizes, for movement time. The results of Experiment 2 indicated that there was a constant between-hand difference in performance across task difficulty, showing further support for the findings of van Horn and McManus (1994).

The purpose of the third experiment was to investigate the performance of the two hands on a task requiring a high degree of manual dexterity: the Grooved pegboard. In addition, a wider range of task difficulty could be examined within a single task by using this pegboard. Participants were asked to position the pegs in their respective holes (Place phase), and also to remove the pegs and place them in a large receptacle (Remove phase). The results from the Grooved Pegboard revealed a large right-hand advantage for the more difficult task (Place phase), which required the greatest amount of manual dexterity. In contrast, there was only a negligible difference between the hands for the easy task (Remove phase). However, the Place and Remove phases were not only different with respect to the index of difficulty but also the Place phase required participants to orient the peg into its hole, by twisting the wrist. The Remove phase placed no such demands upon the individual. Thus, the differences seen in the Place phase between the two hands might have been caused by the need to orient the peg.

Considering these findings, a fourth experiment was conducted to further investigate the role of orientation on hand performance. Performance of the two hands was compared on the Annett pegboard and a new pegboard, which required participants to orient or twist pegs into their respective holes. Analysis revealed that there was a greater difference between the hands for the orientation pegboard than for the Annett pegboard. The results were interpreted as evidence that the significant hand by ID interaction observed in Experiment 3 was at least partially a result of the orientation factor rather than the index of difficulty factor. The fact that orientation appears to influence hand performance will be discussed in more detail in a later section.

It had now been determined that the orientation of a peg during positioning causes the preferred-hand advantage to increase significantly. But, Experiment 3 also examined the performance of the hands across a very wide range of indices of difficulty. Hence, it had yet to be determined whether a wide-range of indices of difficulty also influenced the magnitude of the difference between the hands. Consequently, Experiment 5 compared Place and Remove phases in the Annett pegboard, where there was no orientation component in the task. Overall, it was found that the between-hand difference was larger (approximately 800 milliseconds) for the Place phase than for the Remove phase (approximately 300 milliseconds). Therefore, the results of Experiment 5 provide evidence that the between-hand difference increases as a function of index of difficulty.

Experiment 6 was conducted to investigate a wide-range of IDs on the performance of the two hands, in a task where the movements did not change (standard Annett pegboard). Both peg size and hole size were manipulated. A significant hand by index of difficulty interaction was observed, but the pattern of results did not show a systematic increase in hand differences for increasing indices of difficulty. Thus, index of difficulty may not be an appropriate measure of difficulty, especially for peg-moving tasks. Therefore, four separate peg size by hand analyses were performed for each hole size. All analyses revealed significant peg size by hand interactions, where larger between-hand differences were found when the peg was almost the same size as the hole. A non-significant trend for increased between-hand differences was also observed for the smallest relative peg sizes. The findings of Experiment 6 suggest that task difficulty does influence the magnitude of the performance difference between the hands.

Consequently, the results of Experiment 6 contradict the findings of Experiment 1. Recall that virtually the same pegboard was used in both experiments. Subsequent analysis of Experiment 6 showed that when the order of presentation was taken into account for the pegboard in question, the discrepancies could be understood. It was found that when pegboard 1 was presented first there was no interaction between peg size and hand ($F_{(3,42)}$=2.12, p=0.1122), but when pegboard 1 was presented last the interaction between peg size and hand approached significance ($F_{(3,42)}$=2.31, p=0.08). These results help to account for the discrepant findings between Experiment 1 and 6, and suggest that practice may have some role in the extent of the preferred-hand advantage.

It was also reasoned in Experiment 6 that the effects of context may also play a role in the extent of the preferred hand advantage. Experiment 6 was the only study where participants were exposed to many different pegs and different hole sizes in one experimental testing situation. As noted, none of the previous work, including Experiment 1 and 2, was conducted in this manner. Experiments that have observed an interaction between difficulty and hand performance for peg-moving tasks have required participants to move the same peg to holes of different sizes (Annett et al., 1979), while those which have not observed an interaction between these two factors have required participants to move different pegs to holes of the same size (van Horn & McManus, 1994; Experiment

1). Thus, the experimental method in which the Annett et al., van Horn and McManus, and the present experiments described here were conducted was different and may account for the different results. More specifically, the number of peg/hole combinations examined in Experiment 6 was greater than in previous research, and so the context in which the experiment was conducted was richer. Also of interest is the fact that the performance difference between the hands is constant for one's first experience with a task, but the preferred-hand advantage increases after experience, as shown earlier in the re-analysis of Experiment 6. These findings could also be interpreted as supporting the notion that the richness of the experimental context may be a factor of importance in manual asymmetries.

Thus, the findings of van Horn and McManus (1994) of a constant between-hand difference across task difficulty have been confirmed by the current studies, but only when the context of the experiment is limited to one dimension of task difficulty, and specifically when the dimension is peg size. In contrast, when other dimensions of difficulty are added an increased preferred-hand advantage is noted, as observed in Experiment 3, 5, and 6. The notion that context plays an important role suggests why both Annett et al. (1979) and Todor and Cisneros (1985) found increasing performance differences between the hands in their studies. These findings raise some interesting questions concerning hand preference, hemispheric control of movement, and the origin of the preferred-hand advantage. These questions and others will be addressed in the next sections.

2. How does the difficulty of a task influence the right-hand advantage?

In all probability, the differences in performance of the two hands reflect the organization of the underlying control structures. First, recall that the motor execution centres or motor cortices of each hemisphere control the contralateral hand. Now, suppose that there is also a lateralized control centre in the left hemisphere, thought to be specialized for the selection and organization of complex or sequential movements over time, which controls both limbs (Kimura, 1992). In order for the right hand to perform a complex movement then, the commands from the lateralized centre are sent to the motor execution centre in the same hemisphere. In contrast, for the left hand to perform the same complex movement, the programming commands must cross the corpus callosum to the right-hemisphere motor centres, at which point the movement can be executed. Given such an organization it is plausible to suggest that for very simple tasks where there are very few end-point constraints, the motor execution centres in each hemisphere control the movement without aid from the lateralized control centre. The small differences noted between the hands for very simple tasks may be attributable to inherent noise in the motor control centre for the non-preferred hand. A schematic diagram of the hypothesized control structure for simple movements is shown in Figure 30.

Once the demands of task reach a particular criterion, however, the motor execution centres are no longer capable of controlling the movement. This "difficulty threshold" may reflect the need to integrate greater amounts of feedback information and/or precisely control motor output in order for the hand to acquire its target successfully. At this point, the execution centres need the assistance of the lateralized motor sequencer. A schematic diagram of the hypothesized control structure for complex movements is shown in Figure 31. Larger differences between the hands would begin to emerge at this point simply because it will take longer for neural signals to arrive at the

Figure 30. Hypothesized control structures for the execution of simple tasks by the preferred and non-preferred hands. The motor control centres of each hemisphere are represented as light grey circles, and the lateralized motor centre is represented as a dark grey oval. Pathways of control are drawn in as arrows.

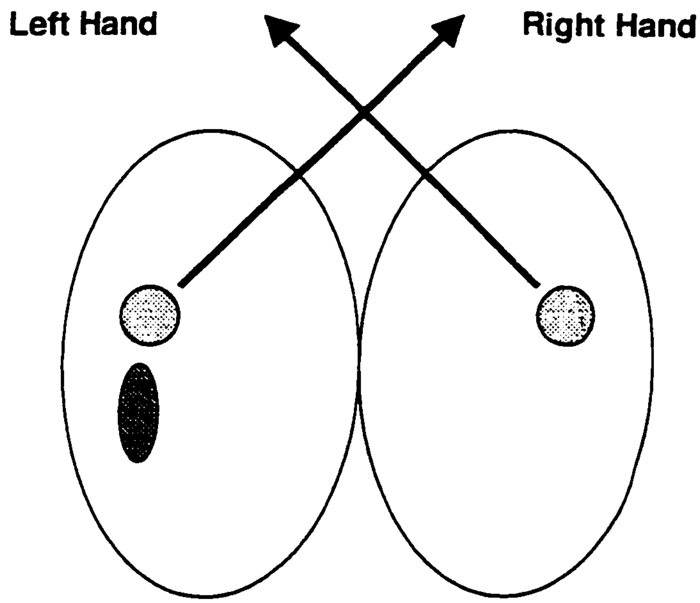
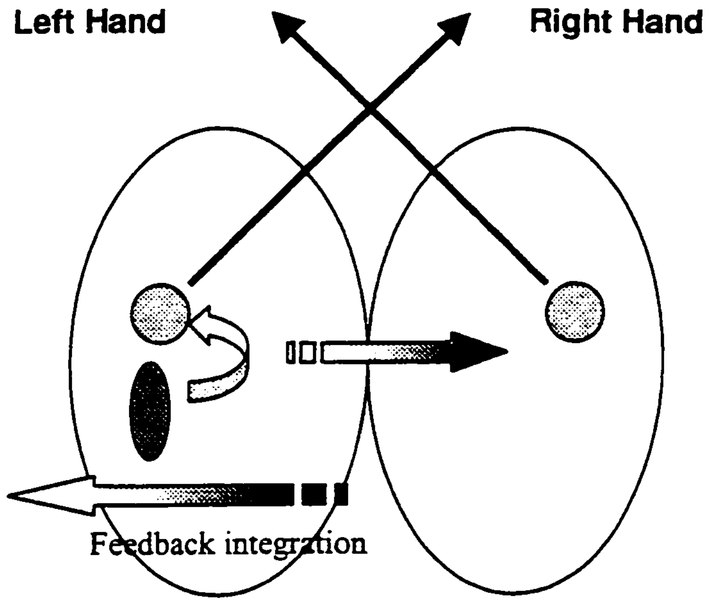


Figure 31. Hypothesized control structures for the execution of complex tasks by the preferred and non-preferred hands. The motor control centres of each hemisphere are represented as light grey circles, and the lateralized motor centre is represented as a dark grey oval. Pathways of control are drawn in as arrows.

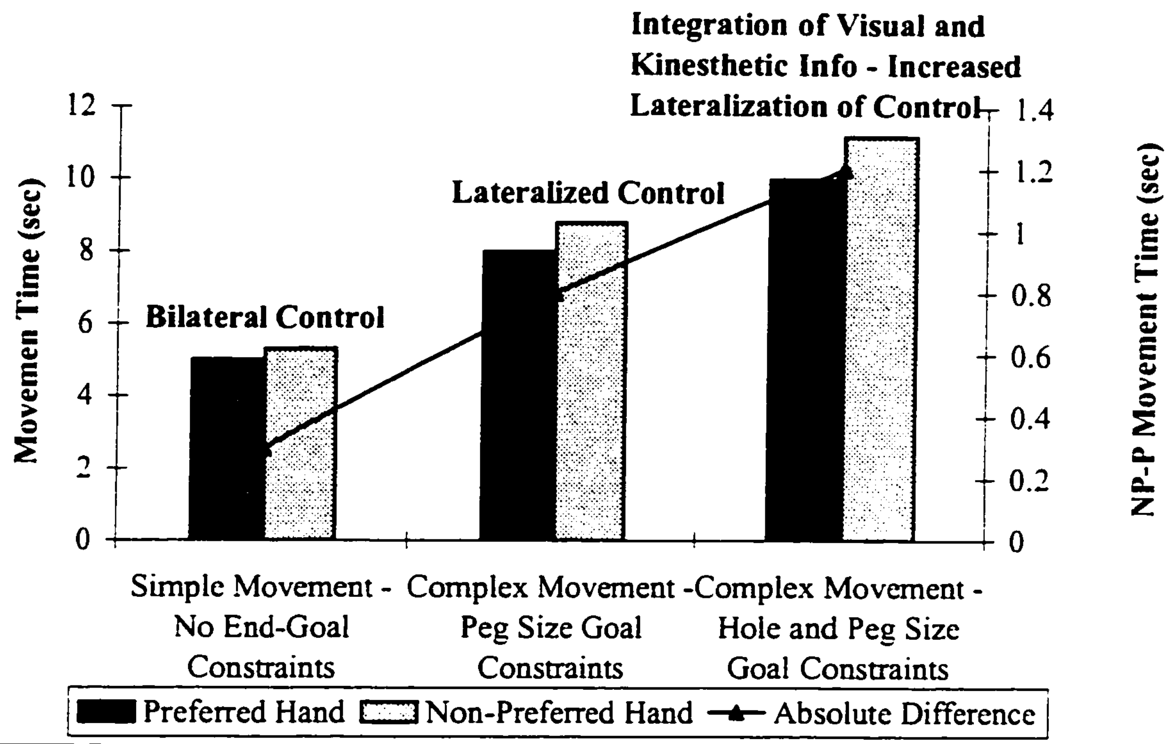


right hemisphere motor centres from the left hemisphere, than for those same signals to travel within one hemisphere.

Now recall that a greater increase in the advantage of the preferred hand was observed when hole size was also manipulated along with peg size, in comparison to when just peg size was manipulated. As well, recall that experiments that have found an increasing between-hand difference as a function of task difficulty have manipulated the size of the holes on the Annett pegboard. Let us propose that the perception or visual calibration of hole size and end-point orientation requires the utilization of visual on-line control which needs to be routed through the lateralized control centre of the left hemisphere, essentially adding processing time to the entire movement for both hands. The increase in movement time between the hands may occur because incorporating the visual information to the motor program, and perhaps integrating that information with kinesthetic feedback, may be lateralized to a greater extent. In other words, as more feedback information needs to be integrated, increasingly lateralized control structures are utilized.

In contrast, the control structure utilized when only the size of the pegs is manipulated may not be as lateralized, perhaps because the control of discriminations of peg size are based mainly on kinesthetic information rather than visual information. Summarizing, it is suggested that control becomes increasingly lateralized as more information is required to perform the movement, with the synthesis of visual and kinesthetic information perhaps being the most lateralized. Figure 32 presents a summary of the performance differences between the hands across task demands, as indicated by the current research. Here, small between-hand differences are shown when there is bilateral

Figure 32. Hypothesized performance differences between the two hands.



control of the two hands from each motor cortex. Larger differences are portrayed as control switches to the left hemisphere. Finally, the largest differences are noted when visual and kinesthetic information must be integrated by the left hemisphere.

Much of the previous discussion is speculative, however, and direct evidence is needed before a conclusion reached. Future research should focus on isolating the task demands that result in a right-hand advantage, and determine the relative contributions of visual and kinesthetic feedback. As well, examining the control and execution of bimanual movements, or those that require the coordination of both preferred and non-preferred hands, should help to determine the qualities of the left hemisphere that lead to the right-hand advantage.

3. What is revealed about the origins of the right-hand advantage?

The fact that the performance advantage of the right-hand does not increase with a unidimensional change in index of difficulty, as defined simply by Fitts' Law, suggests that current explanations of the origins of the right-hand advantage cannot wholly account for the differences between the hands. For example, one of the foremost theories suggests that the right-hand/left-hemisphere system is superior at processing visual feedback (Flowers, 1975; Woodworth, 1899). This theory postulates that as index of difficulty increases the performance difference between the hands should increases incrementally, as the need to use visual feedback also increases with increasing index of difficulty. The work described here suggests that the need to integrate visual and/or kinesthetic information into the movement may involve the use of strongly lateralized control structures. Thus, Flowers and others are partially correct. The problem lies however, with the usage of index of difficulty as the single metric for task demands. The current work has shown that index of difficulty, as defined by Fitts' Law does not always predict movement time, thus does not aptly describe task difficulty when both peg and hole size change. This breakdown could occur because the relative contributions of visual and kinesthetic feedback are not known for any one peg-hole combination. In fact, two similar indices of difficulty may involve different types of feedback or on-line control. The fact that index of difficulty is not an appropriate independent measure can be best seen when both peg size and hole size were manipulated, for example in Experiments 5 and 6 where the relationship between movement time and index of difficulty was not especially close. It was found, in fact, that the highest index of difficulty did not necessarily produce the largest difference in performance between the hands or even the longest movement times. Equally, the easiest indices of difficulty did not consistently produce the smallest performance difference between the hands, or the shortest movement times. In summary, the notion that visual feedback may increase the preferred-hand advantage appears to be partially correct. However, index of difficulty may not be an appropriate way of examining the performance of the hands when the experimenter wishes to manipulate more than one dimension of the task demands, because doing so may confound the type of information used by the lateralized control structure.

It has also been hypothesized that the performance differences between the hands can be attributed to the fact that the output specification is more variable for the non-preferred hand (Carson et al., 1993). Here, the differences between the hands are attributed to greater programming noise associated with the non-preferred hand that results in significantly more corrections late in the movement (Annett et al., 1979). The findings of the current work show some support for the output specification theory. Recall that this theory would predict larger differences between the hands as the end-point-positioning portion of the task became highly constrained. While increases in the preferred-hand advantage were observed under such conditions, the output specification theory cannot account for the trend of increasing between-hand differences for the small pegs observed, particularly in Experiments 6. Equally, the theory cannot account for the significant interaction between hand performance and peg size in Experiment 6 as well as the lack of such interaction in the first experiment. Nevertheless, the current work has shown that there is a measurable and significant difference between the hands even for very simple tasks. As suggested earlier, these observable between-hand differences may be a result of greater noise in the execution from the motor centre of the non-preferred hand. With practice it is possible that the noise or variable output of the non-preferred hand can be decreased. Neither practice nor movement output theories alone, however, can entirely explain the results.

In summary, it is proposed that there is always greater noise associated with the motor centre of the non-preferred hand. But, the differences in performance between the hands cannot be solely attributed to this inherent noise. Rather, the increase in between-hand differences arises from the switch in control to the lateralized motor sequencer in the left hemisphere, perhaps based on the need to carefully sequence movements temporally. Control becomes increasingly lateralized as the need to integrate visual and kinesthetic information increases.

4. How does end-point orientation affect the right-hand advantage?

It has already been discussed that experiments where only peg size has been manipulated show a constant between-hand difference, while those that have manipulated hole size, or hole size and peg size show an increase in the preferred-hand advantage. As argued earlier, it is thought that manipulations of hole size may cause control to be increasingly lateralized due to the need to integrate visual and kinesthetic information. However, it has also been shown that manipulations to the orientation of the end-point also produce an increased preferred-hand advantage. Effects of object orientation on hand performance were first observed in Experiment 3 and 4, where greater right-hand advantages were observed for tasks requiring an orientation component, as compared to tasks with no orientation component. Experiment 3 showed a greater preferred-hand advantage for the Place phase, which had a high index of difficulty and required participants to orient the pegs, than the Remove phase, which had a low index of difficulty and had no orientation component to the task. Since orientation was confounded in this experiment with the index of difficulty a new pegboard was designed in order to examine only the effects of orientation on hand performance, in Experiment 4. Performance on the new "orientation" pegboard was compared to performance on the standard Annett pegboard. Here, the preferred-hand advantage was larger under conditions requiring orientation because of the poor performance of the non-preferred hand. These results suggest that the right-hand/left-hemisphere system has a greater advantage for tasks that require objects to be oriented in a specific position. This is presumably because end-point orientation not only requires the musculature to be carefully controlled, but may also require the integration of both visual and kinesthetic information. In this case, greater lateralization of control would result in a greater right-hand advantage. It appears then, based on the findings observed in Experiment 3 and 4, that orientation affects the degree and extent of the right-hand advantage. Why orientation affects the right-hand advantage is currently unknown, and research should be directed at examining whether this effect is due to the role of distal musculature in controlling the hand, the additional movements that are required to orient the peg or the greater task demands.

It is plausible that the need to control the orientation may be a factor underlying manual skill and is a determinant of hand preference. One could liken the skills or submovements required for the orientation pegboard to the skills necessary for hand writing, which is perhaps our most strongly lateralized behaviour. Precise timings of the muscular forces as well as the organization and sequencing of the different hand "postures" are needed to orient the peg into its proper position in the pegboard. Similar submovements comprise the task of writing. Therefore, the tasks of handwriting and the orientation pegboard may be related or similar in the underlying skills required. If the same skills do underlie both tasks, the orientation pegboard may prove to be an excellent tool for examining hand performance and preference. Interestingly, questions referring to orientation are not often included in hand preference questionnaires. Preliminary examination of hand preference questionnaires has shown that 96% individuals who write with their right hand also prefer to use their right hand to turn a key in a lock, while only 77% of right-handed individuals prefer to open a door with their right hand, suggesting that orientation may indeed be related to hand preference. Further study of the role of orientation in hand preference should be done.

In summary, the orientation of the end-point appears to increase the advantage of the preferred hand. It has been argued that this is primarily because such movements are controlled by the left hemisphere. The need to integrate both visual and kinesthetic information in order to orient the peg correctly, however, may also increase the preferred-hand advantage for such tasks.

5. *Manual skill, hand preference, and the right-hand advantage*

Work by Steenhuis and M.P. Bryden (1989) and Steenhuis (1996) has suggested that skill may be the underlying determinant of hand preference. They propose that the more skill required for a task, the more likely the individual is to choose their preferred hand to perform the task. In a factor analysis of a hand-preference inventory they found that individuals tended to report using their preferred hand more often for tasks requiring what they termed as a high degree of manual skill. They suggested that a fundamental characteristic underlying tasks requiring a high level of manual skill is that such tasks are composed of a relatively complex sequence of motor behaviours. Since the left-hemisphere is thought to be the seat of the motor control system responsible for selecting and executing motor sequencing in speech and praxis control, they argue that a strongly lateralized preference for such tasks makes inherent sense. For unskilled tasks, or those not requiring complex sequencing, the authors found a decrease in participants choosing their preferred hand to perform the tasks. The findings of the experiments summarized here provide more evidence for these arguments. More specifically, the suggestion that very simple movements are controlled by the contralateral motor cortex may provide an explanation for the decrease in preference of the preferred hand for such tasks. Equally, the switch to left-hemisphere control at a "difficulty-dependent" threshold corroborates the finding that for difficult tasks the preferred hand is more often chosen.

Closer examination of the questionnaire tasks that had high factor loadings for skilled activities (writing, throwing ball, sewing, hammering, erasing, and brushing teeth), indicated that not only did the tasks require complex motor sequencing, but they also required on-line visual control, precise timing, precise orientation of the hand, precise end-point positioning and were highly learned tasks. Equally, those tasks that were characterized as less skilled tended to involve less complex sequencing of movements, did not necessarily require vision, and were tasks that did not require practice. Rather than simply skill (defined by Magill (1993) as a task that has a goal, and requires voluntary action to achieve a goal) underlying the basic preference and performance differences between the hands, one might argue that the preferred hand will be chosen and out-perform the non-preferred hand on any task that requires one or all of the following: anticipatory timing, precise orientation of the hand, complex movement sequencing, on-line visual control, and is highly learned. By the same argument, the preferred hand would not be chosen as frequently, nor would it necessarily perform better at a task that does not encompass these requirements.

6. What is the role of practice or experience?

Recently, the role of experience, learning and practice has resurfaced in attempts to understand the origin of the right-hand advantage. It has been suggested (Provins, 1997; Peters, 1995) that the sole reason the right hand surpasses the left hand in performance is that people have had years of experience using their preferred hand under innumerable circumstances. The work discussed here presents strong evidence that practice and experience cannot account solely for the differences between the hands, as it has been shown that dimensions of task complexity can affect the hands differentially. However, the concepts of practice and experience are important to and affect the extent of manual asymmetries. At one level, experience or practice probably plays a role in augmenting the abilities of the motor execution centre for that particular hand. For instance, the more experience a person has had with a particular task, the better the motor execution centres would be at executing the movement pattern. A greater right-hand advantage would be observed when the right hand had more experience with the task than the left hand. Likewise, if both hands had equal experience with a task there might be less of a difference between the hands in the performance of that task.

The manipulation of small objects is a task where the right hand has had much more experience (pen, needle, buttons). Thus, for such tasks, the right hand execution centre (in the left hemisphere) should be more adept at manipulating small objects, and thereby increasing the difference between the two hands, as, in fact, observed in the current experiments. Recall that in both Experiment 5 and 6 there was an increased preferred-hand advantage for movements made with the smallest relative peg sizes. This effect may be in part due to the preferred hand having more experience with small objects.

Secondly, practice and experience may play a role in how strongly control may be lateralized in the left hemisphere. Recall that it was shown in Experiment 6 that the performance of the two hands relative to each other on one pegboard changed as a function of whether that pegboard was first or last to be performed. These findings could be interpreted as practice effects, where greater practice results in greater lateralization of control. However, these findings could also be interpreted as support for the notion that context plays an important role in lateralization. In other words, the more dimensions required to command the more lateralized control becomes. From the current work, it is not possible to disentangle the effects of practice and context. Nonetheless, it is probable that practice and context interact to influence the performance of the two hands differentially. The extent to which the two interact may be task specific, and dependent upon the number of context dimensions required to control.

In general, it is argued here that practice affects both the motor execution centres and the lateralized motor sequencer. Practice at the level of the motor execution centres probably reduces the amount of motor output noise, while practice at the higher level, may result in increased lateralization of control and thus an increase in the advantage of the preferred hand.

7. Measuring Hand Preference and Hand Performance

As mentioned earlier, there is usually a strong relationship between hand preference and hand performance measures (Peters, 1998). Because both measures of preference and performance were examined in the current work, there is an opportunity to examine the relationship between these two measures. First, the direction of hand preference was related to the direction of hand performance when people were rated as either right or left handed according to their self-reported preference. In other words, people who reported being right handed showed better performance with their right hand. The relationship between the degree of hand preference and the magnitude of performance, however, can not be examined effectively in the current work because the participants were primarily right handers. For interest sake, though, the degree of preference did not correlate with the degree of hand performance in the current work. In other words, strongly right-handed people did not show larger between-hand differences than people who were only weakly right-handed. However, before any conclusions can be reached it is important to examine a much larger group of left-handed participants.

Equally important to consider is whether the peg-moving task examined in the current work was an appropriate task with which to examine manual performance asymmetries. A strong argument for the continued use of the peg-moving task is that the accuracy of the movement is constrained by the task. More simply, movement time only includes accurate trials. As well, Annett (1985) argues that the peg-moving task is a novel task, which is not comprised of highly practiced elements. By the same argument, neither males nor females should have an advantage on the task over the other sex. There are problems, however, of using the peg-moving task to examine hand performance. The largest drawback of the task is that it is difficult to measure the individual components (pick-up, transport, and insertion) of the movement separately. As well, very little is known about the effects various manipulations, such as hole size, peg size and movement amplitude, have on overall performance on such a task. Both of these problems warrant further research. Despite the problems the peg-moving task produces reliable, measurable, and significant movement time differences between the hands and should be considered a useful tool in examining manual asymmetries. Still, the development of a new unimanual task to examine performance differences between the hands would be welcomed.

8. Fitts' Law and Index of Difficulty

The index of difficulty equation (Fitts. 1954) was used in the present research to quantify task difficulty in a more explicit manner than was done by van Horn and McManus (1994). Quantifying task difficulty in this manner should be a better method of manipulating task difficulty than simply comparing simple and complex tasks (Flowers. 1975) and thus should improve the chances of detecting a relationship between task difficulty and hand performance. This method of investigating manual asymmetries has thus also allowed an examination of Fitts' Law to be undertaken across a wide-range of indices of difficulty. for many different tasks. It was found. however. that when multiple elements of a task were manipulated to change difficulty (as in Experiment 5 and 6) only a weak relationship was found between movement time to index of difficulty. These findings show that index of difficulty. as defined by Fitts' Law does not predict movement time. thus does not aptly describe task difficulty when both peg and hole size change. This breakdown could occur because the relative contributions of visual and kinesthetic feedback are not known for any one peg-hole combination. As well. the absolute change in task difficulty that is needed to produce a significant change in movement time is currently unknown. Because of these factors. modifications to how tolerance in defined in Fitts' Law may be necessary when examining peg-moving tasks where multiple dimensions are examined. Further research should examine each aspect that contributes to the difficulty in isolation and then secondly investigate how those different aspects interact. As well. extreme levels of task difficulty should be examined to better understand how movement time is related to index of difficulty under these conditions. Such research may ultimately lead to further modifications of Fitts' Law.

8. Summary

Summarizing, it was suggested that control becomes increasingly lateralized as more information is required to perform the movement, with the synthesis of visual and kinesthetic information perhaps being the most lateralized. For very simple tasks, where relatively little feedback information or complex movement sequences was required, the between-hand difference was observed to be approximately 300 milliseconds. When the movement was complex, control reverted to the lateralized motor sequencer in the left hemisphere. However, as the need to integrate both visual and kinesthetic information increased, lateralization of control also increased. In all probability, the differences in performance of the two hands reflect the organization of the underlying control structures. It was argued that the motor execution centres controlled the contralateral hand under situations where the task was very simple. The small, but significant differences between the hands for very simple tasks was attributed to processing differences in the motor execution centres in both hemispheres. Once a certain threshold of complexity (perhaps the need to temporally sequence distal musculature, where end-point precision is required) is reached, however, the motor execution centres are no longer capable of controlling the movement. At this point, the execution centres need the assistance of the lateralized, left-hemisphere motor centre, presumably to orchestrate the movement. Larger differences between the hands would thus begin to emerge simply because of different control routes for the two hands. More specifically, the amount of time needed for signals to cross from the lateralized motor sequencing centres of the left-hemisphere to the motor execution centres of the right hemisphere to control the left hand, takes longer than the amount of time necessary to control the right hand from within the left hemisphere. The need to synthesize and integrate different types of feedback information utilizes strongly lateralized control structures in the left hemisphere. and effectively increases the preferred-hand advantage.

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APPENDIX A

Table 1. Experiment 1

Factor	df	MS	F	P
Hand (H)	1	3.17	35.83	0.0001
ID	3	2.37	27.93	0.0001
H X ID	3	0.08	1.04	0.3763

Table 2. Experiment 2: Large Stamp

Factor	df	MS	F	P
Hand (H)	1	0.11	158.79	0.0001
Tolerance (T)	2	0.01	13.24	0.0001
Amplitude (A)	2	0.084	10.77	0.0001
H X T	2	0.000	0.6	0.55
A X T	4	0.001	1.49	0.21
H X A	2	0.000	0.01	0.99
A X T X H	4	0.001	2.4	0.055

Table 3. Experiment 2: Small Stamp

Factor	Df	MS	F	P
Hand (H)	1	0.228	87.64	0.0001
Tolerance (T)	2	0.131	54.11	0.0001
Amplitude (A)	2	0.266	16.58	0.0001
H X T	2	0.004	2.61	0.0803
A X T	4	0.002	0.83	0.51
H X A	2	0.004	2.47	0.094
A X T X H	4	0.000	0.52	0.72

Table 4. Experiment 3

Factor	Df	MS	F	p
Hand (H)	1	65660	3643.34	0.0001
Phase (P)	1	765.95	61.25	0.0001
H X P	1	455.92	62.92	0.0001

Table 5. Experiment 4

Factor	Df	MS	F	p
Hand (H)	1	490.5	199.89	0.0001
Orientation (O)	1	50.52	81.76	0.0001
H X O	1	3.56	8.97	0.004

Table 6. Experiment 5: Hand by ID analysis

Factor	Df	MS	F	P
Hand (H)	1	0.545	69.66	0.0001
ID	7	6.39	906.06	0.0001
H X ID	7	0.004	2.3	0.028

Table 7. Experiment 5: Hand by Peg by Phase Analysis

Factor	Df	MS	F	P
Hand (H)	1	0.545	69.66	0.0001
Peg Size (P)	3	0.238	43.1	0.0001
Phase (O)	1	43.49	2005.2	0.0001
H X P	3	0.0018	1.06	0.3712
O X P	3	0.1929	51.86	0.0001
H X O	1	0.0172	6.02	0.02
P X H X O	3	0.0037	1.64	0.1861

Table 8. Experiment Six: Hand by ID analysis

Factor	Df	MS	F	P
Hand (H)	1	212.8	179.35	0.0001
ID	15	34.85	69.15	0.0001
H X ID	15	0.537	3.03	0.0001

Table 9. Experiment Six: Hand by Peg Analysis for 1.25cm Hole Size

Factor	Df	MS	F	P
Hand (H)	1	154.1	144.8	0.0001
Peg Size (P)	3	16.37	25.89	0.0001
H X P	3	2.163	4.42	0.0061

Table 10. Experiment Six: Hand by Peg Analysis for 1.1cm Hole Size

Factor	Df	MS	F	P
Hand (H)	1	149.2	99.9	0.0001
Peg Size (P)	3	181.5	124.1	0.0001
H X P	3	1.51	3.5	0.018

Table 11. Experiment Six: Hand by Peg Analysis for 1cm Hole Size

Factor	Df	MS	F	P
Hand (H)	1	160.8	138.92	0.0001
Peg Size (P)	3	151.8	101.01	0.0001
H X P	3	1.39	3.89	0.0117

Table 12. Experiment Six: Hand by Peg Analysis for 0.9cm Hole Size

Factor	Df	MS	F	P
Hand (H)	1	175.2	86.1	0.0001
Peg Size (P)	3	67.65	63.17	0.0001
H X P	3	2.78	4.32	0.0068

IMAGE EVALUATION TEST TARGET (QA-3)

150mm

6"

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