INFORMATION TO USERS

This reproduction was made from a copy of a document sent to us for microfilming. While the most advanced technology has been used to photograph and reproduce this document, the quality of the reproduction is heavily dependent upon the quality of the material submitted.

The following explanation of techniques is provided to help clarify markings or notations which may appear on this reproduction.

1. The sign or "target" for pages apparently lacking from the document photographed is "Missing Page(s)". If it was possible to obtain the missing page(s) or section, they are spliced into the film along with adjacent pages. This may have necessitated cutting through an image and duplicating adjacent pages to assure complete continuity.

2. When an image on the film is obliterated with a round black mark, it is an indication of either blurred copy because of movement during exposure, duplicate copy, or copyrighted materials that should not have been filmed. For blurred pages, a good image of the page can be found in the adjacent frame. If copyrighted materials were deleted, a target note will appear listing the pages in the adjacent frame.

3. When a map, drawing or chart, etc., is part of the material being photographed, a definite method of "sectioning" the material has been followed. It is customary to begin filming at the upper left hand corner of a large sheet and to continue from left to right in equal sections with small overlaps. If necessary, sectioning is continued again - beginning below the first row and continuing on until complete.

4. For illustrations that cannot be satisfactorily reproduced by xerographic means, photographic prints can be purchased at additional cost and inserted into your xerographic copy. These prints are available upon request from the Dissertations Customer Services Department.

5. Some pages in any document may have indistinct print. In all cases the best available copy has been filmed.

University Microfilms International
300 N. Zeeb Road
Ann Arbor, MI 48106

8319786

**Nadler, Leslie Gary**

# LATERAL DIFFERENCES IN KINESTHESIS: THE INFLUENCE OF HANDEDNESS, GENDER AND DELAY INTERVAL

*City University of New York* PH.D. 1983

University
Microfilms
International 300 N. Zeeb Road, Ann Arbor, MI 48106

# LATERAL DIFFERENCES IN KINESTHESIS: THE INFLUENCE OF HANDEDNESS, GENDER AND DELAY INTERVAL

by

LESLIE NADLER

A dissertation submitted to the Graduate Faculty in
Psychology in partial fulfillment of the requirements
for the degree of Doctor of Philosophy, The City
University of New York.

1983

This manuscript has been read and accepted for the Graduate Faculty in Psychology in satisfaction of the dissertation requirement for the degree of Doctor of Philosophy.

3/2/83
date

Chairman of Examining Committee

March 8. 1983
date

Herbert D. Saltzstein
Executive Officer

Dr. Doreen Berman

Dr. Jack Orbach

Dr. Mitchell Kietzman
Supervisory Committee

The City University of New York

## Abstract

# LATERALITY EFFECTS IN KINESTHESIS:
# THE INFLUENCE OF HANDEDNESS, GENDER AND DELAY INTERVAL

by

Leslie Nadler

Adviser: Professor Doreen Berman

This study investigated the influence of handedness, gender and delay interval on lateral differences in replication of a horizontal arm movement, a task which is assumed to assess one aspect of kinesthetic sensitivity.

The subjects were 20 right-handed and 20 left-handed college students. Handedness of subjects was determined by responses to a handedness questionnaire and by familial handedness history. Within each handedness group there were an equal number of men and women subjects.

Data were subjected to six-way analyses of variance, one each for absolute error, constant error and variable error. These analyses showed no significant difference in performance between the two handedness groups for any of the response measures. There was, however, a significant interaction between handedness and arm for the absolute and variable error measures: the right-handed group showed a smaller absolute and variable error with the left than the right arm; the left-handed group showed no difference in performance between the two arms for either measure. The left arm superiority among right-handed subjects was also found when individual subject data were analyzed. Although there were other significant interaction effects, neither gender nor delay interval significantly affected the between arm performance patterns.

The results are discussed in terms of hemispheric specialization of function. It is suggested that, for right-handed adults, the right hemisphere plays a more important role than the left hemisphere in mediating performance on a task requiring the replication of arm movements to various end-positions. For left-handed adults, there appears to be no difference in the role of the two hemispheres in mediating task performance. It is further suggested that the superiority of the right hemisphere for this task in right-handed adults could be indicative of right hemisphere specialization for either the spatial aspects of the task or for the kinesthetic processing requirement of the task. This latter alternative is consistent with, and therefore might explain, the left side/right hemisphere advantage found on most tasks presented through the somatosensory modality.

## Acknowledgements

I wish to thank all the people who have helped make this dissertation possible. I am grateful to Dr. E. Spaney for statistical advice and to Karl Regnat, Larry Feldman and Jon Leong for their superb technical assistance.

Special thanks are extended to all the members of my dissertation committee: to Drs. Lila Ghent Braine and Tina Moreau for their thoughtful comments; to Dr. Mitchell Kietzman for his helpful suggestions and excellent instruction in experimental method throughout my graduate education; to Dr. Jack Orbach for his invaluable guidance, scholarly criticism, encouragement and support, both intellectual and emotional, as my teacher and adviser; and to my sponsor, Dr. Doreen Berman, for her insights, scholarship, diligence, enthusiasm, and most of all, for her never failing faith and confidence in me.

To my friends and family who provided limitless understanding and continual support which, no doubt, figured significantly in my being able to complete this work. I thank them all. To my children, Stacy and Lindsay, who despite their young years, evidenced considerable understanding and tolerance throughout the writing of this dissertation. I love and appreciate them deeply. Of course, my deepest gratitude, respect and

admiration is expressed to my wife, Joanne, who not only shared with me the frustrations, trials, tribulations and joys of this endeavor, but also provided the continuous psychological and emotional commitment and support without which this work could not have been accomplished.

## TABLE OF CONTENTS

APPENDICES

## LIST OF TABLES

## LIST OF FIGURES

# CHAPTER 1

# INTRODUCTION

It is well established that there are functional differences between the two cerebral hemispheres for the processing of information presented through the visual and auditory modalities. In general, among right-handed individuals, linguistic information is processed better by the left hemisphere, whereas non-linguistic information is processed better by the right hemisphere. With respect to the somatosensory modality, it has been difficult to obtain clear, unequivocal evidence for complementary specialization of function. Rather, in this modality, most of the evidence seems to indicate a right hemisphere superiority regardless of whether the information presented is linguistic or non-linguistic in nature (e.g., Hermelin & O'Connor, 1971; Varney & Benton, 1975).

Absence of clear evidence of a complementary specialization of function in the somatosensory modality is not the only contrast between this and the visual and auditory modalities. On most measures of sensitivity, lateral differences have not been found in the visual and auditory modalities (e.g., Kimura, 1969), whereas there is evidence for them in the somatosensory modality (e.g., Weinstein, 1968). In most instances, the lateral differences in sensitivity that have been reported relate to the tactile component of the somatosensory system while little or no attention has been paid to the kinesthetic component of this system. In view of the fact that most of the somatosensory tasks used to investigate hemispheric specialization of function have required the processing of kinesthetic information, the question of whether there are lateral differences in kinesthetic sensitivity merits further attention.

This investigation presents evidence for laterality effects for one aspect of kinesthesis, postion sense. Normal right-handed subjects were required to replicate, without visual guidance, the end position of horizontal arm movements. Performance of this task has been shown to depend heavily on the ability to process and utilize kinesthetic cues relating to the final position of the limb (e.g. Cratty, 1972).

Also investigated here was the influence of certain subject and task variables which have been shown to affect lateral differences in performance. The subject variables examined were handedness and gender; the task variables were mode of initial limb movement (active vs passive) and delay interval between the initial movement and the replication movement (5 vs 20 sec).

## Historical Review: The Concept of Hemispheric Specialization of Function

It has been noted for many years that the two cerebral hemispheres of man are not functionally equivalent. Among the earliest evidence of hemispheric asymmetry were reports by Broca (1861, 1863) in which he described a specific association in right-handed individuals between brain lesions restricted to the left cerebral hemisphere and speech disturbances. Based on this observation, Broca concluded that the left hemisphere of dextrals played a more prominent role than the right hemisphere in mediating speech processes. The supposed prominence of the left hemisphere over the right hemisphere was soon expanded to include not only speech, but most, if not all, higher mental processes (Bastian, 1898; Brown-Sequard, 1874). This was the beginning of the "dominance" theory of brain function.

The idea that higher mental functions are mediated largely by the left hemisphere was widely accepted for many years. In fact, it was bolstered by the findings of Liepmann (1900) that patients with lesions in the left hemisphere were more likely to show disturbances in motor execution, a deficit which he called "apraxia", than patients with right-sided lesions. A number of investigators, however, remained skeptical of this rather one-sided view of brain function. Chief among these was

Hughlings Jackson who, as early as 1870, suggested that the so called "non-dominant" right hemisphere was not simply a reserve hemisphere activated in the event that the left hemisphere became dysfunctional but, rather, that it subserved functions of its own. Jackson even went so far as to suggest that the right hemisphere might play an important role in what he termed "visual ideation". Despite such reservations, the "dominance" view of brain function remained relatively intact, without serious challenge for several decades.

Interest in the functions of the right hemisphere was briefly rekindled by Babinski (1914) who described disturbances of body image (anosognosia) which occurred more often in patients with right than left hemisphere lesions. It was not until World War II, however, that serious consideration was finally given to the idea that the right hemisphere subserved unique functions of its own. At this time, the unfortunate casualties of war provided researchers an opportunity to investigate systemtically large numbers of patients with lateralized brain lesions.

Perhaps most influential in this regard was the work of two groups of researchers, Paterson and Zangwill (1944) in England and Hecaen, deAjuriaguerra and Massonet (1951) in France. Both groups reported that constructional deficits occurred more frequently following injuries to the right than to the left hemisphere. Paterson and Zangwill further noted that patients with right hemisphere lesions showed more marked deficits on visuospatial tasks than did patients with left hemisphere lesions. Several years later, a more extensive investigation by Hecaen and Piercy (1956) revealed that constructional deficits could occur after left as well as right hemisphere lesions, but the association between these deficits and other clinical symptoms depended upon the side of the lesion. Specifically, they found that among patients with right hemisphere lesions constructional deficits were associated with spatial agnosia, directional and sensory disorders, oculomotor disturbances and indifference of mood. In contrast, among patients with left hemisphere lesions the only clinical symptoms associated to any significant degree with constructional deficits was "catastrophic reaction", an extreme emotional reaction to performance deficits, which had been described previously by Goldstein (1942).

At the present time, the "dominance" view of brain function has been supplanted by a conceptualization of brain function which emphasizes the "complementary specialization" of the two cerebral hemispheres. According to this view, each hemisphere subserves functions of its own; however, it is the coordination and integration of these specialized functions that is essential for the performance of higher-order mental and behavioral activities (Bogen, 1969; Dimond & Beaumont, 1974; Harnard, Doty, Goldstein, Jaynes & Krauthamer, 1977; Milner, 1962, 1975).

There are three primary sources of evidence which support the idea of complementary specialization of function of the two hemispheres: studies of patients who have sustained unilateral hemispheric lesions, studies of patients with cerebral commissurotomy, and studies of neurologically intact individuals. The following is a review of representative studies from each source. The first part of this review focuses on evidence for hemispheric specialization for information presented through the visual and auditory modalities, while the second part focuses on studies involving the somatosensory modality.

## Hemispheric specialization in the visual and auditory modalities: Right-Handers.

*Studies of patient populations*. A major source of information on hemispheric processing asymmetries derives from studies of patients who have sustained unilateral brain lesions. In such studies, the performance of patients with lesions of the right hemisphere is compared to the performance of patients with left hemisphere lesions on one or more tasks, and differences in performance between the groups are assumed to reflect functional differences between the two cerebral hemispheres.

As mentioned earlier, Broca (1861, 1863) noted that speech disturbances were more likely to occur among right-handed patients with left than right hemisphere lesions, suggesting that there was a special relationship between the left hemisphere and speech processes. More recently, systematic investigations comparing patients with left and right hemisphere lesions have not only confirmed this relationship but have shown that lesions of the left hemisphere selectively impair performance on a wide variety of visual and auditory tasks requiring processing of linguistic materials. Moreover, this relationship has been confirmed in persons with unilateral stroke or trauma (Lhermitte & Gautier, 1969), or hemispherectomy (Smith, 1966). Greater deficits following left than right hemisphere lesions have been found on tasks involving perception, learning or retention of such materials as letters and words (Myers & Yates, 1965), digits (Kimura, 1964) and even familiar objects which can readily be named (Milner, 1968). Furthermore, this left hemisphere superiority prevails regardless of whether the linguistic materials are presented through the visual or auditory modality (Blakemore & Falconer, 1967; Milner, 1967) or whether recognition or recall of the material is required (Corsi, 1972; Milner & Teuber, 1968).

In contrast to the above, patients with right hemisphere lesions typically show more marked deficits than those with left hemisphere lesions on tasks requiring the recognition and/or recall of visual or auditory stimuli that do not readily lend themselves to linguistic coding. Greater deficits following right than left hemisphere damage have been found on tasks requiring the recognition or recall of stimuli such as faces, nonsense figures and complex patterns (De Renzi, 1968; Fontenot, 1974; Kimura, 1966). Patients with lesions of the right hemisphere also show greater impairments than do patients with left hemisphere damage on tasks requiring spatial relational abilities (Benton, 1969; Hecaen, deAjuriaguerra and Massonet, 1951; Paterson and Zangwill, 1944; Warrington, 1969). Included among the spatial tasks that have been found to be affected more seriously by right than left hemisphere lesions is one requiring the perception of line orientation (Umilta, Rizzolatti, Marze, Zamboni, Franzini, Camarda and Berlucchi, 1974), another involving dot localization (Hannay, Varney and Benton, 1976; Warrington and Rabin, 1970) and several tasks which presumably tap topographic memory (De Renzi, Faglioni and Scotti, 1969, 1970). Finally, patients with right hemisphere lesions are more likely to display disturbances of both extracorporeal space (i.e. unilateral neglect) and corporeal space (i.e., anosognosia, phantom limbs) than are patients with lesions limited to the left hemisphere (Hecaen, 1973).

Another source of evidence for hemispheric specialization of function are studies of patients who have had their cerebral hemispheres disconnected by commissurotomy. This surgical procedure effectively eliminates the major connections between the two hemispheres while leaving them otherwise intact and functioning independently.

There are several advantages to studying patients with commissurotomy over those with unilateral lesions. First, the capacities of each hemisphere in the same individual can be studied separately, thus eliminating variability due to subject differences. Second, they eliminate the need to control certain extraneous variables that might influence performance which are difficult to control in group studies (i.e., fatigue, experience, anxiety). Despite these advantages, there are some difficulties in interpretating the results of such studies. First, is the issue as to the degree to which commissurotomy separates the hemispheres. Although severing the midline commissures effectively eliminates direct communication between the hemispheres, the possibility that one or more indirect lines of communication remain intact cannot be ruled out (Milner, 1975). A second, and perhaps more important question, relates to whether the results of these studies can be extrapolated to the normal brain. The brain of patients given a midline commissurotomy is not normal to begin with, since this procedure is performed on individuals with epilepsy.

In general, evidence for hemispheric specialization of function deriving from studies of commissurotomy patients is consistent with evidence from patients with unilateral brain injuries. On tasks involving tachistoscopic presentation of linguistic stimuli, such as letters, words or digits, commissurotomized patients recognize more accurately those stimuli that are presented in the right visual field (RVF) than the left visual field (LVF), regardless of whether the response mode is verbal or nonverbal (Gazzaniga & Sperry, 1967; Sperry & Gazzaniga, 1967). However, when chimeras of stimuli which are difficult to code verbally (e.g., faces, antlers) are presented to these patients in such a way that the midline of the joined stimuli is at visual fixation, the mode of response determines the chimera identified. When a nonverbal response (pointing) is required, chimera in the left visual field are identified; when a verbal response is required, chimera in the right visual field are identified (Levy, Trevarthen and Sperry 1972). When presented with simultaneous and conflicting spatial information, such as lines varying in orientation or dots moving in different directions, commissurotomy patients respond more accurately to the left than the right visual field stimulus (Nebes, 1974).

In audition, commissurotomy patients recognize and recall linguistic stimuli including letters, words and digits more accurately and faster when these stimuli are presented to the right than the left ear (Milner, 1968). In contrast, it has been difficult to obtain reliable evidence for specialized functions of the right hemisphere in the auditory modality. Milner had hoped to obtain such evidence by instructing patients to sing or hum simple melodies of three or four notes which were presented to them dichotically. It proved impossible to obtain a consistent vocal output (singing or humming) except in the case of one patient, who hummed only melodies presented to the left ear. For the other five patients tested the results were quite variable, as if the right hemisphere could not compete effectively for control of the vocal musculature, even though speech was not involved.

In summary, the findings of studies of patients with unilateral brain injuries and of those receiving commissurotomy are consistent with the idea that there are functional differences between the two cerebral hemispheres. It appears that, among right-handed individuals, the left hemisphere plays a more prominent role when the processing of linguistic information is required, whereas the right hemisphere seems to be more important for the processing of non-linguistic information, especially if the task is spatial in nature.

Studies of non-clinical populations. During the early 1950's, experimental techniques involving the lateralized presentation of stimuli were devised which, for the first time, made possible the investigation of hemispheric specialization of function in neurologically intact individuals. The rationale underlying these techniques is a simple one which rests on the anatomical relationship between the sense organs and the brain. By presenting stimuli in a lateralized manner, it is possible, at least initially, to limit the transmission of information to the hemisphere contralateral to the side of presentation. It is assumed that if the hemisphere initially receiving the information happens to be the one specialized for its processing, then this should confer a performance advantage on that side. Thus, a right side advantage is expected on tasks requiring the processing of information for which the left hemisphere is specialized and a left side advantage is expected on tasks requiring the specialized functions of the right hemisphere.

To investigate functional hemispheric differences, in the visual modality, most researchers have employed tasks involving the lateralized tachistoscopic presentation of different types of stimuli. Using this procedure, Mishkin and Forgays (1952) found that words are better recognized when they are presented in the RVF than the LVF of right-handed subjects. Similarly, a RVF advantage has been found on tasks requiring the recognition of words presented simultaneously to both visual fields (McKeever&Huling, 1971). In contrast, when stimuli that are not readily amenable to linguistic coding are presented to one visual half-field at a time, a LVF advantage is generally found. On tasks requiring the recognition or recall of stimuli such as faces or complex shapes, normal right-handed individuals typically perform more accurately when these stimuli are presented in the LVF than the RVF (Berlucchi, 1975; Fontenot, 1974). In addition, a LVF superiority frequently is found on tasks involving spatial aspects of perception. Thus, for example, a LVF advantage has been reported on a task requiring the spatial localization of dot stimuli (Kimura, 1969), on a depth discrimination task, and on a task requiring discrimination of line slant orientation (Kimura & Durnford, 1974). Taken together, these findings are consistent with the view that the left hemisphere has an advantage over the right hemisphere on tasks requiring the processing of linguistic materials, whereas the right hemisphere has an advantage over the left hemisphere on tasks involving the processing of non-linguistic and/or spatial materials (Benton, 1969; Kimura, 1966; Milner, 1968).

In the auditory modality, most of the evidence for hemispheric asymmetry in normal individuals has come from studies employing the dichotic listening procedure originally developed by Broadbent (1954). Kimura (1961) presented strings of spoken digits to normal right-handed adults and found that more digits presented to the right ear than the left ear were recalled correctly. Kimura postulated that this right ear superiority reflected prominence of the contralateral over the ipsilateral auditory pathways, since there is a 60/40 ratio of crossed to uncrossed fibers in this system, as well as privileged access of the right ear to the language processing left hemisphere. In another study conducted by Kimura (1966), a left ear advantage was found on a task requiring the recognition of melodies, presented dichotically, in the same normal subjects who showed a right ear superiority for digits. This finding of a complementary hemispheric specialization for linguistic and non-linguistic sound stimuli in the same individual has been replicated many times and remains the most impressive evidence available supporting the idea of complementary specialization of function for the two hemispheres in the neurologically intact brain (Segalowity & Gruber, 1977).

## Hemispheric specialization in the somatosensory modality: Right-handers.

Studies of patient populations. In many studies comparing the performance of patients with unilateral lesions of the left or right hemisphere, somatosensory tasks involving various spatial aspects of perception have been employed. De Renzi, Faglioni, and Spinnler (1971), for example, had patients perform a task requiring the reproduction of the spatial orientation of two rods. As predicted, they found that patients with right hemisphere lesions showed greater deficits on this task than did patients with left hemisphere lesions. A similar finding was reported by Faglioni, Scott; and Spinnler (1971), who required subjects to place drawing pins, without visual guidance, on a corkboard in a pattern corresponding to a somesthetically explored model. Employing a somesthetic-visual cross-modal task, Carmon and Benton (1969) used metal probes arranged in a 3 x 3 array to stimulate the palms of the hands of right or left unilaterally brain injured patients. Stimuli varied in number (1, 2, or 3) as well as in direction (vertical, horizontal and oblique), with the response consisting of pointing to or calling the appropriate number on a visual display card. There was no performance asymmetry for tactile perception of numerosity; the hand contralateral to the lesion was always inferior. With respect to the perception of direction, patients with lesions of the left hemisphere showed only contralateral deficits, but those with lesions of the right hemisphere showed bilateral deficits in judging directionality. Carmon and Benton attributed this finding to the greater role of the right than the left hemisphere in the "mediation of behavior requiring the appreciation of spatial relations" (p.531). These findings were replicated by Fontenot and Benton (1971) who included aphasic patients in their group with left hemisphere lesions, assuring that the superiority of that group was not attributable to the fact that their lesions were less extensive than those with right hemisphere lesions. It is worth noting that the study by Carmon and Benton is one of a few involving the passive presentation of somatosensory stimuli. In most studies employing somatosensory tasks, subjects are required to explore actively or to manipulate the stimuli presented.

More marked deficits following right than left hemisphere lesions have been found on a number of somatosensory tasks where the spatial aspect of the task is not readily identifiable. Using the Sequin-Goddard formboard, which requires placing geometric forms in their matching recessed spaces, it has been found that, patients with right hemisphere lesions showed greater deficits in speed and accuracy of performance than patients with left hemisphere lesions (De Renzi, Faglioni and Scotti, 1968; Milner, 1954; Reitan, 1964; Teuber and Weinstein, 1954). Similarly, on a size discrimination task requiring matching a wooden cube by palpation to one of a like size in an array, patients with right hemisphere lesions showed greater impairment than patients with left hemisphere lesions (Weinstein, 1962). Moreover, patients with right hemisphere lesions showed more impairment than those with left hemisphere lesions on a task requiring them to trace the outline of wooden nonsense and geometric forms with their index fingers and then to identify the traced shapes from a simultaneously observed visual display.

A fairly comprehensive review of the literature failed to reveal studies in which superior ability of the right hand/left hemisphere, as compared to the left hand/right hemisphere, was reported in unilaterally brain damaged individuals for tasks involving the processing of somesthetic stimuli.

Studies of somesthetic perception in commissurotomized patients yielded somewhat different results depending upon whether or not verbal responses were required. Familiar objects felt with the right hand were more accurately reported than those felt with the left hand. Similarly, right hand performance was superior to to that of the left hand on tasks requiring the retrieval of objects which were named, described or defined verbally (Gazzaniga and Sperry, 1967; Sperry and Gazzaniga, 1967). However, when tasks requiring the spatial manipulation of stimuli or the matching of stimuli that were not readily amenable to verbal coding were used, a clear left hand/ right hemisphere superiority was shown (Bogen and Gazzaniga, 1965; Milner and Taylor, 1972; Sperry and Gazzaniga, 1967; Sperry, Gazzaniga and Bogen, 1969). A left hand superiority has been found on the following tasks: construction of Kohs block designs (Bogen and Gazzaniga, 1965), the matching and demonstration of the use of objects through manipulation even after a delay (Milner and Taylor, 1972; Sperry, Gazzaniga and Bogen, 1969), the matching of two-dimensional visually-presented layouts to tactually-presented three-dimensional structures (Levy-Agresti and Sperry, 1968), and a cross-modal (visual-to-tactile and tactile-to-visual) matching of arcs to their proper size circles (Nebes, 1971, 1972).

It seems likely that the left side/right hemisphere superiority found among commissurotomy patients on somatosensory tasks which are spatial in nature reflects a right hemisphere specialization for the processing of spatial material. However, a recent study by LeDoux, Wilson and Gazzaniga (1977) suggests an alternative interpretation. These authors noted that some form of manual activity is usually required of commissurotomy patients, either in the perception of spatial relationships or in the production of spatial responses. Based on this, they modified a number of spatial tasks (i.e., block design, wire figures) in such a way as to eliminate manual activity while retaining their spatial features. In testing one commissurotomy patient, the authors reported that elimination of the manual component resulted in the disappearance of the left arm superiority. Although LeDoux, et. al. concluded from this that,evidence for right hemisphere specialization for spatial processing is highly dependent upon the involvement of manual activities, there is still another possible interpretation. Eliminating the manual component on these somatosensory tasks also resulted in the elimination of kinesthetic stimuli associated with manual activity. Therefore, the findings of this study are also consistent with the view that removal of kinesthetic processing requirement on these tasks was responsible for the disappearance of the left arm advantage.

<u>Studies of non-clinical populations</u>. Since, in the present study, a task requiring the processing of somatosensory information was employed, a brief review of the anatomy of the somatosensory system would appear in order.

Most of the information transmitted through the somatosensory system emanates from receptors located on the skin surface (tactile component) or in deep tissue beneath the skin (kinesthetic component). These receptors are generally activated by mechanical stimuli applied either directly to the skin surface or, as is the case for receptors in the muscles and joints, through movement of body parts. The activity generated in these receptors is transmitted to the spinal cord by afferent fibers of varying diameters. Upon entering the cord, through the posterior roots, these fibers separate into two divisions, one medial and the other lateral. The medial fibers enter the dorsal columns of the cord (dorsal column system) and ascend the entire length of the cord, while the lateral fibers travel up or down a few segments in the spinal cord and then synapse with dorsal horn cells. These cells give rise to the ventral and lateral spinothalamic tracts (spinothalamic system).

There is considerable evidence which distinguishes between the dorsal column and spinothalamic systems on functional as well as anatomical grounds (Mountcastle, Poggio & Werner, 1963; Sinclair, 1967; Werner & Mountcastle, 1965). As most of this evidence indicates that kinesthetic stimuli are transmitted primarily by the dorsal column system, the central projections of this system only will be described below.

The fibers in the dorsal column system synapse in the dorsal column nuclei in the medulla. From here, second order neurons decussate immediately to the opposite side and then pass upward through the medial lemnisci. Each medial lemniscus terminates in a ventrobasal complex of nuclei located in the thalamus. From the ventrobasal complex, third order neurons project mainly to the postcentral gyrus of the cerebral cortex but, in addition, neurons also project to closely associated regions of the cortex behind and in front of the postcentral gyrus. Furthermore, in addition to this major pathway, collateral fibers from the dorsal column system project to other cerebral structures including the cerebellum, tegmentum and other thalamic nuclei.

Based on the above, it seems reasonable to conclude that kinesthetic stimuli associated with movements of the right and left arm are transmitted predominantly to the left and right cerebral hemisphere, respectively.

Studies investigating hemispheric specialization of function in non-clinical populations for information presented through the somatosensory modality fall into two major categories: those in which higher-order perceptual and cognitive tasks have been employed and those investigating lateral differences in somatosensory sensitivity.

Benton, Levin and Varney (1973), using normal right-handed subjects, presented a cross-modal task which required identification of the direction (vertical, horizontal or diagonal) of a linearly arranged array of three metal probes which were applied to the palms of the hands. After presentation of the stimuli, the subjects were asked to select, from a visual display card, a line oriented in the same direction as the probes. Benton, et. al. found that a significant proportion of subjects showed superior performance for stimuli applied to the left than the right hand, as measured by the number of correct identifications. In a related study, Benton, Varney and Hamsher (1978) investigated whether the overall left hand advantage reflected the spatial nature of the task or its cross-modal character (somatosensory-to-visual). Subjects were asked to explore an array of three metal probes oriented in different directions and then to select from a tactile, rather than visual, display a line oriented in the same direction. Again, a left hand superiority was found, suggesting that it was the spatial aspect that accounted for the results obtained earlier.

Employing a different and more complex spatial task, Dodds (1978) had right-handed adults palpate forms with either hand and then asked them to select the palpated form tactually from a three item array.

To increase the tasks complexity and to emphasize its spatial character, Dodds rotated the forms into one of eight different orientations. A left hand superiority was found and Dodds suggested that this reflected the prominent role played by the right hemisphere in the processing of tactuo-spatial information.

A left hand advantage has been reported for other somatosensory tasks, including some that involve the processing of material that could be considered linguistic, not spatial, in nature. Most notable are tasks in which letters of the Braille alphabet have been used as stimuli. On these tasks, it might have been predicted that, evidence indicative of left hemisphere specialization for linguistic processing would be found,particularly among blind individuals who used Braille linguistically(have a right hand performance advantage). Hermlin and O'Connor (1971), however, reported that blind children read Braille letters and words more accurately with their left than their right hands.

Braille letters have been used with normally sighted subjects. Rudel, Denckla and Spalten (1974) taught sighted children 7-14 years of age to name Braille configurations palpated with their left or right hand. While a right hand superiority was found until age ten, superior left performance was evident thereafter. In addition, boys showed a left hand superiority earlier than girls (11 years for boys, 13 years for girls). To explore whether the delayed left hand superiority in females was due to greater reliance of females upon verbal strategies, Rudel, Denckla and Hirsch (1977) tested male and female subjects (7-14 years of age plus some adults), who were naive to the Braille alphabet, on a task requiring the tactile matching of Braille patterns, thus eliminating the verbal (meaning) component of the task. Again, a left hand superiority was observed after age 10, which led Rudel et. al. to conclude that somatosensory stimuli, and especially unfamiliar somatosensory stimuli, are processed primarily by the right hemisphere. They further suggested that hemispheric specialization of function differs for the visual and somatosensory modalities, such that initial somesthetic exploration confers an advantage on the right hemisphere, regardless of the specific processing requirements of the task employed (i.e., linguistic or non-linguistic).

Several authors have suggested that certain features unique to Braille letters could account for the right hemisphere advantage found on Braille tasks (Hermelin and O'Connor, 1971; Rudel, Denckla and Spalten, 1974). Since Braille letters are composed of raised dots which vary in number as well as spatial orientation, it is possible that a right hemisphere specialization for dot enumeration might confer an advantage to the left hand. Kimura (1966), found a LVF superiority on a dot enumeration task. To assess whether a similar process was operating in the somatosensory modality, Myers (1976) evaluated right and left hand counting of Braille dots in adults naive to the Braille alphabet. No difference between hands was found. Thus, it appears that left hand superiority on Braille tasks reflects right hemisphere specialization for some function or functions other than enumeration.

A left hand advantage on linguistic tasks presented through the somatosensory modality is not limited to tasks involving Braille letters. L.P. Gardner (1942) tested blindfolded right-handed college students on a task requiring the identification of nonsense syllables palpated with the hands. The stimuli were created by outlining letters with cord secured to cardboard backing. Subjects appeared to perform faster and more accurately with their left than their right hands, although no statistical treatment of data was reported. Similar results were found in another study conducted by Hatta (1978), where normal right-handed adults were trained on a somatosensory-verbal paired associates learning task. There were a larger number of correct responses and a steeper learning curve for the left than the right hand.

Although the majority of studies investigating hemispheric specialization of function in neurologically intact individuals seem to suggest that there is a right hemisphere superiority for most, if not all, information presented through the somatosensory modality, there have been a few reports indicating a left hemisphere superiority. Witelson (1974), using a dichhaptic paradigm, presented stimuli simultaneously to both hands of adults. The stimulus pairs consisted of either nonsense forms or cut-out letters of the alphabet. Testing 6-14 year old right-handed boys, she found better recognition of nonsense shapes felt with the left than the right hand and no lateral difference in performance on the letter recognition task. In a letter study (Witelson, 1976), however, she reported a significant right hand advantage for letter recognition. This is one of the few times that evidence of complementary specialization for information presented through the somatosensory modality has been reported.

Another example of evidence of complementary specialization in the somatosensory modality was provided by Cioffi and Kandel (1979). Using a dichhaptic design similar to the one employed by Witelson, these investigators presented nonsense forms, two-letter words and two-letter bigrams to children between the ages 6½ and

14½ years. Both boys and girls showed superior recognition of nonsense forms with the left than the right hand and superior word recognition with the right than the left hand. Bigrams were better recognized with the left hand of boys and the right hand of girls, suggesting a gender difference for the processing of these ambiguous stimuli.

In contrast to the above findings, other investigators who have used Witelson's paradigm have not found lateral differences in haptic perception. La Breche, Manning, Goble and Markham (1977) reported that neither deaf nor hearing right-handed adolescents showed the predicted left hand superiority for nonsense form recognition. Moreover, neither group showed any lateral advantage for perception of letters, whether responding by finger spelling, with left or right hand, or writing. Rather, a trend toward right hand superiority for nonsense form recognition was demonstrated, with significant right hand superiority when the shape recognition task followed the letter identification task. Cranney and Ashton (1980) administered Witelson's nonsense-shape recognition task to right-handed hearing and deaf children falling within the age range of the children studied by Witelson, and to a number of adults. They too failed to replicate the hand asymmetries reported by Witelson (1974, 1976) or others (Cioffi and Kandel, 1979; Gardner, English, Flannery, Harnett, McCormick and Wilhelm, 1977).

Although performance asymmetries which have been found in neurologically intact individuals generally are assumed to reflect hemispheric differences for perceptual and/or cognitive functions, lateral differences in sensitivity might also contribute to asymmetrical performance. In the visual modality, lateral differences in sensitivity have rarely been found (Durnford, 1971; Kimura, 1969). Furthermore, even if lateral differences were found, it would be difficult to understand how such differences alone could explain a RVF advantage for linguistic stimuli and a LVF advantage for non-linguistic and spatial stimuli. The same argument, of course, would apply to the complementary specialization of function in the auditory modality.

The situation is different, however, in the somatosensory modality where it has been difficult to find clear evidence for complementary specialization of function. In this modality, a left side superiority has been found on most tasks regardless of their specific nature. Therefore, the question of whether there are lateral differences in somatosensory sensitivity is one that has important theoretical implications.

Corkin (1978) reviewed studies investigating laterality effects in somesthesis and concluded that there are no laterality effects for elementary somesthetic functions, although there may be lateralization for 'higher order' somatosensory functions. She pointed out, however,that investigators in general, failed to control variables such as age, sex, and handedness making clear interpretation of their findings difficult. As this reservation applies to the studies she herself reviewed, it also indicates that her conclusions regarding lateralization of somesthetic processes must be regarded as tenous at best. Moreover, many of the studies on which Corkin based her conclusions did, in fact, show lateral differences in elementary somatosensory functions. Several examples will serve to illustrate this point.

Semmes, Weinstein, Ghent and Teuber (1960) found that normal right-handed adults showed a significantly lower pressure threshold on the thumb of the left than the right hand. They suggested that this difference in pressure sensitivity reflected differential callus formation on the two hands consequent to their differential use. Weinstein and Sersen (1961) tested this hypothesis by comparing pressure thresholds on the left and right side of the body at three different locations, including two locations where differential callus formation was less likely to have occurred (forearm and soles of feet). They found a lower threshold on the left side at all three locations for right-handers, therefore, rejecting the hypothesis of differential callus formation. Rather, they suggested that a central, and perhaps genetically determined, mechanism was operating. Subsequent studies conducted by Weinstein (1962, 1963, 1968) confirmed his original findings in adults, and similar findings have been reported for children (Ghent, 1961; Moreau and Milner, 1981). Other researchers, however, have failed to find lateral differences in pressure sensitivity in adults (Carmon, Bilstron and Benton, 1969; Satz and Wise, 1967). Thus, evidence for lateral differences in tactile sensitivity remains equivocal.

Several measures of somesthetic sensitivity, other than pressure, have been studied for lateral differences. Semmes, et. al. (1960) found no lateral differences in two-point thresholds on the thumbs or palms of intact right-handed subjects. However, the findings of Weinstein (1963, 1968) indicate that lateral differences do exist for two-point discrimination, but which side shows greater sensitivity depends on the body location tested. For most locations (thigh, calf, sole, forearm and back) greater sensitivity was found on the left, which Weinstein (1968) suggested might be due to right hemisphere specialization for spatial information processing since two-point discrimination provides a spatial measure of tactile sensitivity.

Lateral differences have been found for other aspects of somatosensory sensitivity. Rhodes and Schwartz (1981) found lower thresholds for vibrotactile stimulation on the fingers of the left than the right hand. Greater sensitivity on the left than the right side has been found as well for painful stimuli (Harriman and Castell, 1979; Haslam, 1970; Wolff and Jarvik, 1964).

The evidence presented above indicates that, for certain measures of tactile sensitivity, there is greater sensitivity on the left than the right side. This suggests that lateral differences in tactile sensitivity might be, at least in part, responsible for the left side performance advantage found on tasks presented through the somatosensory modality. There are, however, two reasons for questioning this interpretation. First, the lateral differences which have been reported involve stimuli presented at or around threshold levels, whereas above-threshold stimuli are used generally on somatosensory tasks. Second, and perhaps more important, on most somatosensory tasks subjects are required to explore stimuli manually with either their entire hand or their fingers. In fact, in a few studies (DeRenzi, et. al., 1969; Witelson, 1974), subjects were specifically instructed to trace the outline of objects with their fingers in such a way as to maintain the spatial component while reducing the availability and usefulness of tactile stimuli. Thus, it appears unlikely that lateral differences in tactile sensitivity alone could explain the performance asymmetries which have been found in the somatosensory modality.

In light of the presence of a manual component on most somatosensory tasks, it seems reasonable to assume that the processing and utilization of kinesthetic information regarding arm, hand or finger movement and position would be important for accurate task performance. Thus, it would seem worthwhile to review studies investigating lateral differences in kinesthesis.

In the studies of Semmes et. al. (1960) and of Corkin, Milner and Rasmussen (1970), a measure of kinesthesis was included, but no lateral differences were found in either brain-injured or intact subjects on this measure. In both of these studies, however, kinesthesis was assessed by means of the standard clinical test in which a digit is moved passively and the subject is required to identify whether a movement has occurred and its direction (usually up or down). Although this test might be adequate for clinical assessment or for detecting gross deficits in kinesthesis it is not sensitive enough to detect subtle differences or changes in sensitivity. Hence, it is possible that lateral differences in kinesthesis do exist in normal individuals, but that a more sensitive measure is needed to detect them.

Kinesthesis has a number of dimensions which can be measured in several ways: by detection of movement, by changes in movement direction, by changes in movement velocity and by changes in position. In most of the studies investigating lateral differences in kinesthesis, a task has been used which requires subjects, with vision excluded, to move their limb to a point in space and then to replicate the movement to this location either from the same or a different start position than was used on the initial movement. This type of task presumably assesses the dimension of kinesthesis commonly referred to as position sense (Cratty, 1972).

Christina (1967) tested right-handed adults on a task requiring the blind replication of vertical arm movements made to various positions. He found that subjects performed more accurately with their left than their right arm. Employing a similar task, Phillip and Summers (1954) also found a left arm superiority for certain passively made vertical movements, but either no difference or a right arm advantage for other movements. These authors suggested that familiarity of a movement may have been an important factor determining which arm performed more accurately: the right arm performed better on familiar movements, worse on unfamiliar movements. The authors, however, failed to distinguish clearly between familiar and unfamiliar movements. In contrast to these findings, Lloyd and Caldwell (1965), measured position sense in the legs of normal subjects, and found no lateral differences, while Wallace (1977), measuring position sense in the arms of normal individuals, also found no lateral differences.

In view of the contradictory findings from studies investigating lateral differences in kinesthesis, it would seem worthwhile to consider task, procedural or subject variables which might account for the discrepancies. In the study by Lloyd and Caldwell, in which no differences were found, position sense was tested at the knee joint, whereas in other studies reporting lateral difference, position sense was measured at the shoulder joint. Different results might also reflect variations in the response measure used. Lloyd and Caldwell required subjects to report verbally the position assumed by their limb, while other investigators (Christina, 1967; Phillip and Summers, 1954) required subjects to replicate, through limb movements, the end-position of their limb. Other studies of hemispheric specialization in normal subjects have similarly shown the importance of response measure in producing performance asymmetries (Gardner, et.al. 1977; White, 1969; Witelson, 1976).

While differences in joint tested or response measure used might account for the differences between the findings of Lloyd and Caldwell and those of Christina and of Phillip and Summers, neither factor can account for the difference in results reported by these latter authors and those reported by Wallace (1977). Wallace measured position sense in the same body location (shoulder), and employed a similar arm movement replication task to the one used in both the Christina and Phillip and Summer studies. Despite this, there was one important difference between the tasks used which might have accounted for the different results obtained. In both the Christina and the Phillip and Summer studies, subjects attempted to replicate the end position of movements which were imposed, initially, by the experimenter moving the subject's arm; the end position was defined through a passive movement. In contrast to this, in the Wallace study, the initial movement defining the end position was made by the subject; the end position was defined through active movement. In all three studies, the replication movements were made actively. Thus, in the two studies in which lateral differences in position sense were found, a combination of passive and active movements was used, while in the one study reporting no lateral difference, all movements were performed actively.

There are several sources of evidence which justify distinguishing between active and passive movements. Paillard and Brouchon (1974), for example, found that subjects matched the end position of a movement made with one hand (target hand) with the other hand more accurately when the target hand movement was made actively than when it was made passively. Similar findings have been reported by other investigators, using movements involving the arms (Jones, 1974; Stelmach, Kelso and Wallace, 1975), the legs (Lloyd and Caldwell, 1965), and even the eyes (Festinger and Canon, 1975). That there are differences between active and passive movements is also suggested by the findings of studies involving the rearrangement of visual space through the use of distorting prisms. In such studies it has been shown that subjects are best able to adapt or compensate for prism distortion if they are permitted to make free movements of their body or of an appropriate limb. If, however, while wearing prisms, restrictions are placed on the subjects movements or if parts of the body are moved by external force (i.e., passive movements), relatively little adaptation occurs (Held and Freedman, 1963). Although the mechanisms underlying the differences between active and passive movements are not completely understood, several researchers have suggested that monitoring of efferent signals during active, but not passive movements, May play an important role (Festinger and Canon, 1965; Jones, 1974; von Holst, 1954). Regardless of whether this is the case, the fact that reliable differences have been found between active and passive movements raises the possibility that the discrepant findings reported by Christina, Phillip and Summers and Wallace may have stemmed from differences in the mode of movement used in these studies.

In addition to task and procedural differences in studies of laterality effects in kinesthesis, differences in the handedness of the subjects tested in these studies may have been an important factor accounting for the discrepant results. In one of the studies reporting no lateral difference in position sense (Lloyd and Caldwell), no information was given on subject handedness. In the other three studies, the basis for identifying the handedness of subjects was not specified, and it seems likely that self-report alone was used for this purpose. Furthermore, in none of the studies was familial handedness history provided. Inasmuch as both of these factors have been shown previously to influence lateral difference in performance (Hardyck and

Petrinovich, 1977), it is possible that the subjects tested in each of these studies did not represent a homogeneous group and that differences in subject handedness and/or familial handedness history might account for the discrepant results.

## Factors influencing hemispheric specialization of function.

Left-handedness. It has been known for some time that the functional organization of the brain of left-handed individuals is different from that of right-handed persons. One of the earliest views of brain organization in the left-handed (Broca, 1863) suggested that it simply mirrored the organization found in right-handed individuals. Thus, language functions were thought to be subserved by the right rather than the left hemisphere of sinistrals. However, as more clinical evidence accumulated, the validity of this view became suspect. Systematic studies of left-handed patients with unilateral brain injury revealed that disturbances in linguistic functions, including speech, were not necessarily associated with lesions of the right hemisphere, but that such disturbances were as likely to occur following lesions of either hemisphere (Hecaen & Sauguet, 1971; Zangwill, 1960). Similarly, on nonlinguistic or spatial information possessing tasks, left-hand patients frequently manifested deficits following lesions of the left as well as the right hemisphere (Branch, Milner and Rasmussen, 1964; Gloning, Gloning, Haub and Quatember, 1969; Goodglass and Quadfasel, 1953; Hecaen and Piercy, 1956; Luria, 1970; Subirana, 1958). Taken together, these observations led a number of researchers to conclude that clear-cut cerebral specialization, either left or right, is less likely to exist in left-handed individuals than right-handed individuals and, perhaps more importantly, that there is less lateralization and a more bilateral representation of function in left-handers than right-handers (Hecaen and deAjuriaguerra, 1956; Hecaen and Sauguet, 1971; Levy, 1969; Zangwill, 1960).

Although this idea was believed to apply to most, if not all, left-handed individuals, several investigators have pointed out that sinistrals appear to represent a less homogeneous group than dextrals when it comes to the functional organization of their brains (Hecaen and Sauguet, 1971; Varney and Benton, 1975; Weinstein and Sersen, 1961; Zurif and Bryden, 1969). In trying to account for this, heredity has received particular attention. In studies involving patient populations, only left-handed individuals with a sinistral family background show performance deficits suggesting a bilateral representation of function. Left-handers not having such a history typically show a performance pattern similar to that found among right-handed individuals (Bryden, 1965; Hecaen and Sauguet, 1971; Hines and Satz, 1971; McKeever, Van Deventer and Suberi, 1973; Zurif and Bryden, 1969).

On tasks involving the lateralized tachistoscopic presentation of linguistic stimuli, normal right-handed adults with or without family history of sinistrality generally show a common pattern of performance. That is, both show greater accuracy and faster reaction times for stimuli presented in the RVF than the LVF (Cohen, 1972; Dimond and Beaumont, 1974; Hines and Satz, 1971). In contrast, among left-handed adults with a history of sinistrality, it has been found that there is either no difference in accuracy or speed between the two visual fields (Beaumont and Dimond, 1975; Buffery, 1974; Cohen, 1972; McKeever, Gill and Van Deventer, 1975) or, in some cases, a difference favoring LVF (Bryden, 1965; Zurif and Bryden, 1969). For left-handed adults not having a family history of sinistrality, the pattern of performance is frequently one similar to that found among right-handed individuals (Hines and Satz, 1974; Zurif and Bryden, 1969). Comparable findings have been reported for information presented through the auditory (Dee, 1971; Zurif and Bryden, 1969) and somatosensory modalities (Varney and

Benton, 1975; Weinstein and Sersen, 1961). When the data are examined for common trends, the most striking characteristic is the variability in performance among the left-handed especially, when compared to the very consistent pattern of performance found among right-handed individuals. Most of the evidence suggests that there is a more bilateral representation of function among left than right-handed individuals, and especially among those left-handed individuals having a family history of sinistrality (Hardyck and Petrinovich, 1977).

Memory. At one time it was assumed that any complementary specialization of the two hemispheres related to differences in sensory/perceptual mechanisms. It has been pointed out (Dee and Fontenot, 1973), however, that there is usually some time delay between the presentation of a stimulus and the requisite response. This observation has led a number of investigators to suggest that hemispheric asymmetry for memory functions may be of equal, or greater, significance than perceptual mechanisms in understanding functional differences between the hemispheres.

The importance of memory in the genesis of lateral asymmetries is highlighted by a study by Corsi (1972). Corsi presented two tasks, one verbal and the other visuo-spatial, to patients with right or left temporal lobe lesions. She found, as expected, that patients with left hemisphere lesions performed significantly worse on the verbal task than did patients with right hemisphere lesions, whereas patients with right hemisphere lesions showed the greatest deficits in visuo-spatial performance. Even more interesting, however, was the finding that the difference between the patient group increased significantly as a function of increases in the time delay between the presentation of the stimulus material and the requisite response (0-20 sec).

Further evidence indicating that there are, indeed, hemispheric differences for memory functions comes from studies of normal subjects. Dee and Fontenont (1973), presented complex shapes in the right or left visual fields of normal right-handed individuals. Following delays of 0, 5, 10, or 20 sec, another shape was presented in central vision and subjects were asked to indicate whether the second shape was the same or different than the shape presented initially. The anticipated LVF advantage was found, however, this appeared only following the 10 or 20 sec delay interval. In another study, Hines and Satz (1971) presented stimuli composed of a varying number of letters to normal right-handed adults and examined the effects of serial position on performance. They found that increasing the number of letters contained in the stimulus increased the RVF superiority and, further, that the magnitude of the difference between the visual fields increased for those letters most remote in time.

The role of memory in the somatosensory modality was investigated by Oscar-Berman, Rehbein, Porfiet and Goodglass (1978). Normal right-handed subjects were asked to identify, in a particular hand order, different stimuli (letters, digits and lines differing in orientation) presented dichhaptically. It was found that letters were identified more accurately with the right hand, while lines differing in orientation were identified more accurately with the left hand. This complementary superiority, however, was manifested only for the stimuli reported for the second hand. This finding led the authors to suggest that tasks involving tactile storage mechanisms might better reflect hemispheric specialization of function than do those involving other sensory/perceptual mechanisms.

Gender. The study of individual differences in verbal and spatial abilities has been a topic of considerable interest in the cognitive literature for many decades. One variable that has been frequently implicated has been gender. It has been observed that women tend to excel on measures of verbal ability and men on measures of spatial ability (Bryden, 1978; Buffery and Gray, 1972; Maccoby and Jacklin, 1974; Ray, Morell, Frediani & Tucker, 1976).

Many theories have been advanced to explain gender differences in cognitive abilities, but the major focus has been on genetic and neurological interpretations. One popular genetic theory (Stafford, 1961) suggests that spatial abilities may be enhanced by a sex-linked recessive gene, which accounts for the finding that more men than women exhibit the trait. Another explanation has been that of differential lateralization of function patterns of men and women (Levy & Reid, 1978). It has been suggested that language functions in women may become bilaterally represented resulting in a decrease in the neural tissue that is available for spatial processing mechanisms which, inturn, impedes the development of spatial abilities in women. This notion, first advanced by Levy (1969), has come to be known as the "crowding" hypothesis. The major premise of this hypothesis that females may be less lateralized for language is supported by tachistoscopic, dichotic listening and EEG studies of normals (Briggs & Nebes, 1976; Lake & Bryden, 1976; Trotman & Hammond, 1979), and also by clinical studies of patient populations (Hecaen, DeAgostini & Monzon-Montes, 1981; Inglis & Lawson, 1981).

Evidence suggesting that there is relatively less lateralization of function among women than men has not been limited to functions subserved by the left hemisphere (i.e., language). Kimura (1969) found that on a visuospatial task requiring the localization of dot stimuli presented to either the right or left visual half-field, normal right-handed men showed the expected LVF superiority, whereas right-handed women showed no difference in performance between the two visual fields. This finding, which was subsequently replicated by McGlone and Davidson (1973), is consistent with the view that there is less lateralization of spatial functions among right-handed females than males. A similar conclusion was reached by Witelson (1976), who found gender differences in performance on a somatosensory task. Children, 6-13 years of age were required to palpate and then identify from a visual display nonsense shapes presented simultaneously to the right and left hand. Witelson found that boys as early as age 10, performed this task in a manner consistent with right hemisphere specialization (left hand superiority), whereas girls showed no lateral difference in performance, even at age 13.

Further evidence supporting the conclusion that there is greater lateralization of spatial functions in males than females, derives from the study of patients with unilateral brain lesions. It has been observed that males show more marked impairments than females on spatial tasks following lesions of the right hemisphere (McGlone and Kertesz, 1973).

In summary, it has been suggested that gender differences in cognitive abilities may be associated with gender differences in laterialization of function. Thus, right-handed males show lateral differences in performance on various linguistic and spatial tasks, whereas right-handed females sometimes fail to show such differences. Moreover, among patients with unilateral brain injuries, males typically show more marked deficits than females.

Rationale for the present experiment. The present study was designed to investigate lateral differences in kinesthesis in right-handed individuals selected on the basis of their responses to a handedness questionnaire and their familial handedness history. To facilitate comparison with other studies, an arm movement replication task similar to the one used in previous studies was employed. This task, which presumably taps one aspect of kinesthesis, position sense, requires subjects to replicate, without visual guidance, the end-position of arm movements.

Performance error, as measured by the difference between a performance score and a correct or target score, is the dependent variable of intest in most motor performance experiments. The magnitude of this error, however, can be expressed in different ways. In most early motor performance studies (e.g., Williams &

Roy, 1972) performance error was expressed as the average algebraic or constant error or the average absolute error. More recently, a number of investigators (e.g., Roy, 1976) have advocated the use of another error score which reflects error about the constant error, that is, the within-subject variance or variable error.

Roy (1976) reviewed a number of motor performance studies and pointed out that not only was there a general lack of consistency with regard to results, but that there was inconsistency relating to the response measures that were used. In view of the fact that there is controversy in the motor performance literature regarding the appropriate and/or best response measure to use, it was decided, in the present study, to respect Roy's recommendation that all three measures, absolute error, constant error and variable error, be employed.

In view of the evidence suggesting a basis for distinguishing between active and passive movements (Paillard & Bouchard, 1969; Lloyd & Caldwell, 1965; Marteniuk, 1975), it is possible that the discrepant findings of studies investigating lateral differences in position sense might stem from differences in the mode of initial movement. To investigate this possibility, subjects were required to replicate the end-position of movements made either actively or passively.

To investigate the influence of handedness, lateral differences in kinesthesis were assessed in a group of left-handed adults having at least one left-handed parent. Only left-handers having a sinistral familial handedness history were tested in this study. In most studies investigating laterality effects in left-handers, it has been found that left-handed individuals having a family history of left-handedness frequently fail to show performance asymmetries on tasks which, in right-handed individuals, seem to tap functional hemispheric differences. This finding has led to the conclusion that there is a more bilateral representation of function among familial left-handers (Hardyck & Petrinovich, 1977).

Another subject variable, which has been shown to influence performance asymmetries is gender. In several studies it has been reported that right-handed men are more likely to show lateral differences than right-handed women (e.g., Kimura, 1969). To assess the influence of gender, an equal number of men and women were included in each handedness group.

It has been noted that increasing the time interval between the presentation of a stimulus and the requisite response increases the likelihood of observing lateral differences in performance. This observation has led a number of investigators to suggest that hemispheric asymmetry for memory functions might underlie performance asymmetries (Dee & Fontenont, 1971; Hines, Satz & Clementino, 1973). The role of memory in the genesis of laterality effects in kinesthesis was assessed by requiring subjects to replicate arm movements following two different delay intervals (5 and 20 sec).

## STATEMENT OF HYPOTHESES

The specific hypotheses investigated in the present study were as follows:

1. Right-handed men will show greater accuracy in replicating the end-position of horizontal arm movements made with their left than their right arm; right-handed women either will show a smaller difference or no difference between the arms.

2. Familial left-handed adults will show little or no difference between the arms in replicating horizontal arm movements to various end-positions.

3. In general, men will show greater accuracy in replicating arm movements than women.

4. For right-handed adults differences in performance between the arms will increase as a function of increases in the time delay between the initial movement and the attempted replication of the movement.

5. For right-handed adults a difference in performance between the arms will occur when the initial movement to an end-position is made passively, but not when it is made actively.

# CHAPTER 2

# METHOD

## Subjects

Forty Queens College undergraduate students between the ages of 19 and 38 were selected from a larger group of individuals who had volunteered to participate in the study. Twenty were right-handed and twenty were left-handed; ten in each handedness group were men and ten were women. To minimize experimenter bias based on prior knowledge, handedness was assessed after completion of the arm movement task. As a consequence, forty-six subjects were tested before the requisite number of right and left-handed men and women were obtained.

Handedness was determined by questionnaire and parental handedness history (see Appendix A). The questionnaire consisted of 15 manual activity items selected for their demonstrated reliability and validity (Oldfield, 1971; Raizkowski & Kalat, 1974). To be assigned to a handedness group, subjects had to indicate which hand was used for writing and at least 9 of the remaining 14 activities included on the questionnaire. In addition for the right-handed group, parents had to be right-handed, whereas for the left-handed group, at least one parent had to be left-handed. The less stringent criterion for left-handedness was necessitated by difficulty in finding left-handers with both parents left-handed.

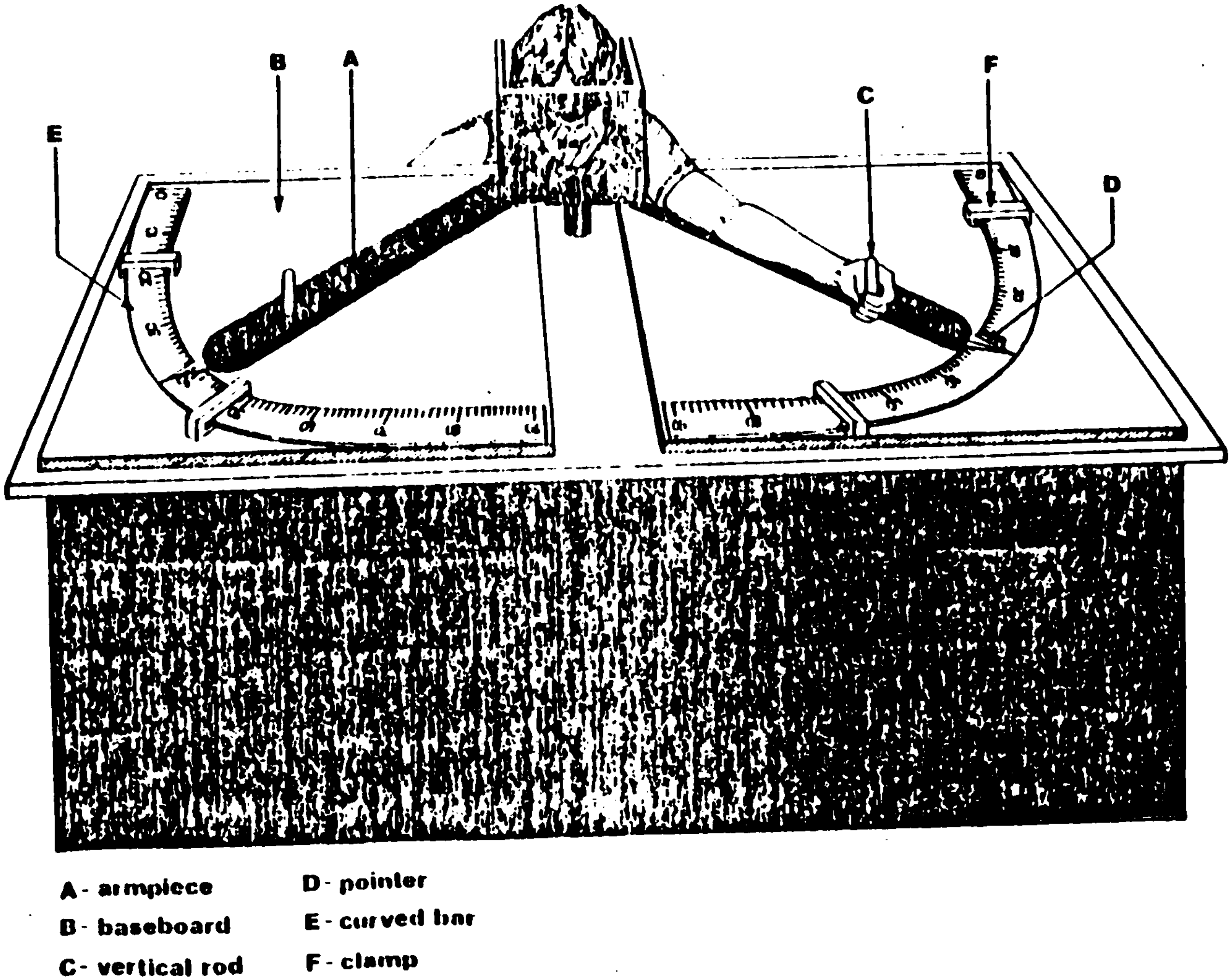
Subjects were given a brief description of the task but were naive as to the purpose of the study.

### Apparatus

The apparatus (Figure 1) consisted of two flat armpieces. (A), mounted on separate baseboards (B) which moved laterally in relation to each other to accommodate different size subjects. The armpieces, 70 cm. in length, pivoted on ball bearings so that each moved in a $90^{\circ}$ arc with minimal friction. A vertical rod (C), adjustable for position on each armpiece, served as a handgrip. A pointer (D) extended from the end of each armpiece to indicate position on a calibrated, curved bar (E) attached to the periphery of each baseboard. Position could be measured to the nearest $\frac{1}{2}^{\circ}$. Moveable clamps (F) fastened to the bars served as mechanical stops defining the start and end-position for movements. An adjustable chin rest was positioned between the two baseboards, and a three-sided screen attached to the base of the chin rest prevented subjects from viewing their arms during movements.

A white noise generator connected to headphones served to mask auditory cues emanating from the equipment. Two electronic timers, each activated by a manual

FIGURE 1. Arm movement apparatus



switch were used to measure time intervals between the initial and replication movements; a third timer, activated by movement of the armpieces, served to measure the duration of practice trial movements.

### Procedure

Upon entering the laboratory for individual testing, each subject read and signed a form which briefly described the experiment and stated that subjects were not required to participate. Following this, the subject was seated on a stool centered between the two baseboards. The stool height was adjusted so that the chin rested comfortably on the chin rest. With both arms fully extended to the side, the baseboards were positioned so that the pivots of the armpieces were directly beneath the axillae. The hand grip on each armpiece was then adjusted so that the subject's arms, when fully extended on the armpiece, did not touch its surface. After these adjustments were completed, the subject was read instructions (Appendix C) which described the task.

Each trial consisted of two movements made either with the right or left arm. At the start of a trial, the experimenter told the subject to place the right or left arm on the corresponding armpiece already positioned at one of two start positions ($10^{\circ}$ or $20^{\circ}$) and to place their chin on the chin rest. Approximately

2 seconds later the experimenter said the word "Move" and depending on whether the movement was to be active or passive either the subject (active) or the experimenter (passive) moved the armpiece in a slow continuous manner until it contacted a metal clamp positioned at one of three predetermined end-positions ($50^{\circ}$, $60^{\circ}$, or $70^{\circ}$). For both movement conditions, the subject maintained the arm at the end-position until the command "Release" was given, at which time they removed the arm from the armpiece and placed it in the lap. The chin remained on the chin rest. Upon contacting the clamp, the experimenter manually activated one of two timers, set for 5 or 20 sec, respectively, and then said "Release". Following the appropriate delay interval, the experimenter said the word "Replicate" signalling the subject to reposition the same arm on the armpiece and to attempt to return it to the same end-position as the initial movement. All replication movements were made actively. Once the subject decided that the desired end-position was reached, he/she indicated this to the experimenter by saying "Now" or "O.K.". The experimenter recorded the position of the armpiece to the nearest half degree and then signalled the end of the trial. There was a 25 second inter-trial interval during which the subject removed the chin from the chin rest and placed the arm in the lap.

For each subject, the experimental session consisted of 96 trials and lasted approximately 90 minutes. Half the trials in a session were performed with the right arm and half with the left arm; half with each arm were performed actively and half passively; half of the active and passive trials performed with each arm were replicated after a 5 sec delay interval and half after a 20 sec interval.

To assess whether subjects understood the instructions and whether movement durations for the two arms were equivalent, 12 practice trials were given to each subject; six with the right arm, six with the left arm. Three trials with each arm were performed actively, three passively. All practice trial movements involved a 10 sec delay interval between the initial and replication movements and were made to a $55^{\circ}$ end-position which was not included as an end-position in the experimental session. The duration of all movements was measured by a timer which started when the pointer on the armpiece separated from the clamp at the start position and it terminated when the pointer contacted the clamp placed at the end-position ($55^{\circ}$). Table 1 shows that, for both handedness groups, there was no significant difference between the two arms in the duration of practice trial movements; nor did the right-handed group differ from the left-handed group in this regard.

Table 1

Mean duration (sec) of practice trial movements as a function of arm and handedness group.

| Group | | Arm | | | |
|---|---|---|---|---|---|
| | | Right | Left | t | p |
| Right-handed | | | | | |
| | $\bar{x}$ | 1.8 | 1.9 | 1.23 | ns |
| | sd | 0.8 | 0.5 | | |
| Left-handed | | | | | |
| | $\bar{x}$ | 1.7 | 1.7 | -- | ns |
| | sd | 1.1 | 0.6 | | |
| All subjects | | | | | |
| | $\bar{x}$ | 1.8 | 1.8 | -- | ns |
| | sd | 1.0 | 0.9 | | |

## Experimental Design

Each session was subdivided into four blocks of 24 trials. Two blocks involved active movements and two involved passive movements and these were presented in a counter-balanced order. Half the subjects in each gender-handedness group received an active-passive-passive-active order, the other half a passive-active-active-passive order of blocks. Within each block, the 24 trials were divided into four sub-blocks of six trials each. These six trials included one trial with each arm to each of three end-positions. A pseudo-random order of arm-end-position presentation was used for each sub-block, with the constraint that each arm-end-position combination appeared sixteen times per session. The two delay intervals were assigned in such a manner that within a block of 24 trials each combination of arm and end-position was paired twice with each delay interval. Within each sub-block of six trials the two arms always received an identical combination of all treatment conditions. Within a session there were four trials under each of the 24 possible combinations of conditions (Appendix B contains a sample of the data sheet used for each subject).

The experiment conformed to a 2 x 2 x 2 x 2 x 2 x 3 split-plot factoral design (Kirk, 1968), with two independent factors, Handedness (2 levels) and Gender (2 levels), and four repeated measures, Arm (2 levels), Mode of Initial Movement (2 levels), Delay Interval (2 levels) and End Position (3 levels).

## Response Measures

As stated previously, three response measures were used in this study. The absolute error was the difference, in degrees, between the initial movement end-position and the position reached on the replication movement, without regard to direction of error. Algebraic or constant error was the same difference in degrees as the absolute error, but with the direction of error taken into account (over-shooting=positive error; under-shooting=negative error). Variable error was the variance of each subjects error about their own constant error. In as much as each of these error measures is associated with performance accuracy it might have been expected that they would be inter-related. There is evidence, however, indicating the statistical independence of two of these measures, constant error and variable error (Roy, 1976).

## Data Analysis

Three six-way analyses of variance were carried out; one for absolute error, one for constant error and one for variable error. In addition, chi-square analyses were performed on each measure to assess whether the proportion of subjects showing performance asymmetry differed between the two handedness groups. A correlation coefficient was calculated to determine the with-in session reliability of any between arm differences in performance. To reduce the likelihood of Type 1 errors, differences were considered significant only if they reached or exceeded the .01 level of confidence.

# CHAPTER 3

## RESULTS

The assumption of homogeneity of variance for each response measure was tested and accepted on the basis of the results of Hartley's $F_{max}$ test (absolute error: $F_{max} = 4.52$, $p>.10$; variable error: $F_{max} = 4.80$, $p>.10$: constant error: $F_{max}$ 5.7, $p>.10$). Separate analyses of variance were carried out on the data for each response measure and a summary of these appear in Appendices D-F.

Table 2 shows the mean absolute, variable and constant error as a function of arm and handedness group. It can be seen that the significant main effect for arm reflected a smaller absolute and variable error for the left than the right arm when the errors for each arm were combined across handedness group. Although the main effect for handedness group failed to reach statistical significance, the handedness group x arm interaction did, for the absolute and variable error. This suggested that group differences might exist when the performance of each arm was considered separately. To assess this, analyses of variance for simple main effects were carried out (Tables 3 and 4). For the absolute error, there was a significant group effect for the left but not the right arm. With the left arm, right-handed subjects showed a significantly smaller absolute error than did left-handed

## Table 2

Mean absolute, variable and constant error (deg) as a function of arm and handedness group

| Group | | Absolute error | | Constant error | | Variable error | |
|---|---|---|---|---|---|---|---|
| | | Arm | | Arm | | Arm | |
| | | Right | Left | Right | Left | Right | Left |
| Right-handed | $\bar{x}$ | 6.4 | 4.4 | 1.9 | 1.5 | 5.5 | 4.0 |
| | sd | 1.5 | 1.4 | 1.6 | 1.2 | 0.9 | 0.6 |
| Left-handed | $\bar{x}$ | 5.3 | 5.7 | 2.4 | 2.1 | 4.7 | 5.1 |
| | sd | 1.6 | 1.8 | 2.1 | 1.4 | 1.0 | 1.5 |
| All subjects | $\bar{x}$ | 5.8 | 5.0 | 2.2 | 1.8 | 5.1 | 4.5 |
| | sd | 0.8 | 0.6 | 1.3 | 1.5 | 0.6 | 0.5 |

Table 3

Analysis of variance of absolute error: simple main effects for handedness group and arm.

| Source of Variance | | SS | df | MS | F | p |
|---|---|---|---|---|---|---|
| | Left arm | 189.6 | 1 | 189.6 | 8.6 | <.01 |
| Handedness group X | | | | | | |
| | Right arm | 145.1 | 1 | 145.1 | 6.6 | ns |
| Error | | 1573.5 | 72 | | | |
| | Right-handed group | 440.3 | 1 | 440.3 | 67.7 | <.001 |
| Arm X | | | | | | |
| | Left-handed group | 23.4 | 1 | 23.4 | 3.5 | ns |
| Error | | 245.9 | 38 | 6.5 | | |

Table 4

Analysis of variance of variable error: simple main effects for handedness group and arm

| Source of Variance | | SS | df | MS | F | p |
|---|---|---|---|---|---|---|
| Handedness group X | Left arm | 133.3 | 1 | 133.3 | 15.79 | <.01 |
| | Right arm | 77.37 | 1 | 77.37 | 9.16 | <.01 |
| Error | | 608.01 | 72 | 8.44 | | |
| Arm X | Right-handed group | 257.19 | 1 | 257.19 | 56.52 | <.001 |
| | Left-handed group | 18.53 | 1 | 18.53 | 4.29 | ns |
| Error | | 163.86 | 38 | 4.31 | | |

subjects (4.4 vs 5.7 deg; Table 2). For the variable error, there were also group differences which varied depending on the arm being considered: with the left arm, right-handed subjects obtained a significantly smaller error than did left-handed subjects; (4.0 vs 5.1 deg) with the right arm, the left-handed group showed a smaller error than the right-handed group (4.7 vs 5.5 deg).

Tables 3 and 4 also indicate that there was a significant difference between the arms among the right-handed but not the left-handed group. Among right-handed subjects, there was a smaller absolute and variable error with the left than the right arm (Table 2).

In contrast to the above, for the constant error, there was neither a significant main effect for handedness group or for arm nor a significant interaction between these variables. Table 2 shows that, for both groups, the performance of the two arms was nearly identical.

To ascertain whether the group differences in between-arm performance were attributable to only a few subjects in each group or were characteristic of the group as a whole, the number of subjects showing lateral differences or no difference between the arms was tabulated for the absolute (Table 5) and variable (Table 6) error measures. In tabulating these data, between arm

Table 5

Distribution of individual subject comparative arm performance as a function of handedness group: absolute error.

Arm comparison ($\geq 1^\circ$)

| Group | L<R | L>R | L=R |
|---|---|---|---|
| Right-handed | 18 | 0 | 2 |
| Left-handed | 0 | 6 | 14 |
| *p* | <.01 | ns | <.01 |

Arm comparison ($\geq 2^\circ$)

| | L<R | L>R | L=R |
|---|---|---|---|
| Right-handed | 11 | 0 | 9 |
| Left-handed | 0 | 1 | 19 |
| *p* | <.01 | ns | <.01 |

Arm comparison ($\geq 3^\circ$)

| | L<R | L>R | L=R |
|---|---|---|---|
| Right-handed | 3 | 0 | 17 |
| Left-handed | 0 | 0 | 20 |
| *p* | ns | ns | ns |

Table 6

Distribution of individual subject comparative arm performance as a function of handedness group: variable error.

Arm comparison ($\geq 1^{\circ}$)

| Group | L<R | L>R | L=R |
|---|---|---|---|
| Right-handed | 15 | 1 | 4 |
| Left-handed | 1 | 4 | 15 |
| *p* | <.01 | ns | <.01 |

Arm comparison ($\geq 2^{\circ}$)

| | L<R | L>R | L=R |
|---|---|---|---|
| Right-handed | 9 | 0 | 11 |
| Left-handed | 0 | 1 | 19 |
| *p* | <.01 | ns | <.01 |

Arm comparison ($\geq 3^{\circ}$)

| | L<R | L>R | L=R |
|---|---|---|---|
| Right-handed | 3 | 0 | 17 |
| Left-handed | 0 | 0 | 20 |
| *p* | ns | ns | ns |

differences of at least 1°, 2° or 3° were considered and analyzed separately. In the right-handed group, a majority of subjects showed a smaller absolute and variable error with the left than the right arm when a difference of at least 1° or 2° defined a difference. In the left-handed group, a larger number of subjects showed a smaller absolute error with the right than the left arm when a difference of at least 1° was used to define a difference. For the variable error, a majority of left-handed subjects showed no difference between the arms, regardless of which criterion difference value was applied. Separate chi-square analyses perfomed on these data indicated that there was a significant difference in the distribution of arm advantage between handedness groups (for absolute error: $X^2_{(1^\circ)}$ $(2)=17.57$, $p<.01$; $X^2_{(2^\circ)}$ $(2)=10.26$, $p<.01$, for variable error: $X^2_{(1^\circ)}$ $(2)=13.82$, $p<.01$; $X^2_{(2^\circ)}$ $(2)=12.14$, $p<.01$)

The proportion of subjects showing a smaller absolute and variable error with the left than the right arm was significantly greater in the right than the left-handed group when 1° or 2° was used to define a between-arm difference ( $Z_{(1^\circ)}=5.72$, $p<.01$; $Z_{(2^\circ)}=3.87$, $p<.01$ for absolute error, $-Z_{(1^\circ)}=4.52$, $p<.01$; $Z_{(2^\circ)}=3.40$, $p<.01$ for for variable error). In contrast, a significantly greater proportion of left than right-handed subjects showed no difference between the arms at these same criterion difference values (for absolute error: $Z_{(1^{o})}=3.87$, $p<.01$; $Z_{(2^{o})}=3.45$, $p<.01$, for variable error-: $Z_{(1^{o})}=3.45$, $p<.01$; $Z_{(2^{o})}=2.92$, $p<.01$). Thus, taken together, the various frequency analyses were consistent with the grouped data analyses in showing a left arm superiority among right-handed subjects and no difference between the arms among left-handed subjects.

Although the grouped data analysis of the constant error failed to reveal a significant handedness x arm interaction, it was, nevertheless, possible that an analysis of the individual subject data would show between arm differences. Therefore, the number of subjects in each handedness group either showing lateral differences or no difference in constant error between the arms was tabulated (Table 7). A chi-square analysis failed to reach significance($X^2_{(1^{o})}(2)=2.71$, $p>.10$) indicating that the between-arm performance pattern was not different for the two handedness group. Thus, once again, there was consistency between the individual and grouped data.

Varying the mode of initial movement (active vs passive) did not produce significant differences for any of the response measures. Tables 8 & 9 show the mean absolute, and variable error as a function of arm,

Table 7

Distribution of individual subject comparative arm performance as a function of handedness group: constant error.

Arm comparison ($\geq 1^{\circ}$)

| Group | $L<R$ | $L>R$ | $L=R$ |
|---|---|---|---|
| Right-handed | 7 | 5 | 8 |
| Left-handed | 4 | 4 | 12 |
| p | ns | ns | ns |

Table 8

Mean absolute error (deg) as a function of arm, handedness group and mode of initial movement.

| Group | Mode | Arm | | | |
|---|---|---|---|---|---|
| | | Right | Left | t | p |
| Right-handed | Active | | | | |
| | $\bar{x}$ | 6.3 | 4.2 | 4.62 | $<.01$ |
| | sd | 1.5 | 1.3 | | |
| | Passive | | | | |
| | $\bar{x}$ | 6.4 | 4.7 | 2.82 | $<.01$ |
| | sd | 1.8 | 1.2 | | |
| Left-handed | Active | | | | |
| | $\bar{x}$ | 5.0 | 5.4 | 0.72 | ns |
| | sd | 1.8 | 1.6 | | |
| | Passive | | | | |
| | $\bar{x}$ | 5.5 | 6.0 | 0.83 | ns |
| | sd | 2.1 | 1.6 | | |

Table 9

Mean variable error (deg) as a function of arm, handedness group and mode of initial movement.

| Group | Mode | Arm | | t | *p* |
|---|---|---|---|---|---|
| | | Right | Left | | |
| Right-handed | Active | | | | |
| | $\bar{x}$ | 5.4 | 4.0 | 3.80 | $<.01$ |
| | sd | 1.4 | 0.8 | | |
| | Passive | | | | |
| | $\bar{x}$ | 5.6 | 4.0 | 3.03 | $<.01$ |
| | sd | 1.9 | 1.3 | | |
| Left-handed | Active | | | | |
| | $\bar{x}$ | 4.6 | 4.9 | 0.83 | ns |
| | sd | 0.9 | 1.3 | | |
| | Passive | | | | |
| | $\bar{x}$ | 4.7 | 5.3 | 1.02 | ns |
| | sd | 1.4 | 1.6 | | |

handedness group and mode of movement presentation. It can be seen that, for the right-handed group, the mean absolute and variable error with the left arm was significantly smaller than that with the right arm and that this was true regardless of whether the initial movements were active or passive. There were no significant interactions between mode of initial movement and the other variables being studied (Appendices D-F).

A significant main effect was found for delay interval for the variable and constant error but not the absolute error. Movements replicated after a 5 sec delay resulted in a smaller variable error and a larger positive constant error than movements replicated after a 20 sec interval. ($VE_{5\ sec}=4.6^{\circ}$, sd=0.8; $VE_{20\ sec}=5.9^{\circ}$, sd=0.7--$CE_{5\ sec}=3.2^{\circ}$, sd=1.1; $CE_{20\ sec}=1.5^{\circ}$, sd=0.8).

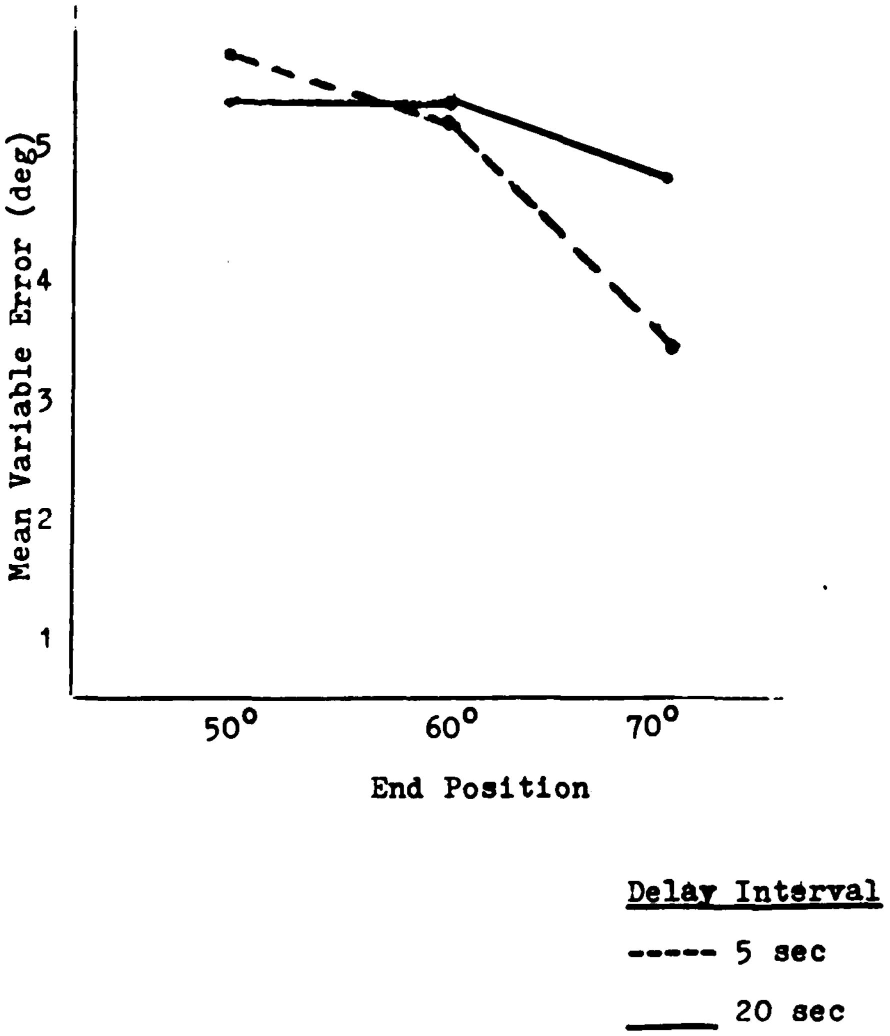
Although the hypothesized interaction between handedness group, arm and delay interval failed to reach statistical significance, there were a number of other interactions involving delay interval that were significant. One was the interaction between delay interval and end-position for variable error and this is illustrated in Figure 2. An analysis of variance for simple main effects (Table 10) revealed that the difference in mean variable error at the two delay intervals reached significance at the $70^{\circ}$ end-position only. At this

Table 10

Analysis of variance of variable error: simple main effects for delay interval and end-position

| Source of Variance | | SS | df | MS | F | p |
|---|---|---|---|---|---|---|
| Delay Interval X | 50° | 12.2 | 1 | 12.2 | 2.6 | ns |
| | 60° | 7.2 | 1 | 7.2 | 1.6 | ns |
| | 70° | 74.0 | 1 | 74.0 | 16.1 | <.001 |
| Error | | 174.8 | 38 | 4.6 | | |
| End Position X | 5 sec | 457.3 | 2 | 228.6 | 40.8 | <.001 |
| | 20 sec | 114.8 | 2 | 57.4 | 10.25 | <.01 |
| Error | | 428.1 | 76 | 5.6 | | |

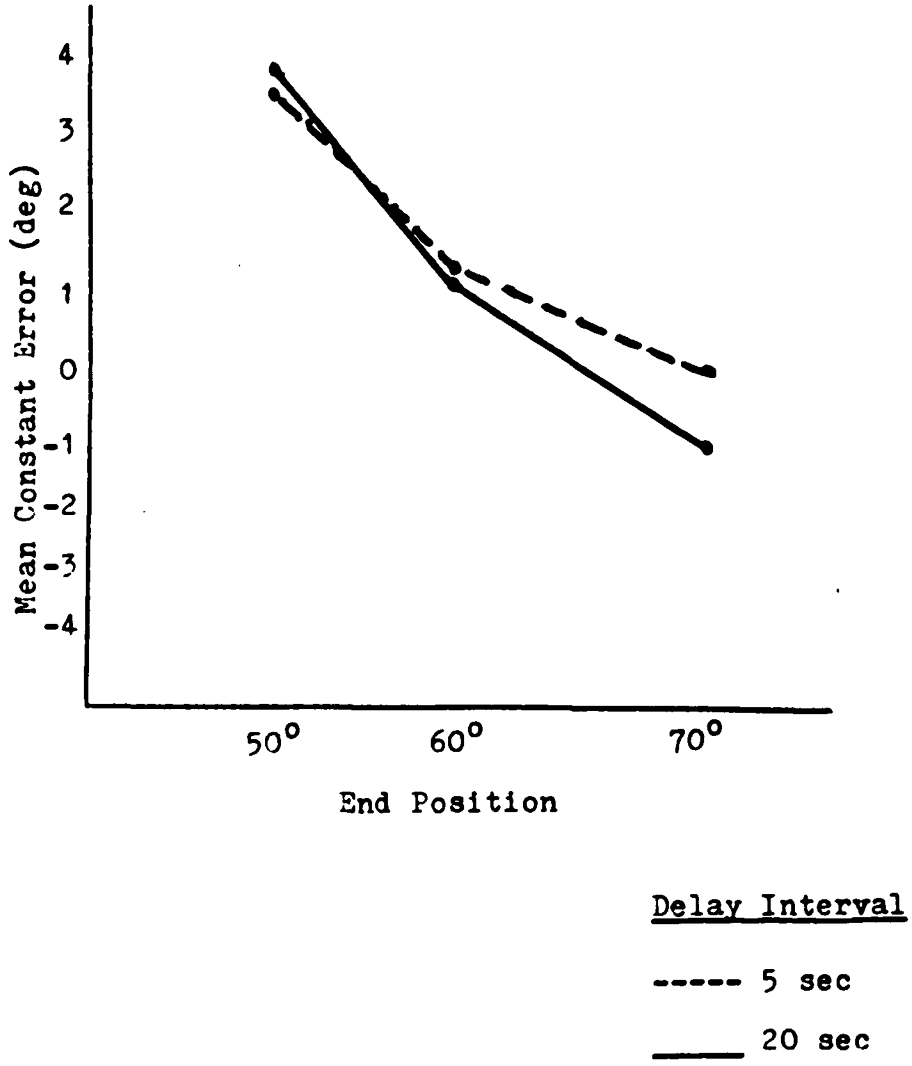
Figure 2. Interaction of delay interval and end position: Mean variable error.



position, movements replicated after a 20 sec interval resulted in a larger variable error than movements replicated after a 5 sec interval. Table 10 also indicates that, at both delay intervals, there was a significant end-position effect. The variable error at the 70° end-position was significantly smaller than the error at the other two end-postions, which did not differ from each other (Tukey's B multiple comparison test).

Two interactions involving delay interval reached significance for the constant error. One was the delay interval x end-position interaction illustrated in Figure 3. At the 60° and 70° positions, a more positive constant error (increased overshooting) was obtained after a 5 sec than a 20 sec delay interval. An analysis of variance for simple main effects (Table 11), however, indicated that the difference between delay intervals was significant at the 70° end-position only, and that, there was a significant end-position effect at both delay intervals, but the effect varied depending upon the interval. At the 5 sec interval, there was a significantly larger constant error at the 50° end-position than at the other two end-positions, which did not differ from each other. For the 20 sec delay interval, the constant error at each end-position differed significantly from the error obtained at the other two positions. Nevertheless, at both intervals a similar trend was

Figure 3. Interaction of delay interval and end position: Mean constant error.



## Table 11

**Analysis of variance of constant error: simple main effects for delay interval and end-position.**

| Source of Variance | | SS | df | MS | F | p |
|---|---|---|---|---|---|---|
| Delay Interval X | 50° | 8.25 | 1 | 8.25 | 0.92 | ns |
| | 60° | 16.41 | 1 | 16.41 | 1.83 | ns |
| | 70° | 1094.01 | 1 | 1094.01 | 121.82 | <.001 |
| Error | | 969.99 (a) | 108 (b) | 8.98 | | |
| End Position X | 5 sec | 595.92 | 2 | 297.96 | 27.36 | <.001 |
| | 20 sec | 5132.56 | 2 | 2566.28 | 235.65 | <.001 |
| Error | | 1568.98 (a) | 144 (b) | | | |

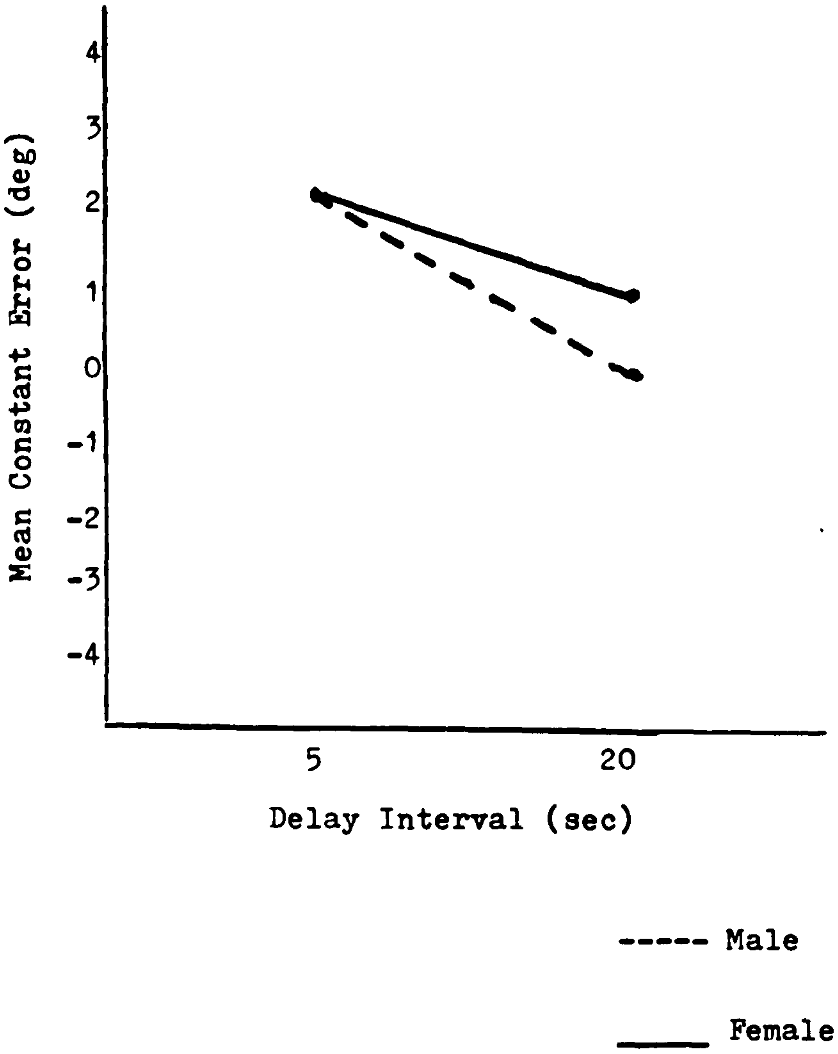
(a) pooled error term

(b) pooled degress of freedom

evident in that the constant error decreased as a function of increases in the distance between the start and end-position. The other significant interaction, delay interval x gender, is illustrated in Figure 4. It can be seen that for both men and women a larger positive constant error was found after the 5 sec than the 20 sec delay interval. Analysis of variance for simple main effects (Table 12) showed that the difference between the two intervals was significant for both men and women. Table 12 also revealed that there was no significant difference between men and women at either delay interval.

For all three response measures, the main effect for gender failed to reach statistical significance and there was no significant interaction effects between gender and handedness group or arm. However, since one of the hypotheses of this study predicted a gender difference in performance among right-handed subjects, a further analysis seemed justifiable. Tables 13 & 14 show the mean absolute and variable error, respectively, as a function of handedness arm group, and gender. It can be seen that, among right-handed subjects, both men and women showed a smaller absolute and variable error with the left than the right arm, however, the difference between the arms reached significance only for the women. For the left-handed group, men and women showed no dif-

Figure 4. Interaction of delay interval and gender: Mean constant error.



## Table 12

Analysis of variance of constant error: simple main effects for delay interval and gender

| Source of Variance | | | | | | |
|---|---|---|---|---|---|---|
| Delay Interval X | Male | 369.92 | 1 | 369.92 | 42.27 | <.001 |
| | Female | 77.38 | 1 | 77.38 | 8.84 | <.01 |
| Error | | 315.01(a) | 36(b) | 8.75 | | |
| Gender X | 5 sec | 1.2 | 1 | 1.2 | 0.01 | ns |
| | 20 sec | 85.9 | 1 | 85.9 | 0.66 | ns |
| Error | | 9397.23 | 72 | 130.51 | | |

(a) pooled error term

(b) pooled degrees of freedom

## Table 13

Mean absolute error (deg) as a function of arm, handedness group and gender.

| Group | Gender | Arm | | t | p |
|---|---|---|---|---|---|
| | | Right | Left | | |
| | Male | | | | |
| | $\bar{x}$ | 6.4 | 4.9 | 2.59 | ns |
| | sd | 2.1 | 1.4 | | |
| Right-handed | Female | | | | |
| | $\bar{x}$ | 6.3 | 4.0 | 5.34 | $<.01$ |
| | sd | 0.8 | 1.7 | | |
| | Male | | | | |
| | $\bar{x}$ | 4.7 | 5.2 | 1.22 | ns |
| | sd | 1.1 | 1.4 | | |
| Left-handed | Female | | | | |
| | $\bar{x}$ | 5.8 | 6.2 | 0.68 | ns |
| | sd | 2.0 | 1.6 | | |

Table 14

Mean variable error (deg) as a function of arm, handedness group and gender.

| Group | Gender | Arm | | t | p |
|---|---|---|---|---|---|
| | | Right | Left | | |
| | Male | | | | |
| | $\bar{x}$ | 5.2 | 4.2 | 2.56 | ns |
| | sd | 1.1 | 1.3 | | |
| Right-handed | Female | | | | |
| | $\bar{x}$ | 5.8 | 3.8 | 3.40 | <.01 |
| | sd | 2.0 | 1.6 | | |
| | Male | | | | |
| | $\bar{x}$ | 4.7 | 5.0 | 0.57 | ns |
| | sd | 1.6 | 1.3 | | |
| Left-handed | Female | | | | |
| | $\bar{x}$ | 4.7 | 5.2 | 1.43 | ns |
| | sd | 0.8 | 1.3 | | |

ference in performance between the arms.

A significant interaction was found between gender and end-position for the variable error measure, which is illustrated in Figure 5. An analysis of variance for simple main effects (Table 15) revealed that the gender difference in performance reached significance at the 50° end-position only. At this position, men obtained a smaller variable error than did women. Furthermore, as shown in Table 15, there was a significant position effect for both men and women. For men, there was a smaller variable error at the 70° end-position than at the other two positions; for women, the variable error at each position differed from that found at the other positions (Tukey's B multiple comparison test). Nevertheless, the performance trend for men and women was similar, in that the variable error decreased as the distance between the start and end-position increased.

Although there was no main effect for arm for the constant error, there was a significant interaction between arm and end-position and this is illustrated in Figure 6. An analysis of variance for simple main effects (Table 16) indicated that the difference between the errors for the right and left arm at the 70° end-position came close to, but did not reach, statistical significance. At this position, the right arm showed a

Figure 5. Interaction of gender and end position: Mean variable error.

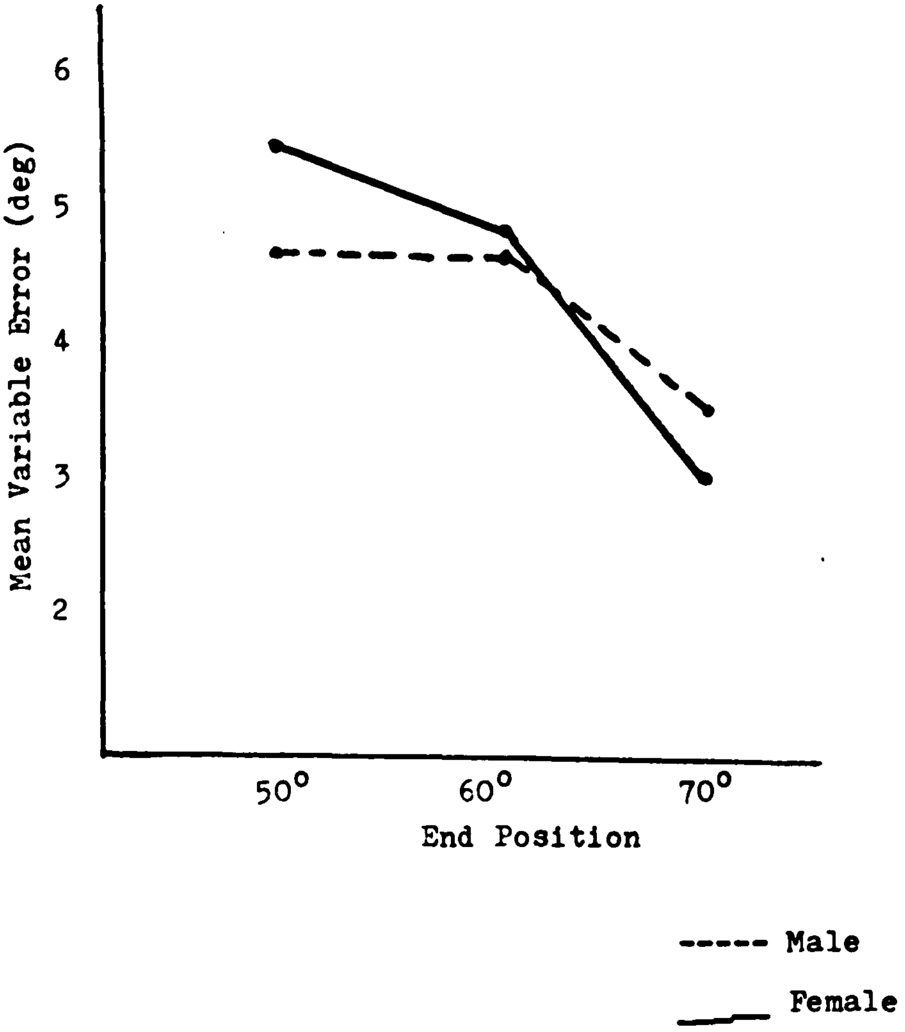


Table 15

Analysis of variance of variable error: simple main effect for gender and end-position.

| Source of Variance | | SS | df | MS | F | p |
|---|---|---|---|---|---|---|
| Gender X | $50^{\circ}$ | 54.4 | 1 | 54.4 | 7.0 | $<.01$ |
| | $60^{\circ}$ | 0.7 | 1 | 0.7 | 0.08 | ns |
| | $70^{\circ}$ | 21.36 | 1 | 21.36 | 2.74 | ns |
| Error | | (a) 841.51 | (b) 108 | 7.79 | | |
| End Position X | Males | 119.03 | 1 | 119.01 | 21.60 | $<.001$ |
| | Females | 450.98 | 1 | 450.98 | 81.84 | $<.001$ |
| Error | | 397.36 | 72 | 5.51 | | |

(a) pooled error term

(b) pooled degrees of freedom

Figure 6. Interaction of arm and end position: Mean constant error.

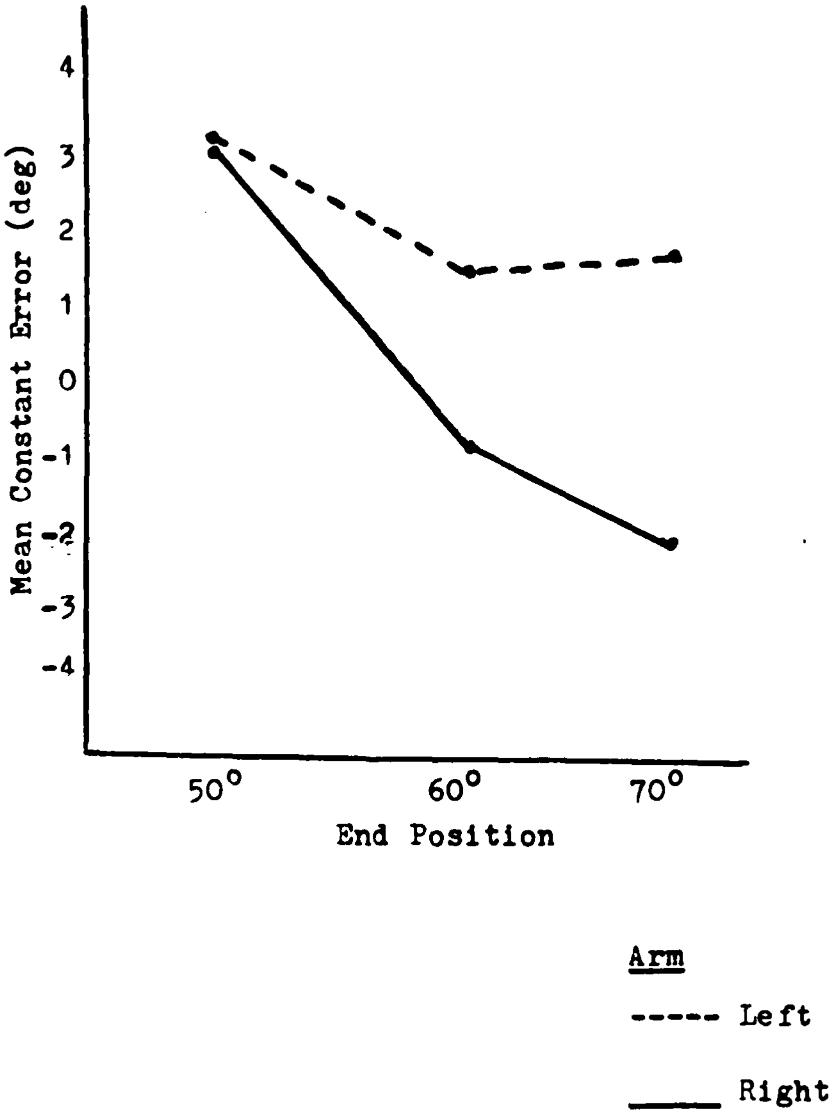


Table 16

Analysis of variance of constant error: simple main effects for arm and end-position.

| Source of Variance | | SS | df | MS | F | p |
|---|---|---|---|---|---|---|
| | 50° | 15.81 | 1 | 15.81 | 1.05 | ns |
| Arm X | 60° | 8.55 | 1 | 8.55 | 0.57 | ns |
| | 70° | 88.53 | 1 | 88.53 | 5.90 | ns |
| Error | | 1620.55 (a) | 108 (b) | 15.0 | | |
| | Right arm | 3098.3 | 2 | 1549.15 | 167.5 | <.001 |
| End-Position X | | | | | | |
| | Left arm | 1358.9 | 2 | 679.47 | 73.5 | <.001 |
| Error | | 1332.69 (a) | 144 (b) | 9.25 | | |

(a) pooled error term

(b) pooled degrees of freedom

small negative constant error while the left arm showed a small positive error. Table 16 also shows that there was a significant effect for end-position with both arms. A multiple comparison test (Tukey's B) indicated that the constant error at the $50^{\circ}$ end-position was significantly larger than the error at the other two end-positions, and that these failed to differ significantly from each other.

A significant main effect was found for end-position on each of the response measures. Table 17 shows the mean absolute, variable and constant error as a function of end-position. The error at each position was significantly different from the error obtained at the other positions (Tukey's B multiple comparison test).

To determine whether arm differences in absolute and variable error for individual subjects were stable within the time frame of the experimental session, a between-arm difference score was tabulated for each measure for trials in the first vs the second half of the session (Tables 18 & 19). Correlation coefficients computed on these scores were statistically significant ($r = .64$, $p < .01$ for absolute error; $r = .54$, $p < .01$, for variable error) suggesting that arm differences for individual subjects were fairly stable, at least over the time span of the session.

Table 17

Mean absolute, variable and constant error (deg) as a function of end-position

| End-Position | | Absolute Error | Variable Error | Constant Error |
|---|---|---|---|---|
| 50° | $\bar{x}$ | 6.3 | 5.6 | 3.4 |
| | sd | 1.4 | 0.8 | 0.9 |
| 60° | $\bar{x}$ | 5.5 | 5.0 | 1.2 |
| | sd | 0.7 | 0.5 | 1.2 |
| 70° | $\bar{x}$ | 4.6 | 3.8 | -0.5 |
| | sd | 0.9 | 1.1 | 0.8 |

Table 18

Individual subject between-arm difference (L-R) in absolute error for trials in first and second half of experimental session.

| | Handedness group | | | |
|---|---|---|---|---|
| | Right | | Left | |
| Subject | First Half | Second Half | First Half | Second Half |
| 1 | -1.9 | -2.4 | -0.5 | -0.7 |
| 2 | -1.6 | -1.9 | 1.4 | -1.9 |
| 3 | -1.2 | -2.9 | 0.7 | -1.1 |
| 4 | -3.8 | -1.1 | 1.1 | 0.5 |
| 5 | 1.4 | -3.1 | 0.9 | 2.5 |
| 6 | -1.4 | -1.5 | 1.5 | 0.5 |
| 7 | -2.2 | -1.8 | 0.4 | 1.6 |
| 8 | -0.8 | -1.5 | -0.8 | 0.9 |
| 9 | -2.1 | -4.6 | -1.1 | 0.1 |
| 10 | -0.4 | -3.1 | -0.9 | 1.6 |
| 11 | -1.7 | 0.7 | 1.0 | 1.9 |
| 12 | -5.0 | -3.5 | -0.7 | 1.1 |
| 13 | -3.8 | -0.3 | -1.0 | -1.9 |
| 14 | -2.7 | -1.4 | 0.9 | -4.6 |
| 15 | -0.5 | -2.3 | 1.0 | 2.5 |
| 16 | -1.2 | -2.0 | 0.1 | 0.2 |
| 17 | -1.2 | -2.2 | -0.1 | 0.7 |
| 18 | -2.9 | -2.0 | 3.7 | 2.2 |
| 19 | -3.2 | -3.9 | 0.1 | 1.7 |
| 20 | -4.0 | -0.9 | -1.1 | 0.5 |
| $\bar{x}$ | -2.0 | -2.1 | 0.3 | 0.4 |

Table 19

Individual subject between-arm difference (L-R) in variable error for trials in first and second half of experimental session.

| | Handedness group | | | |
|---|---|---|---|---|
| | Right | | Left | |
| Subject | First Half | Second Half | First Half | Second Half |
| 1 | 1.2 | 1.5 | -0.2 | 0.7 |
| 2 | -4.0 | -1.2 | 0.0 | -0.8 |
| 3. | 0.1 | 1.5 | 0.5 | 0.0 |
| 4 | -1.6 | -2.7 | 0.3 | 1.1 |
| 5 | -2.1 | -1.7 | -1.1 | 0.5 |
| 6 | -0.1 | -3.4 | -0.5 | 0.7 |
| 7 | -0.7 | -2.0 | 0.4 | 2.3 |
| 8 | -3.0 | -2.5 | 0.2 | -0.9 |
| 9 | -2.0 | -0.8 | -0.4 | 0.8 |
| 10 | 0.7 | -0.2 | 0.3 | -2.3 |
| 11 | -0.7 | -0.7 | -0.5 | -0.5 |
| 12 | -2.4 | -1.6 | 0.6 | -0.6 |
| 13 | -3.7 | -1.9 | -0.2 | 0.3 |
| 14 | -4.2 | -2.0 | 1.1 | -0.4 |
| 15 | -4.1 | -1.6 | 2.4 | 1.3 |
| 16 | -2.6 | -0.6 | -1.6 | 0.5 |
| 17 | -3.6 | -2.7 | 0.6 | 0.8 |
| 18 | -0.3 | 0.3 | 3.5 | 1.7 |
| 19 | -0.4 | 0.1 | 1.9 | 0.7 |
| 20 | -3.1 | -2.8 | 0.1 | 0.2 |
| $\bar{x}$ | -2.0 | -1.3 | 0.4 | 0.3 |

In summary, the analysis of variance of the absolute error yielded significant main effects for arm and end-position. For the variable and constant error, significant main effects were found for delay interval and end-position. The interaction between handedness group and arm reached statistical significance for the absolute and variable error but not for the constant error. This interaction reflected the fact that a smaller error was obtained on movements replicated with the left than the right arm among right but not left-handed subjects. Other interactions reaching significance were arm x end-position and delay interval x gender for the constant error; gender x end-postion for the variable error; delay interval x end-position for both the constant and variable error. Analyses of individual subject data (chi-square) yielded results consistent with the analyses of grouped data. In the right-handed group, a majority of subjects showed smaller absolute and variable error with the left than the right arm, while in the left-handed group, a majority of subjects showed no difference between the arms. Moreover, the proportion of subjects showing a smaller absolute and variable error with the left than the right arm was significantly greater in the right than the left-handed group, whereas a significantly greater proportion of left than right-handed subjects showed no difference between the arms.

# CHAPTER 4

# DISCUSSION

The major finding of this study was that lateral differences on a non-visually guided horizontal arm movement replication task depended on the handedness of subjects. Among right-handed adults, greater accuracy, as revealed by a smaller absolute and variable error, was found for movements replicated with the left than the right arm. In contrast to this, among left-handed adults, no difference in performance was found between the arms on any of the dependent measures. Inasmuch as performance on the task used in this study presumably reflects one aspect of kinesthetic sensitivity, position sense, the above results support the conclusion that there are lateral differences in kinesthesis among right but not left-handers.

Acceptance of the above conclusion rests heavily on the assumption that kinesthetic cues rather than other somatosensory cues (i.e., tactile) mediated performance. It is conceivable that in performing the present movement task other somatosensory cues, such as those associated with the stretching of skin, might have had some influence on movement replication accuracy. Moreover, Cohen (1957) has pointed out, the difficulty of isolating kinesthetic stimuli for position sense from other somatosensory stimuli. Despite this, the results of studies investigating the contribution of tactile stimuli on positioning tasks suggest that these cues have little or no influence on task performance (Cohen, 1957; Sarnoff & Arrowhead, 1965). Moreover, Weinstein (1968) reported finding greater tactile sensitivity (two-point discrimination) on the right than the left shoulder of right-handed adults. In light of this finding, if tactile cues were indeed important in the performance of the arm movement task employed in this study, then a right rather than a left arm advantage would have been expected.

The fact that all of the movements made in this study were horizontal and were directed toward the midline (adductive) raises the issue of the generalizability of the present results to other types of movement (i.e., vertical or abductive movements). A review of the literature failed to reveal studies which specifically investigated lateral differences on a movement task requiring the replication of abductive movements. However, Christina (1967), and Phillip and Summers (1954) did find a left arm advantage on a vertical arm movement replication task. Furthermore, in an unpublished pilot study conducted by this investigator, a left arm advantage was found on a vertical arm movement task similar to the one used in the present study.

## Interpretation of findings: Right-handers.

As with all performance asymmetries found in non-clinical populations, the present findings for right-handers are open to several interpretations. These generally fall into two major categories: 1) those based on the operation of peripheral mechanisms; 2) those positing the operation of central processing mechanisms. A number of alternative interpretations in each of these categories will be considered.

One interpretation, involving a peripheral mechanism, is that the performance asymmetry found in this study is related to the differential use of the two arms. This interpretation is similar to the suggestion that greater use of one hand (right) results in greater callus formation on this hand, and that this accounts for the greater pressure sensitivity found on the other hand (left) of right-handers (Semmes, et. al., 1960). For an interpretation such as this to apply, it would have to be shown that greater use of the right arm reduces either or both the quality and/or quantity of kinesthetic signals coming from that arm.

There is evidence of differences in muscular development between the two arms. On tasks requiring strength, right-handed individuals perform better with their right than their left arm (Provins, 1966). Furthermore, a right arm advantage has been found on tasks involving rapid movements, such as tapping (Provins, 1966). There is no evidence, however, suggesting that differences in muscular development *per se* affect kinesthetic sensitivity. On the contrary, studies of motor and sensory development have shown that, despite marked increases in muscular development throughout childhood, there is a relatively little, if any, change in kinesthetic sensitivity as a function of age (Hermelin and O'Connor, 1975).

A further argument against the interpretation that differential use of the two arms underlies lateral differences in kinesthetic sensitivity is that a similar mechanism should have resulted in a right arm advantage among left-handed subjects. This was not the case, however. Left-handed subjects showed no difference in accuracy or consistency of replication between the arms.

A second interpretation involving peripheral factors is that systematic lateral differences in speed, acceleration or duration of movements may have occurred either during the initial or replication movements, and that these may have mediated in differential accuracy of the two arms. There are three reasons for questioning this interpretation. First, one movement parameter, duration, was monitored during the practice movements and no systematic differences between the two arms were found in either right or left-handed subjects. (Table 1).

Second, there is evidence suggesting that differences on two movement parameters, speed and acceleration, do not significantly affect movement replication accuracy (Martenuik, Shields and Campbell, 1972). Third, and perhaps most importantly, the lack of a difference between the arms of left-handed subjects is not consistent with this explanation. Nevertheless, the fact that movement parameters were not monitored or controlled during either the initial or replication movements leaves open the possibility that between-arm differences on one or more of these parameters may have contributed to the performance asymmetry among right-handed subjects.

Turning to interpretations based on central mechanisms, the most frequently expressed views assert that performance asymmetries found in non-clinical populations reflect functional differences between the two hemispheres. According to these interpretations, a right side performance advantage occurs on tasks requiring functions for which the left hemisphere is specialized; a left side advantage occurs on tasks based upon functions subserved primarily by the right hemisphere. Therefore, the left arm advantage among right-handed individuals found in the present experiment might have occurred, as a result of specialization of the right hemisphere for one or more aspects of the arm movement replication task employed.

tance), the start position for the initial and replication movements was always different. Furthermore, changing the start position of the two movements, reduced the usefulness of non-kinesthetic cues (i.e., counting) for purposes of controlling replication movement.

It seems reasonable to assume that, subjects had to make a judgement regarding the location of their arms at the predetermined end-positions, thus making this a kinesthetically mediated spatial task. If this was indeed the case, then the aforementioned right hemisphere specialization for spatial judgements, which has been amply demonstrated in the visual modality, might have conferred an advantage to the left arm. The validity of this interpretation depends on whether subjects did indeed encode and store kinesthetic information relating to movement end-position. Relevant to this issue are the findings of physiological studies which suggest that there are neural mechanisms available for the encoding of kinesthetic cues associated with limb position. Boyd and Roberts (1953), studying the knee joint of the cat, reported that there is a characteristic discharge frequency of receptors for particular joint positions and rates of limb movement. Mountcastle, Poggio and Werner (1963) manipulated the knee joint of monkeys and found that some neurons in the thalamic ventrobasal nuclei

In considering the arm movement replication task used in this study, it seems likely that there were two aspects of the task, in particular, for which the right hemisphere might be specialized; 1) the spatial component and 2) the kinesthetic processing component.

There is considerable evidence indicating a right hemisphere specialization for the processing of spatial information. For example, in the visual modality, on tasks requiring spatial judgements or an appreciation of spatial relations, right-handed adults frequently show a LVF performance advantage (Benton, 1969; Berlucci, 1975; Kimura, 1969; Kimura & Durnford, 1974; McGlone & Davidson, 1973; Umilta, et. al., 1974; Warrington, 1969; Warrington & Rabin, 1970). Moreover, patients with lesions of the right hemisphere typically show greater impairment on spatial tasks (e.g., dot localization) than do patients with lesions of the left hemisphere (Benton, 1969; Carmon & Benton, 1969; Corkin, 1965; DeRenzi, Faglioni & Scotti, 1968; Faglioni, Scotti & Spinnler, 1971; Hanney & Malone, 1976).

On the task employed in the present study, subjects were instructed to replicate, without visual guidance, arm movements to various locations. To increase the likelihood that subjects would utilize kinesthetic cues associated with the end-position of their arm and not other kinesthetically mediated movement cues (i.e., disfired maximally when the limb is fully extended while others fired maximally when the limb is fully flexed. Similarly, Mountcastle and Powell (1959), found a rather precise relation between the activity of cortical neurons and changes in joint angle.

The mere demonstration that there is a transduction followed by a central reception of kinesthetic information about limb position does not, by itself, provide the necessary evidence that this information is stored centrally or that it is used in movement replication. For this type of evidence it is necessary to turn to behavioral studies that have focused on identifying and isolating those kinesthetic cues which are stored in short-term memory and which provide a basis for movement control.

Marteniuk, Shields and Campbell (1972) compared the accuracy of movement replication under conditions where kinesthetic cues for either movement end-position or movement extent were made reliable. They found greater accuracy when cues for end-position as compared to extent of movement were reliable, and concluded that movement extent was not as precisely codable in short-term memory. Marteniuk and Roy (1972) assessed the influence that random, passively imposed movements had on the replication accuracy of movements to various positions and of varying extents. They reasoned that if information about movement extent was not as precisely coded in memory as was end-position information, then random movements imposed following the presentation of a standard extent of movement should have little or no effect on the accuracy of movement replication. Their results were consistent with this prediction, leading the authors to conclude that, at least for linear movements, position cues provide the most reliable form of information which can be stored in short-term memory.

The above cited findings have figured prominently in at least one theory advanced to explain the mechanisms of movement production and control. Although a detailed discussion of this theory would not be relevant here, one key concept of this theory will be elaborated upon since it provides a possible explanation for the results of this study.

The "target" theory, which was originally proposed by MacNeilage (1972) to explain the mechanism for movement control in speech production has, more recently, been expanded to explain movement production and control in general (Russell, 1976). Central to this theory is the idea that information about the end-position of a movement, which initially emanate from various sense receptors (e.g., kinesthetic, visual), is transformed in the central nervous system into a spatial code and is stored as a point within a three dimensional "space coordinate system". The theory goes on to suggest that this stored spatial location information is the only information needed for the generation of novel movements or for the replication of prior movements. Given that the end-position for movement is stored in memory, the motor system would be controlled by any discrepancy between the current end-position and the desired end-position. It is believed that a movement control mechanism such as this would have the advantage of freeing the motor system from reliance on either stored motor commands or on storage of the sensory consequences of movements (Russell, 1976).

Actually, the idea that there is a neural mechanism subserving a spatial reference system is not new. Lashley (1951) had proposed the existence of such a mechanism to explain man's ability to perform serial actions. Specifically, in relation to movements, Lashley stated,

> Their (spatial reference systems) influence prevades the motor system so that every gross movement of limb or body is made with reference to the space system. The perception from the distance receptors, vision, hearing and touch are also constantly modified and referred to this same space coordinates. The stimulus is there, in a definite place, it has definite relation to the position of the body and it shifts with respect to the general orientation, with changes in body posture...

Although Lashley specifically advanced the idea of space coordinating systems to explain serial actions, the above quote suggests that a mechanism such as this might be important for understanding many other spatial abilities. Furthermore, if it is assumed that, one of the functions of the space coordinating systems is to integrate information relating to the position or changes in position of body segments, then these systems might be crucial for understanding the concept of body schema. Critchley (1953) defined body schema as an imaginal entity, constructed from afferent impulses, which subserves body awareness in general and, more specifically, awareness of changes in the relative location of body parts. Based on this definition, it seems likely that the mechanism(s) subserving the space coordinating systems and body schema is (are) closely related if not identical. Notwithstanding the evidence and utility for postulating, existence of a spatial reference mechanism like the one described by Lashley, the question remains as to whether the neural substrate for this mechanism is localizable within the nervous system. Relevant to this issue are findings from studies of both clinical and non-clinical populations. In studies of patients with unilateral brain lesions, it has been found that those patients with lesions localized to the right hemisphere show greater impairment than do patients with lesions of the left hemisphere, on tasks requiring the precise localization of objects in space (e.g., Hannay & Malone, 1976) and are more likely to show disturbance of body image than are patients with lesions of the left hemisphere (e.g., Hecean, 1969). In studies of non-clinical populations, right-handed individuals are more likely to show a left side performance advantage on tasks involving spatial localization (e.g., Kimura, 1969). Taken together, these findings suggest that the neural substrate subserving a spatial reference mechanism is localized in the right hemisphere of right-handed individuals.

A somewhat different view of the mechanisms underlying movement control has been advanced by Bizzi and Polit (1979). These authors trained monkeys to point to a target light with their forearm, without visual guidance. Following training, and on certain reaching trials, the initial position of the monkey's arm was mechanically displaced immediately after the appearance of the target light and it was stopped just prior to the activation of the motor units in the agonist muscle. Thus, when the motor commands specifying a given forearm movement occurred, the positional disturbance had altered the length of the agonist and antagonist muscles. Despite these changes, it was found that the intended final arm position was always reached accurately, regardless of whether the forearm was displaced further away from, closer to, or even beyond the intended final position. From these findings the authors concluded that the mechanism subserving arm movements specifies, through the selection of an appropriate set of length-tension curves, an equilibrium point between agonist and antagonist muscles that correctly positions the arm in relation to the visual target. Similarly, on the task used in the present study, it is possible that, during the initial arm movement, kinesthetic cues from agonist and antagonist muscles involved in the movement were encoded and stored in short-term memory and that this information was then used to control the replication movement. If this was indeed the case, then the present findings raise the possibility that the substrate of this selection process might be predominately lateralized in the right hemisphere.

Although a right hemisphere specialization for the spatial component of the task used in this study could explain the results obtained, there is another central interpretation that can be offered. To perform the arm movement task, it seems likely that subjects had to process and utilize kinesthetic cues associated with movements. Hence, it is conceivable that, the superior left arm performance of right-handed individuals might reflect a right hemisphere specialization for the processing and/or utilization of kinesthetic information.

Some support for this interpretation comes from studies of patients with unilateral brain injuries. Carmon (1969) reported that, on a finger positioning task where vision was precluded, patients with right hemisphere lesions showed deficits as compared to patients with lesions of the left hemisphere and normal controls. Moreover, as the amount of available kinesthetic information was increased, the difference in performance between the two patient groups also increased. Carmon concluded that the deficit in performance among patients with right hemisphere lesions reflected damage to a right hemisphere mechanism responsible for the utilization of kinesthetic information. Levin (1973) employed a similar task and obtained similar results. Employing a different task, DeRenzi (1971), required patients to explore manually and identify various unseen objects. To minimize the availability of tactile stimuli in performing this task, he instructed them to trace the borders of the objects with one finger only. He found that patients with right hemisphere lesions performed significantly worse than did patients with left hemisphere lesions and interpreted this deficit as reflecting an inability to process kinesthetic information associated with changes in finger direction and position.

Because spatial tasks frequently are used to investigate hemispheric specialization in the somatosensory modality, it is difficult to determine whether the spatial or the kinesthetic processing feature common to these tasks is responsible for the results obtained.

A study by LeDoux, Wilson and Gazzaniga (1977), however, might clarify this issue. These authors noted that, in most studies of commissurotomized patients, right hemisphere specialization was revealed by having subjects perform tasks requiring some type of manual activity. The activity related either to stimulus presentation (Nebes, 1971, 1972; Zaidel and Sperry, 1973) or to response production (Gazzaniga, Bogen and Sperry, 1967; Bogen and Gazzaniga, 1965). Based on this, LeDoux, et. al. hypothesized that the manual component of "spatial" tasks was more important than the spatial aspect in producing evidence for right hemisphere specialization. To test this hypothesis, they modified several spatial tasks (e.g., block design, wire figures, etc.) to eliminate the manual activity while maintaining their spatial features. They found that eliminating the manual activity also eliminated the left side advantage typically found on these "spatial" tasks. The results of this study, which the authors interpreted as supporting the view that right hemisphere specialization for spatial tasks depends heavily on the manual component found on these tasks, are also compatible with another interpretation. Elimination of manual activity also eliminated the kinesthetic cues associated with manual activity. Thus, the findings of this study are consistent with the conclusion that some processing of kinesthetic information associated with manual activities is important for demonstrating left side/right hemisphere superiority on spatial tasks.

Right hemisphere specialization for the processing of kinesthetic information might provide an explanation for the left side advantage that has been found on other tasks presented through the somatosensory modality. As noted previously, a left side advantage has been found among right-handers not only on non-linguistic, spatial tasks but also on linguistic tasks involving letters of the traditional (Gardner, 1942; Rudel et. al., 1974) and braille alphabets (Hermelin and O'Connor, 1971). These results pose a problem for a model of hemispheric specialization which assumes that linguistic materials are processed better by the left hemisphere and that non-linguistic and spatial materials are processed better by the right hemisphere. However, if it is assumed that the right hemisphere is specialized for the processing of kinesthetic information in general, then the kinesthetic component of most somatosensory tasks might explain why a left side advantage is found regardless of the nature of the task.

Although most of the somatosensory tasks used to investigate hemispheric specialization of function require the processing of kinesthetic information, this is not true for all of them. In a few studies, somatosensory tasks have been employed which involved the passive presentation of stimuli (Benton, Levin and Varney, 1973; Carmen and Benton, 1969). On these tasks a left side/right hemisphere advantage has also been found, which suggests that kinesthetic processing is a sufficient but not necessary condition for demonstrating right hemisphere specialization of function.

In conclusion, it seems likely that the left arm advantage found in this study reflects a right hemsphere specialization for either the spatial or kinesthetic processing requirements of the task. It is not possible, based on the results of this study alone, to determine which of these interpretations is correct. However, the kinesthetic processing interpretation might best serve to explain the left side performance advantage found on most tasks presented through the somatosensory modality, even when these tasks involve materials believed to be processed better by the left hemisphere (i.e., linguistic). Finally, it is conceivable that a right hemisphere specialization for both features of the present task combined to produce the marked performance asymmetry among right-handed subjects.

### Interpretation of findings: Left-handers.

In contrast with the abundance of evidence for hemispheric specialization of function found among right-handed individuals, it has been difficult to obtain such evidence among left-handed individuals. In studies of patient populations, for instance, left-handers frequently show similar deficits following lesions of the right or left hemisphere (Hecaen, 1962; Hecaen and Sauget, 1971). Furthermore, in studies of non-clinical populations, left-handers typically show little or no performance asymmetries on tachistoscopic and dichotic listening tasks (Beaumont, 1974; Curry, 1967; Curry & Rutherford, 1967; Satz, Achenbach, Pattishall & Fennel, 1965) or on certain tasks presented through the somatosensory modality (Weinstein & Sersen, 1961). Taken together, these findings are consistent with the conclusion that the brain of left-handed individuals is less lateralized or has a more bilateral representation of function than does the brain of right-handed individuals. Based on this conclusion, it was hypothesized in the present study that no lateral differences would be found in the left-handed group. The results confirmed this hypothesis in that no significant difference was found between the arms on any of the response measures.

Recently, evidence has accumulated suggesting that familial handedness history is an important factor determining the pattern of functional representation in left-handed individuals.

Hardyck and Petrinovich (1977), reported that in fifteen studies in which familial handedness history was as a classificatory variable, ten reported smaller between hemisphere differences for familial left-handers than for non-familial left-handers or right-handed individuals. The authors concluded that bilaterality of cerebral function is present in the left-handed primarily when there is a family history of left-handedness. In the present study, only left-handers having a familial history of left-handedness (at least one left-handed parent) were tested, so that the finding of no lateral difference supports the above conclusion. However, since non-familial left-handers were not included in this study, it is not possible to assess the relative contribution of handedness and familial handedness history to the results.

Despite the evidence cited above, left-handers with a left-handed family background have occasionally been reported to show asymmetry of performance opposite to that found among non-familial left-handers or right-handers (Knox & Boone, 1970; Weinstein & Sersen, 1961; Zurif & Bryden, 1969). In the study by Weinstein and Sersen (1961), it was reported that for left-handers as a group, there were no lateral differences in pressure sensitivity. However, when these subjects were subdivided on the basis of family history of left-handedness, a significant proportion of familial left-handers showed greater pressure sensitivity on the right than the left hand. Among left-handed subjects not having a family history of left-handedness, the pattern of performance was similar to that found among right-handed subjects (i.e., greater sensitivity on the left hand). Weinstein and Sersen also found that those left-handers having a sinistral mother and a dextral father were most likely to show a right side superiority. A trend toward better performance (smaller absolute error) on the right side among left-handers was evident in the present study. Of the twenty left-handed subjects tested, six (31%) replicated arm movements more accurately with their right than their left arm when a between-arm difference of at least $1^{o}$ was considered. Although this proportion was not significantly different than the proportion expected by chance, it is worth noting that none of the left-handed subjects showed better performance with their left than their right arm. Regarding the effect of different parental combinations, of the six left-handed subjects who showed greater accuracy on the right side, two had a sinistral father and a dextral mother; two had both sinistral parents; two had a sinistral mother and a dextral father. Thus, based on these limited data, it appears that different combinations of parental handedness did not influence the pattern of performance .

Another factor which has been found to influence the performance pattern of left-handed subjects is the degree of left-handedness. Satz et. al.,(1965) failed to find lateral differences on a verbal dichotic listening task among left-handed subjects who were strongly left-handed (80% of items on their questionnaire performed with left hand), but did find a right ear advantage among weakly left-handed subjects. Knox and Boone (1970) also found no lateral difference among strongly left-handed subjects. In contrast to these findings, Dee (1971), found that strongly left-handed subjects demonstrated a pattern of ear asymmetry that was indistinguishable from that of right-handed subjects, while weakly left-handed subjects showed no difference in performance between the two ears. In the present study, the fact that 14 of the 20 left-handed subjects indicated that they used their left hand for at least 12 of the 15 items on the handedness questionnaire suggests that the majority of the subjects tested were strongly left-handed. Therefore, the results for left-handed subjects are consistent with the findings of Satz et. al., and of Knox and Boone, that strongly left-handed subjects do not show lateral differences in performance. However, the issue of whether the degree of manual preference is an important factor influencing the pattern of performance of left-handers remains open to question in this study, since no direct comparison between strong and weak left-handers was made. Nevertheless, regarding this factor, Dee (1971) cautioned that significant methodological differences between studies investigating degree of hand preference (e.g., criteria for handedness, characteristics of stimulus materials, method of analysis) could account for the contradictory results reported. He also suggested that a lower reliability of performance for left-hand individuals, might be a significant factor underlying the contradictory findings. The fact that, in the present study, the split-half reliability coefficients for right and left-handed subjects were nearly identical does not, however, support this contention.

### Influence of mode of initial movement.

It was hypothesized that lateral differences in performance would be found among right-handers when the initial movements were made passively but not actively. This hypothesis was based upon the observation that, in two previous studies in which lateral differences on an arm movement replication task were obtained, initial movements were made passively (Christina, 1967; Phillip and Summers, 1954) but in another study where no lateral difference was found, initial movements were made actively (Wallace, 1977). The finding that there was no significant interaction effects between mode of initial movement and arm failed to support this hypothesis. Instead, among right-handed subjects, a significant left arm advantage was found for movements made both passively and actively.

In addition to there being no lateral differences related to mode of initial movement, there was also no main effect of mode of initial movement on accuracy. This finding was at variance with the results of a number of other studies where active movements have been reported to result in more accurate replication than passive movements. (Lloyd & Caldwell, 1965; Marteniuk, 1975; Paillard & Bouchard, 1969). The results of two recent investigations could explain this discrepancy, however. In one, conducted by Roy (1978), subjects were required to replicate movements of varying extents which were of two types: preselected or constrained. In the preselected condition, the subject defined the extent of movements to be replicated, while in the constrained condition, the experimenter defined the extent. For both conditions, movements were made either actively or passively. Roy found that for preselected movements there was no significant difference in accuracy between active and passive movements. In the constrained condition, however, active movements were passive movements. A very different picture emerged in a study by Stelmach, Kelso & Wallace (1975). Stelmach et. al. like Roy, had subjects perform preselected or constrained movements, made either actively or passively. However, in contrast to Roy's study where subjects were required to replicate the extent of a movement, Stelmach et. al. instructed subjects to replicate the end-position of a movement. They found that for the preselected condition, movements were replicated more accurately when the end-position was presented active than passive, while for the constrained condition no difference between active and passive movements was found. To explain their findings, Stelmach et. al. suggested that, for movements where subjects themselves defined the end-position (preselected condition), central monitoring of efferent signals in addition to kinesthetic cues were available and stored in memory, whereas for movements defined by the experimenter (constrained condition) only kinesthetic cues were available for storage in memory. The idea that efferent signals can be monitored centrally and that this information plays a role in movement control has been proposed by others (e.g., vonHolst, 1954). Since, in the present study, subjects were instructed to replicate the end-position of movements which were predetermined (constrained), the finding of no difference between the active and passive modes of movement presentation is consistent with the results reported by Stelmach.

One final point should be made regarding the absence of evidence of a difference between active and passive movements. It is possible that, during the passive movement condition, subjects did not remain completely passive, that is there may have been some muscle activity during this movement condition. Some support for this possibility comes from studies in which muscle activity has been monitored during a supposed passive movement condition (Lloyd & Caldwell, 1965; Roy, 1978). Subjects had great difficulty maintaining complete passivity during passive movements without extended practice and/or close monitoring of muscle activity. In the present study, during the passive movement condition, subjects may have exerted some active motor control and this could explain the lack of a significant difference between the two modes of movement presentation.

### Influence of gender.

While a number of investigators have reported that males frequently perform better than females on tasks involving spatial abilities (Bryden, 1978; Buffery & Gray, 1972; Maccoby & Jacklin, 1974), others have failed to find such an effect (Kimura & Durnford, 1974; Lake & Bryden, 1976). Inasmuch as the task used in the present study involved spatial judgments, it was hypothesized that the performance of males would be superior to that of females, but, in fact, there was a lack of significant main effect for gender, for any of the dependent measures. Thus, it appears that the performance advantage of males on spatial tasks is not a general phenomenon, but is task specific.

On certain spatial tasks it has been found that right-handed men but not right-handed women, show a left side performance advantage. This suggests that there might be a right hemisphere superiority for these tasks among men but not women (Kimura, 1969; McGlone & Davidson, 1973; Witelson, 1976). Based on this it was hypothesized that among right-handed subjects, males would show a difference in performance between the arms whereas females would not. My results did not support this hypothesis. First, the interaction between handedness group and gender was not significant, as would have been predicted from this hypothesis. Second, among right-handed subjects, both males and females showed a similar pattern of performance; that is, a significant left arm advantage for absolute and variable error.

In trying to account for the difference between the results of this study and those of others with regard to gender, two factors seem particularly significant. First, a somatosensory task was used in the present study, whereas in most previous studies reporting gender differences, visual or auditory tasks were employed (Kimura, 1969; Lake & Bryden, 1976). In the few studies where a somatosensory task has been used any gender differences which have been found occurred early in ontogeny (i.e., before age 10) and subsequently faded (Ghent, 1961; Witelson, 1974). The relationship between gender and hemispheric specialization is therefore probably both modality specific and age-related.

Another possible explanation for the discrepancy between the present findings and those of others reporting gender differences relates to the nature of the task. Kimura (1969) suggested that when a task can be performed by either left or right hemispheric mechanisms, men tend to employ right hemisphere non-verbal spatial systems whereas women tend to employ left hemisphere, verbal systems. Intuitively, it is difficult to imagine how kinesthetic information regarding limb position could be encoded through a verbal system. Therefore, the finding that right-handed women showed a pattern of performance identical to that of right-handed men may have been based on the fact that subjects of both sexes had to rely on right hemisphere mechanisms in performing the task.

Although the interaction between handedness group and gender failed to reach statistical significance, it is worth noting that, for the left-handed subjects, the difference in absolute error between men and women approached significance. McGee (1976) compared right and left-handed subjects on a three-dimensional spatial visualization task (Mental Rotation Test). He found a significant gender difference in performance favoring men but pointed out that, when left-handed subjects were eliminated from the data analysis, the gender difference failed to reach significance. In McGee's study the ordering of performance between the four groups of subjects was as follows: left-handed men showed the best performance; this was followed by right-handed men who, in turn, performed better than right-handed women; left-handed women showed the poorest performance. An identical ordering was found in the present study, although none of the differences reached statistical significance.

There were two significant interaction effects involving gender. One was the interaction between gender and end-position for the variable error measure. This interaction reflected the fact that women showed a significant difference in variable error between all three end-positions, while men showed a difference only between the variable error at the 50° and 70° positions. The trend, however, for both groups was similar. The amount of error decreased as a function of increases in the distance from the start to the end-position. The other significant interaction was that between gender and delay interval for the constant error measure. For both men and women there was an increase in the amount of error as a function of increases in delay interval, but the difference in performance as a function of interval was greater for males than females.

### Influence of delay interval.

The influence of time delay on the accuracy of movement replication has been the focus of a number of investigations. Stelmach, Kelso, and Wallace (1975), for example, found significant increases in variable error after a 15 sec unfilled time interval when compared to an immediate replication condition (actually a 3-5 sec delay). They also found that the constant error became less positive (less overshooting) as a function of increasing delay. Other researchers, however, have reported finding no significant retention interval effect for movement tasks requiring replication of the end position of a movement and an unfilled retention interval (Laabs, 1973; Martiniuk, 1977). In the present study, a significant main effect for delay interval was found for both the variable and constant error measures but not for the absolute error measure. For the variable error, increasing delay resulted in increasing error, while for the constant error increasing delay produced a less positive constant error (decrease in the amount of overshooting). These findings, which essentially replicate those reported by Stelmach et. al. (1975), suggest that there is a significant information loss during an unfilled time interval and that this occurs even when the information being retained related to the end-position of a movement.

One theory that has been advanced to explain the spontaneous forgetting of movement information is the "decaying trace" theory (e.g., Adam & Dijkstra, 1966). According to this theory, the execution of a movement results in the formation of a perceptual trace which decays over time. Subsequently, when attempts are made at replication of the original movement, the trace used for comparison purposes has been reduced resulting in a decrease in accuracy. The increase in variable error and decrease in overshooting (smaller positive constant error) as a function of increases in delay interval found in the present study are consistent with this theory.

While increases in variable error as a function of increases in delay interval could be explained by a decaying trace model of motor short-term memory, the findings for the constant error present problems for this model. Figure 4 shows that as the delay interval increased, the constant error for movements to the 70° end-position decreased, a finding that is in line with a decaying trace. For movements to the 50° and 60° end-positions, however, increases in delay interval produced little or no change in constant error. In fact, at the 50° end-position, there was a slight increase in constant error rather than a decrease as the decaying trace model would predict.

A similar effect of delay interval on constant error was reported by Laabs (1973). To explain his results, Laabs proposed an alternative to the decaying trace model of motor short-term memory. This model assumes that replication movements are made in reference to an "average" or "central" movement trace in addition to the decaying trace of the original movement. According to Laabs, this average or central trace is made up of the combination of all movements over the set of movements to be replicated and is thus similar in concept to adaption level (Helson, 1964). The model further assumes that as the memory trace of the original movement decays with increases in delay interval, greater emphasis will be given to the average trace or adaption level during replication. Consequently, with increases in delay there will be an assimilation toward the average or central trace, thus producing a central tendency effect.

The above formulations suggest that the small increase in overshooting at the 50° end-position and the shift from slight overshooting to undershooting at the 70° end-position with increases in delay interval, might reflect a central tendency effect due to the influence on replication movements of a central movement trace.

A recent study by Martinuik (1978) might provide some insight into the possible reasons for the discrepant findings reported in the motor performance literature. Martenuik found that minor methodological alterations on movement replication tasks (e.g., method of returning arm piece to start position) affect results. Moreover, he found that these methodological variables sometimes interact with the independent variables frequently investigated in studies of motor short-term memory (e.g., delay interval).

A significant interaction was found between delay interval and end-position for the variable and constant error measures. For both measures, there was a significant difference in performance between the two intervals at the 70° end-position only. Relevant to these findings is the hypothesis advanced by Stelmach et. al. (1975), that the mechanisms underlying movement replication for short vs long movements may differ. Stelmach et. al. found that movements of varying extents were affected differently by increases in delay interval. To explain this, the authors hypothesized that subjects might use different movement cues (i.e., extent, duration, and end-position) for replicating short vs long movements, and that this could account for the differential effect of delay on movements of varying extents.

In previous studies it has been found that increasing the time interval between the presentation of a stimulus and the requisite response increases the likelihood of observing lateral differences in performance among right-handed individuals (Dee & Fontenont, 1973; Hines & Satz, 1971; Oscar-Berman, Rehbein, Porfiet & Goodglass, 1978). This has led some investigators to conclude that performance asymmetries in normal subjects reflect hemispheric specialization for memory functions rather than perceptual functions (Dee, 1971; Dee & Fontenont, 1973). Others (Gardner et. al., 1977; Witelson, 1974) however, have suggested that increasing the memory demands of a task simply increases the task difficulty and that this is the factor responsible for producing lateral asymmetries in performance. Regardless of which interpretation is correct, it was hypothesized in the present study that increasing the time delay between the presentation of the stimulus (initial movement) and the response (replication movement) would enhance any lateral differences in performance found among right-handed subjects. The lack of a significant interaction between handedness group, arm and delay interval, however, failed to support this hypothesis. In fact, a significant left arm advantage was found at both delay intervals among right-handed subjects. Thus, it was not necessary to increase the demand on memory or increase task difficulty to find lateral differences in performance.

The two delay intervals used in this study (5 and 20 sec) were selected on the basis of findings reported by Dee and Fontenont (1973). These authors reported no visual field differences on a complex form recognition task when subjects responded five seconds after the presentation of a stimulus, but a significant difference between the fields after delays of 10 and 20 seconds. The fact that the task used in the Dee and Fontenont study required the processing of visual information while the task used in the present study involved the processing of kinesthetic information raises the question of whether the intervals selected in the present study were appropriate. It is conceivable that if subjects had been required to replicate movements, after a briefer time delay than was used, a different picture would have emerged. Support for this possibility comes from a study by Wallace (1977), in which right-handed subjects who replicated arm movements to various end-positions after a 2-3 sec delay displayed no difference in performance between the right and left arms.

## Response Measures

In the present study, different results were obtained for each of the response measures. This lack of correspondence between measures was not unexpected since it had been found in other studies (e.g., Laabs, 1973; Stelmach et. al., 1975) and highlights the importance of providing data on all three measures. For instance, had the decision been made to include only data on constant error no lateral difference in performance would have been found.

Notwithstanding the differences in the results between response measures, there were some important similarities, the most notable one being the fact that a left arm advantage was found for both the absolute and variable error. A similar correspondence between these two error measures has been reported by others (e.g., Schutz, 1974) and a possible explanation for it has been offered by Schutz and Roy (1973). Based on an elaborate statistical analysis, these authors concluded that the absolute error statistic is completely dependent on constant and variable error. That is, absolute error is the weighted sum of constant and variable error; and further, that under the condition where the constant error is small, absolute error is largely a measure of variability and as such is equivalent to variable error.

Regarding the issue of the meaning of the different response measures, Laabs (1973) hypothesized that variable and constant error might reflect the operation of two independent processes in motor short-term memory. According to this, variable error provides a measure of the decay of the movement trace in short-term memory while the constant error reflects the independent operation of a response biasing mechanism on the to-be-remembered movement. The fact that a left arm advantage was found for variable error but not for constant error suggests that the mechanism(s) reflected in these performance measures might be differentially lateralized. Those processes involved with the formation and/or retention of a movement trace appear to be predominately mediated by the right hemisphere, whereas the processes responsible for response biasing seem not to be lateralized.

## Issues for Future Study

As is usually the case, the findings of any one study raise many questions in need of further study. In the present study, it was found that normal right-handed adults replicated arm movements more accurately and consistently with their left than their right arm. One explanation for this is based on the premise that a right hemisphere specialization may exist, for either or both the spatial feature and/or for the kinesthetic processing component of the movement replication task. Future research could attempt to separate these two components. If the kinesthetic processing interpretation is correct, then it would be predicted that on tasks requiring the processing of kinesthetic cues but with end-position not a relevant cue, a left arm superiority would be found. This question is presently under investigation in the laboratory where this study was conducted.

No lateral difference was found among left-handed subjects, however, they had to meet a fairly stringent hand preference criterion. Furthermore, only left-handed individuals having a familial history of left-handedness were included. Thus, another question is whether the performance of left-handed subjects applies to left-handers in general or only to those having a family history of left-handedness and who are strongly left-handed.

Increasing the time delay between the initial movement and the replication movement failed to influence the pattern of performance found among right-handed subjects. However, the fact that the replication movements were performed after two delay intervals and that there was no immediate replication condition, leaves the issue of the role of memory in the genesis of performance asymmetries on a kinesthetically mediated task unresolved and in need of further investigation.

# SUMMARY

Right-handed adults replicated horizontal arm movements to predetermined end-positions more accurately with their left than their right arm. This left arm advantage was indicated not only by the results of an analysis of group data but by the finding that a significant majority of right-handed subjects showed superior performance with their left arm. Since the arm movement replication task used presumably provides a measure of position sense which is one aspect of kinesthetic sensitivity, this finding supports the conclusion that there are lateral differences in kinesthesis among right-handed individuals.

To explain these results, two interpretations invoking central mechanisms appear most reasonable. Both have in common the assumption that the performance assymmetry derives from functional differences between the two cerebral hemispheres. They differ, however, in regard to the precise nature of these functional difference. According to one, the left arm superiority reflects the specialized role of the right hemisphere in mediating performance on spatial tasks. The other interpretation suggests that the left arm advantage stems from the superior capacity of the right hemisphere for the processing and utilization of kinesthetic information. It is not possible, based on the evidence from this study, to determine which of these interpretations is correct. However, the latter interpretation is consistent with the left side advantage generally found for tasks presented through the somatosensory modality, even when these tasks involve functions subserved by the left hemisphere (i.e., linguistic). Furthermore, it is conceivable that a combination of these two factors (i.e., the spatial and kinesthetic components of the task) accounted for the obtained results.

No difference in accuracy of replication between the arms was found among left-handed subjects. This is consistent with the conclusion that left-handed individuals display greater bilateral representation of function than right-handed individuals. However, inasmuch as all the left-handed subjects tested had a familial history of left handedness it is not possible to conclude that this applies to left-handers in general, or only to those left-handers with a familial left-handedness history.

This study also investigated the influence of gender, mode of initial movement and delay interval on laterality effects for movement replication. Of these variables, only delay interval produced a significant main effect, and this was found for only variable error. Although there were a number of significant interaction effects, none of these altered the basic findings of a left arm superiority for movement replication among right-handed individuals and no difference between the arms among left-handed individuals.

## Appendix A. Handedness Questionnaire

| | | | |
|---|---|---|---|
| A. Are you right handed or left handed? | R | L | B |
| B. With which hand(s) do you: | | | |
| 1. Write? | R | L | B |
| 2. Draw? | R | L | B |
| 3. Use a tennis racquet? | R | L | B |
| 4. Use a screwdriver? | R | L | B |
| 5. Throw a ball? | R | L | B |
| 6. Use a hammer? | R | L | B |
| 7. Light a match? | R | L | B |
| 8. Use a toothbrush? | R | L | B |
| 9. Hold a knife to carve meat? | R | L | B |
| 10. Use a bottle opener? | R | L | B |
| 11. Use an eraser? | R | L | B |
| 12. Use scissors? | R | L | B |
| 13. Stir a liquid? | R | L | B |

14. Carry books or a book bag? R L B

15. Hold a filled cup or glass? R L B

### C. Familial Handedness

1. Mother's hand preference R L B
2. Father's hand preference R L B

## Appendix B. Sample Data Collection Sheet

Subject Name______________________________Sex____Age____Date__________

Subject Number ____________________________Hand Preference ____________

Calibration: Baseboards_________Stool Height_________Hand Grip_________

Mode of Initial Movement Presentation: Active _____ Passive____

| Trial # | Arm | Initial Start (degrees) | End Position (degrees) | Rep. Start (degrees) | Delay Interval (seconds) |
|---|---|---|---|---|---|
| 1 | L | 10 | 50 | 20 | 20 |
| 2 | L | 20 | 60 | 10 | 20 |
| 3 | R | 10 | 50 | 20 | 20 |
| 4 | L | 20 | 70 | 10 | 5 |
| 5 | R | 20 | 70 | 10 | 5 |
| 6 | R | 20 | 60 | 10 | 20 |
| 7 | L | 10 | 70 | 20 | 5 |
| 8 | L | 20 | 50 | 10 | 20 |
| 9 | R | 10 | 60 | 20 | 5 |
| 10 | L | 10 | 60 | 20 | 5 |
| 11 | R | 20 | 50 | 10 | 20 |
| 12 | R | 10 | 70 | 20 | 5 |
| 13 | L | 10 | 60 | 20 | 20 |
| 14 | R | 20 | 70 | 10 | 20 |
| 15 | L | 10 | 50 | 20 | 5 |

| Trial # | Arm | Initial Start (degrees) | End Position (degrees) | Rep. Start (degrees) | Delay Interval (seconds) |
|---|---|---|---|---|---|
| 16 | R | 10 | 50 | 20 | 5 |
| 17 | R | 10 | 60 | 20 | 20 |
| 18 | L | 20 | 70 | 10 | 20 |
| 19 | R | 20 | 50 | 10 | 5 |
| 20 | L | 20 | 60 | 10 | 5 |
| 21 | R | 10 | 70 | 20 | 20 |
| 22 | L | 20 | 50 | 10 | 5 |
| 23 | L | 10 | 70 | 20 | 20 |
| 24 | R | 20 | 60 | 10 | 5 |

## Appendix C. Task Instructions

The following instructions were read to each subject:

> The task you are about to perform was designed to assess how accurately you can replicate the end-position of movements made with either your right or left arm.
>
> On each trial there will be two movements; the first movement will define the end-position to be replicated, while the second movement will be your attempt at replicating that end-position. The arm tested and the end-position will vary from trial to trial and I will inform you before each trial which arm is to be tested.
>
> The initial movement defining the end-position will be made in one of two ways, either actively or passively. In either condition, once I have indicated the arm being tested you should place that arm on the corresponding armpiece and place your chin on the chin rest. In the active condition, upon hearing the word "Move", begin moving your arm in a slow continuous manner until the armpiece contacts the clamp defining the end-position to be replicated. In the passive condition, upon hearing the word "Move", relax your arm and I will move the armpiece to the clamp. For both conditions, maintain your arm at the end-position until I say the word "Release" at which time you can remove your arm from the armpiece and place it in your lap.
>
> There will be a time delay which will vary from trial to trial. During this delay do not move your arms or remove your chin from the chin rest. Following the appropriate delay I will say the word "Replicate" signalling you to reposition the arm being tested on the armpiece and attempt to return it to the end-position

defined by the initial movement. All replication movements will be made actively. Once you are satisfied that you have reached the desired end-position, indicate this by saying either, "Now" or "O.K.". Do not remove your arm from the armpiece or your chin from the rest until I say the "End" signalling the end of the trial. Do you have any questions?

Appendix D. Analysis of Variable of Absolute Error

| Source | Sum of Squares | DF | Mean Square | F | P |
|---|---|---|---|---|---|
| Handedness (H) | 1.45 | 1 | 1.45 | 0.04 | |
| Sex (S) | 15.40 | 1 | 15.40 | 0.41 | |
| H x S | 104.17 | 1 | 104.17 | 2.74 | |
| Error | | 36 | | | |
| | | | | | |
| Arm (A) | 130.24 | 1 | 130.24 | 20.74 | <.001 |
| A x H | 333.46 | 1 | 333.46 | 53.11 | <.001 |
| A x S | 9.68 | 1 | 9.68 | 1.54 | |
| A x H x S | 10.21 | 1 | 10.21 | 1.62 | |
| Error | 226.01 | 36 | 6.28 | | |
| | | | | | |
| Mode (M) | 29.69 | 1 | 29.69 | 4.62 | |
| M x H | 1.19 | 1 | 1.19 | 0.18 | |
| M x S | 1.91 | 1 | 1.91 | 0.29 | |
| M x H x S | .14 | 1 | .14 | 0.02 | |
| Error | 231.22 | 36 | 6.42 | | |
| | | | | | |
| A x M | 2.36 | 1 | 2.36 | 1.18 | |
| A x M x H | .87 | 1 | .87 | 0.44 | |
| A x M x S | 5.6 | 1 | 5.6 | 2.79 | |

| Source | Sum of Squares | DF | Mean Square | F | P |
|---|---|---|---|---|---|
| A x M x H x S | 1.75 | 1 | 1.75 | 0.87 | |
| Error | 72.10 | 36 | 2.00 | | |
| | | | | | |
| Delay (D) | 12.94 | 1 | 12.94 | 2.55 | |
| D x H | 1.43 | 1 | 1.43 | 0.28 | |
| D x S | 2.32 | 1 | 2.32 | 0.46 | |
| D x H x S | 1.19 | 1 | 1.19 | 0.24 | |
| Error | 182.26 | 36 | 5.06 | | |
| | | | | | |
| A x D | 12.42 | 1 | 12.42 | 4.60 | |
| A x D x H | 0.00 | 1 | 0.00 | 0.00 | |
| A x D x S | 0.49 | 1 | 0.49 | 0.18 | |
| A x D x H x S | 0.23 | 1 | 0.23 | 0.09 | |
| Error | 95.94 | 36 | 2.67 | | |
| | | | | | |
| M x D | 2.28 | 1 | 2.28 | 1.09 | |
| M x D x H | 0.36 | 1 | 0.36 | 0.17 | |
| M x D x S | 1.60 | 1 | 1.60 | 0.77 | |
| M x D x H x S | 1.34 | 1 | 1.34 | 0.64 | |
| Error | 74.73 | 36 | 2.07 | | |
| | | | | | |
| A x M x D | 5.82 | 1 | 5.82 | 2.02 | |

| Source | Sum of Squares | DF | Mean Square | F | P |
|---|---|---|---|---|---|
| A x M x D x H | 0.02 | 1 | 0.02 | 0.00 | |
| A x M x D x S | 7.21 | 1 | 7.21 | 2.50 | |
| Error | 103.88 | 36 | 2.88 | | |
| | | | | | |
| Position (P) | 446.08 | 2 | 223.04 | 25.49 | <.001 |
| P x H | 35.22 | 2 | 17.61 | 2.01 | |
| P x S | 60.41 | 2 | 30.20 | 3.45 | |
| P x H x S | 55.86 | 2 | 27.93 | 3.19 | |
| Error | 630.00 | 72 | 8.75 | | |
| | | | | | |
| A x P | 6.44 | 2 | 3.22 | 0.53 | |
| A x P x H | 5.96 | 2 | 2.98 | 0.49 | |
| A x P x S | 4.63 | 2 | 2.31 | 0.38 | |
| A x P x H x S | 15.68 | 2 | 7.84 | 1.29 | |
| Error | 439.23 | 72 | 6.10 | | |
| | | | | | |
| M x P | 2.34 | 2 | 1.17 | 0.38 | |
| M x P x H | 3.15 | 2 | 1.58 | 0.51 | |
| M x P x S | 2.12 | 2 | 1.06 | 0.34 | |
| M x P x H x S | 2.05 | 2 | 1.03 | 0.33 | |
| Error | 222.94 | 72 | 3.09 | | |

| Source | Sum of Squares | DF | Mean Square | F | P |
|---|---|---|---|---|---|
| A x M x P | 4.81 | 2 | 2.40 | 0.97 | |
| A x M x P x H | 14.07 | 2 | 7.04 | 2.85 | |
| A x M x P x S | 3.53 | 2 | 1.76 | 0.71 | |
| A x M x P x H x S | 3.55 | 2 | 1.78 | 0.72 | |
| Error | 177.60 | 72 | 2.47 | | |
| D x P | 28.28 | 2 | 14.14 | 1.94 | |
| D x P x H | 17.33 | 2 | 8.66 | 1.19 | |
| D x P x S | 0.79 | 2 | 0.39 | 0.05 | |
| D x P x H x S | 6.59 | 2 | 3.29 | 0.45 | |
| Error | 523.85 | 72 | 7.28 | | |
| A x D x P | 9.88 | 2 | 4.94 | 1.26 | |
| A x D x P x H | 10.37 | 2 | 5.19 | 1.32 | |
| A x D x P x S | 2.53 | 2 | 1.27 | 0.32 | |
| A x D x P x H x S | 5.59 | 2 | 2.79 | 0.71 | |
| Error | 282.70 | 72 | 3.93 | | |
| M x D x P | 0.18 | 2 | 0.08 | 0.03 | |
| M x D x P x H | 2.09 | 2 | 1.05 | 0.32 | |
| M x D x P x S | 7.43 | 2 | 3.72 | 1.33 | |
| M x D x P x H x S | 5.19 | 2 | 2.60 | 0.93 | |

| Source | Sum of Squares | DF | Mean Square | F | P |
|---|---|---|---|---|---|
| Error | 201.87 | 72 | 2.80 | | |
| | | | | | |
| A x M x D x P | 1.65 | 2 | 0.83 | 0.35 | |
| A x M x D x P x H | 6.06 | 2 | 3.03 | 1.29 | |
| A x M x D x P x S | 3.99 | 2 | 1.99 | 0.85 | |
| A x M x D x P x H | 2.98 | 2 | 1.49 | 0.63 | |
| Error | 169.52 | 72 | 2.35 | | |

Appendix E. Analysis of Variance of Variable Error

| Source | Sum of Squares | DF | Mean Square | F | P |
|---|---|---|---|---|---|
| Handedness (H) | 3.80 | 1 | 3.80 | .31 | |
| Sex (3) | 2.58 | 1 | 2.58 | .21 | |
| H x S | .21 | 1 | .21 | .02 | |
| Error | 444.16 | 36 | 12.38 | | |
| | | | | | |
| Arm (A) | 68.91 | 1 | 68.91 | 15.14 | <.0001 |
| A x H | 206.83 | 1 | 206.83 | 45.44 | <.0001 |
| A x S | 13.30 | 1 | 13.30 | 2.92 | |
| A x H x S | 12.02 | 1 | 12.02 | 2.64 | |
| Error | 163.87 | 36 | 4.55 | | |
| | | | | | |
| Mode (M) | 9.24 | 1 | 9.24 | 1.89 | |
| M x H | 1.55 | 1 | 1.55 | .32 | |
| M x S | 11.97 | 1 | 11.97 | 2.45 | |
| M x H x S | 2.56 | 1 | 2.56 | .52 | |
| Error | 176.24 | 36 | 4.90 | | |
| | | | | | |
| A x M | .05 | 1 | .05 | .01 | |
| A x M x H | .74 | 1 | .74 | .22 | |

| Source | Sum of Squares | DF | Mean Square | F | P |
|---|---|---|---|---|---|
| A x M x S | .49 | 1 | .49 | .14 | |
| A x M x H x S | 9.36 | 1 | 9.36 | 2.73 | |
| Error | 123.38 | 36 | 3.42 | | |
| | | | | | |
| Delay (D) | 24.75 | 1 | 24.75 | 7.10 | <.011 |
| D x H | 11.57 | 1 | 11.57 | 2.76 | |
| D x S | .38 | 1 | .38 | .09 | |
| D x H x S | .10 | 1 | .10 | .02 | |
| Error | 150.83 | 36 | 4.19 | | |
| | | | | | |
| A x D | .06 | 1 | .06 | .02 | |
| A x D x H | .18 | 1 | .18 | .05 | |
| A x D x S | 1.09 | 1 | 1.09 | .34 | |
| A x D x H x S | 4.59 | 1 | 4.59 | 1.42 | |
| Error | 116.22 | 36 | 3.33 | | |
| | | | | | |
| M x D | .82 | 1 | .82 | .22 | |
| M x D x H | 10.92 | 1 | 10.92 | 2.97 | |
| M x D x S | .08 | 1 | .08 | .02 | |
| M x D x H x S | .72 | 1 | .72 | .19 | |
| Error | 132.49 | 36 | 3.34 | | |

| Source | Sum of Squares | DF | Mean Square | F | P |
|---|---|---|---|---|---|
| A x M x D | .00 | 1 | .00 | .00 | |
| A x M x D x H | .42 | 1 | .42 | .12 | |
| A x M x D x S | 5.37 | 1 | 5.37 | 1.61 | |
| A x M x D x H x S | 8.70 | 1 | 8.70 | 2.60 | |
| Error | 120.30 | 36 | 3.34 | | |
| | | | | | |
| Position (P) | 506.11 | 2 | 253.05 | 45.85 | <.0001 |
| P x H | 5.18 | 2 | 2.59 | .47 | |
| P x S | 63.74 | 2 | 31.87 | 5.77 | <.005 |
| P x H x S | 17.93 | 2 | 8.96 | 1.62 | |
| Error | 397.37 | 72 | 5.52 | | |
| | | | | | |
| A x P | 7.28 | 2 | 3.64 | .81 | |
| A x P x H | 1.32 | 2 | .66 | .15 | |
| A x P x S | 3.88 | 2 | 1.94 | .43 | |
| A x P x H x S | 21.01 | 2 | 10.51 | 2.33 | |
| Error | 323.37 | 72 | 4.49 | | |
| | | | | | |
| M x P | 1.70 | 2 | .85 | .19 | |
| M x P x H | 1.24 | 2 | .62 | .13 | |
| M x P x S | 9.95 | 2 | 4.98 | 1.08 | |

| Source | Sum of Squares | DF | Mean Square | F | P |
|---|---|---|---|---|---|
| M x P x H x S | 1.30 | 2 | .65 | .14 | |
| Error | 332.29 | 72 | 4.62 | | |
| | | | | | |
| A x M x P | 1.13 | 2 | .57 | .16 | |
| A x M x P x H | 20.52 | 2 | 10.26 | 2.83 | |
| A x M x P x S | 1.92 | 2 | .96 | .26 | |
| A x M x P x H x S | .68 | 2 | .34 | .09 | |
| Error | 273.60 | 72 | 3.80 | | |
| | | | | | |
| D x P | 63.55 | 2 | 31.77 | 5.94 | <.0041 |
| D x P x H | 20.46 | 2 | 10.23 | 1.91 | |
| D x P x S | 4.35 | 2 | 2.17 | .41 | |
| D x P x H x S | 13.84 | 2 | 6.92 | 1.29 | |
| Error | 385.28 | 72 | 5.35 | | |
| | | | | | |
| A x D x P | 13.17 | 2 | 6.59 | 1.94 | |
| A x D x P x H | 16.62 | 2 | 8.31 | 2.45 | |
| A x D x P x S | 14.17 | 2 | 7.09 | 2.08 | |
| A x D x P x H x S | 15.42 | 2 | 7.71 | 2.27 | |
| Error | 244.64 | 72 | 3.40 | | |

| Source | Sum of Squares | DF | Mean Square | F | P |
|---|---|---|---|---|---|
| M x D x P | 1.13 | 2 | .57 | .16 | |
| M x D x P x H | 7.03 | 2 | 3.54 | .98 | |
| M x D x P x S | 20.43 | 2 | 10.21 | 2.83 | |
| M x D x P x H x S | .84 | 2 | .42 | .12 | |
| Error | 260.07 | 72 | 3.61 | | |
| | | | | | |
| A x M x D x P | 13.00 | 2 | 6.50 | 1.97 | |
| A x M x D x P x H | 3.10 | 2 | 1.55 | .47 | |
| A x M x D x P x S | 1.43 | 2 | .71 | .22 | |
| A x M x D x P x H x S | 8.36 | 2 | 4.18 | 1.27 | |
| Error | 237.91 | 72 | 3.30 | | |

Appendix F. Analysis of Variance of Constant Error Measure

| Source | Sum of Squares | DF | Mean Square | F | P |
|---|---|---|---|---|---|
| Handedness (H) | 640.61 | 1 | 640.61 | 2.54 | |
| Sex (S) | 33.82 | 1 | 33.82 | .13 | |
| H x S | 528.65 | 1 | 528.65 | 2.10 | |
| Error | 9082.25 | 36 | 252.28 | | |
| | | | | | |
| Arm (A) | 23.63 | 1 | 23.63 | .71 | |
| A x H | .47 | 1 | .47 | .01 | |
| A x S | .18 | 1 | .18 | .01 | |
| A x H x S | 1.93 | 1 | 1.93 | .06 | |
| Error | 1202.25 | 36 | 33.40 | | |
| | | | | | |
| Mode (M) | 43.60 | 1 | 43.60 | 2.55 | |
| M x H | 3.22 | 1 | 3.22 | .19 | |
| M x S | 40.51 | 1 | 40.51 | 2.37 | |
| M x H x S | .74 | 1 | .74 | .04 | |
| Error | 616.57 | 36 | 17.13 | | |
| | | | | | |
| A x M | 10.67 | 1 | 10.67 | 1.97 | |
| A x M x H | 1.03 | 1 | 1.03 | .19 | |
| A x M x S | 2.80 | 1 | 2.80 | .52 | |
| A x M x H x S | .01 | 1 | .01 | .00 | |

| Source | Sum of Squares | DF | Mean Square | F | P |
|---|---|---|---|---|---|
| Error | 194.65 | 36 | 5.41 | | |
| | | | | | |
| Delay (D) | 392.45 | 1 | 392.45 | 44.85 | <.0001 |
| D x H | 7.70 | 1 | 7.70 | .88 | |
| D x S | 24.15 | 1 | 24.15 | 2.75 | |
| D x H x S | .85 | 1 | .85 | .10 | |
| Error | 315.01 | 36 | 8.75 | | |
| | | | | | |
| A x D | 18.93 | 1 | 18.93 | 2.62 | |
| A x D x H | 2.11 | 1 | 2.11 | .29 | |
| A x D x S | 1.75 | 1 | 1.75 | .24 | |
| A x D x H x S | 16.66 | 1 | 16.66 | 2.30 | |
| Error | 259.67 | 36 | 7.21 | | |
| | | | | | |
| M x D | 6.47 | 1 | 6.47 | 1.56 | |
| M x D x H | 5.08 | 1 | 5.08 | 1.22 | |
| M x D x S | 4.46 | 1 | 4.46 | 1.07 | |
| M x D x H x S | .07 | 1 | .07 | .02 | |
| Error | 149.35 | 36 | 4.15 | | |

| Source | Sum of Squares | DF | Mean Square | F | P |
|---|---|---|---|---|---|
| A x M x D | 7.22 | 1 | 7.22 | 2.21 | |
| A x M x D x H | 12.33 | 1 | 12.33 | 3.78 | |
| A x M x D x S | 1.63 | 1 | 1.63 | .50 | |
| A x M x D x H x S | 12.14 | 1 | 12.14 | 3.72 | |
| Error | 117.45 | 36 | 3.26 | | |
| Position (P) | 2139.54 | 2 | 1069.77 | 84.24 | <.0001 |
| P x H | 70.78 | 2 | 35.39 | 2.79 | |
| P x S | 8.31 | 2 | 4.16 | .33 | |
| P x H x S | 24.34 | 2 | 24.34 | 1.91 | |
| Error | 914.33 | 72 | 12.70 | | |
| A x P | 88.90 | 2 | 44.45 | 7.65 | <.001 |
| A x P x H | 1.22 | 2 | .61 | .11 | |
| A x P x S | 20.53 | 2 | 10.26 | 1.76 | |
| A x P x H x S | 13.55 | 2 | 6.77 | 1.17 | |
| Error | 418.30 | 72 | 5.81 | | |
| M x P | 6.17 | 2 | 3.08 | .46 | |
| M x P x H | 6.72 | 2 | 3.36 | .50 | |
| M x P x S | 1.60 | 2 | .80 | .12 | |

| Source | Sum of Squares | DF | Mean Square | F | P |
|---|---|---|---|---|---|
| M x P x H x S | 10.46 | 2 | 5.23 | .78 | |
| Error | 480.71 | 72 | 6.68 | | |
| A x M x P | 8.69 | 2 | 4.35 | .71 | |
| A x M x P x H | 13.37 | 2 | 6.69 | 1.10 | |
| A x M x P x S | 6.67 | 2 | 3.33 | .55 | |
| A x M x P x H x S | 5.20 | 2 | 2.60 | .43 | |
| Error | 437.90 | 72 | 6.08 | | |
| D x P | 726.40 | 2 | 363.20 | 39.95 | <.0001 |
| D x P x H | .97 | 2 | .49 | .05 | |
| D x P x S | 6.98 | 2 | 3.49 | .38 | |
| D x P x H x S | 22.55 | 2 | 11.27 | 1.24 | |
| Error | 654.66 | 72 | 9.09 | | |
| A x D x P | 8.08 | 2 | 4.04 | .71 | |
| A x D x P x H | 6.30 | 2 | 3.15 | .56 | |
| A x D x P x S | 30.15 | 2 | 15.08 | 2.66 | |
| A x D x P x H x S | 12.50 | 2 | 6.25 | 1.10 | |
| Error | 407.32 | 72 | 5.66 | | |

| Source | Sum of Squares | DF | Mean Square | F | P |
|---|---|---|---|---|---|
| M x D x P | 2.67 | 2 | 1.33 | .21 | |
| M x D x P x H | 15.09 | 2 | 7.55 | 1.16 | |
| M x D x P x S | 7.68 | 2 | 3.84 | .59 | |
| M x D x P x H x S | 10.24 | 2 | 5.12 | .79 | |
| Error | 467.06 | 72 | 6.49 | | |
| | | | | | |
| A x M x D x P | 11.18 | 2 | 5.59 | 1.05 | |
| A x M x D x P x H | 7.93 | 2 | 3.97 | .74 | |
| A x M x D x P x S | 12.57 | 2 | 6.29 | 1.18 | |
| A x M x D x P x H x S | .46 | 2 | .23 | .04 | |
| Error | 384.99 | 72 | 5.35 | | |

## REFERENCES

Adams, J.A., & Dijkstra, S. Short-term memory for motor responses. *Journal of Experimental Psychology*, 1966, *71*, #2, 314-318.

Babinski, J. Contributions a l'etude des troubles mentaux dans l'hemiplegis organique cerebrale (anosognosia). *Review Neurology* (Paris), 1914, *27*, 845-848.

Bastian, H.C. *A treatise on aphasia and other speech disorders*. London: Lewis, 1898.

Beaumont, J.G. Handedness on hemisphere function. In S.J. Diamond and J.G. Neaumont (Eds.), *Hemisphere function in the human brain*. New York: Halstead Press, 1974.

Beaumont, J.G. & Diamond, S. Interchemispheric transfer of figural information in right and non-right handed subjects. *Active Psychologia*, 1975, *39*, 97-104.

Benton, A.L. Disorders of spatial orientation. In P.J. Vinken and G.W. Bruyn (Eds.), *Handbook of clinical neurology*, *3*, Amsterdam: North Holland Publishing Company, 1969.

Benton, A.L., Levin, H.S., & Varney, N.R. Tactile perception of direction in normal subjects. *Neurology*, 1973, *23*, 1248-1250.

Benton, A.L., Varney, N.R. & Hamsher, D.S. Lateral differences in tactile directional perception. *Neuropsychologia*, 1978, *16*, 109-114.

Berlucchi, G. Cerebral dominance and interhemispheric communication in normal man. In B. Milner (Eds.), *Hemisphere Specialization and Interaction*, Massachusettes: MIT Press, 1975.

Bizzi, E., & Polit, A. Processes controlling visually evoked movements. *Neuropsychologia*, 1979, *17*, 203-213.

Blakemore, C.B., & Falconer, M.A. Long term effects of anterior temporal lobectomies on certain cognitive functions. *Journal of Neurology, Neurosurgery, and Psychiatry*, 1967, *30*, 364-367.

Bogen, J.E. The other side of the brain: An appositional mind. *Bulletin of the Los Angeles Neurological Society*, 1969, *34*, 135-162.

Bogen, J.E. & Gazzanigia, M.S. Cerebral commussurotomy in man: Minor hemisphere dominace for certain visuospatial functions. *Journal of Neurosurgery*, 1965, *23*, 394-399.

Boyd, I. & Roberts, T. Propuoceptive discharges from stretch-receptors in the knee joint of the cat. *Journal of Physiology*, 1953, *122*, 38-58.

Branch, C., Milner, B., & Rasmussen, T. Intercarotid sodium amytal for the lateralization of cerebral speech dominance. *Journal of Neurosurgery*, 1964, *21*, 399-405.

Briggs, G.G. & Nebes, R.D. The effects of handedness, family history, and sex on the performance of a dichotic listening task. *Neuropsychologia*, 1976, *14*, 129-133.

Brocadbent, D.E. The role of auditory localization in attention and memory. *Journal of Experimental Psychology*, 1954, *47*, 191-196.

Broca, P. Remarques sur le siège de la faculté du langage articule suivies d'une observation d'aphemie. *Bulletin of the Society of Anatomy*, 1861, 330.

Broca, P. Atrophie complète du lobule de l'insula et de la troisième circonvolution du lobe frontal avec conservation de l'intelligence et de la faculté du langage articule. *Bulletin of the Society of Anatomy*, 1863, *8*, 372.

Brown-Sequard, J. & Reise, W. *A history of neurology*. New York: MD. Publications, 1959.

Bryden, M.P. Tachistoscopic recognition, handedness, and cerebral dominance. *Neuropsychologia*, 1965, *3*, 1-8.

Bryden, M.P. Evidence for sex differences in cerebral organization. In M.A. Wittling and A.C. Petersen (Eds.), *Sex-related differences in cognitive functioning: Developmental issues.* New York: Academic Press, 1978.

Buffery, A.W.H. Asymmetrical lateralization of cerebral functioning and the effects of unilateral brain surgery in epileptic patients. In S.J. Diamond and J.G. Beaumont (Eds.), *Hemisphere function in the human brain.* New York: Wiley, 1974.

Buffery, A. & Gray, J. Sex differences in the development of spatial and linguistic skills. In C. Ounstad and D.C. Taylor (Eds.), *Gender Differences: Their Ontogency and Significance.* Edinburgh: Churchill Livingstone, 1972.

Carmon, A. Impaired utilization of kinesthetic feedback in right hemispheric lesions. *Neurology*, 1969, *20*, 1033-1038.

Carmon, A. & Benton, A.L. Tactile perception of direction and number in patients with unilateral cerebral disease. *Neurology*, 1969, *19*, 525-532.

Carmon, A. Bilstrom, E. & Benton, A.L. Threshholds for pressure and sharpness in the right and left hands. *Cortex,* 1969, *5*, 27-35.

Christina, W. The side arm positional test of kinesthetic sense. *The Research Quarterly*, 1967, *38*, No. 2, 1977-1983.

Bioffi, J. & Kandel, G. Laterality of stereognostic accuracy for words, shapes, and bigrams: A sex difference for bigrams. *Science*, 1979, *204*, 1432-1434.

Cohen, G. Hemispheric differences in a letter clarification task, *Perception and Psychophysics*, 1972, *11*, 139-142.

Cohen, L.A. Contribution of tactile musuilo-tendinous and joint mechanisms to position sense in human shoulder. *Journal of Neurophysiology*, 1958, *21*, 563-568.

Corkin, S. Tactually-guided maze learning in man: Effects of unilateral cortical excisions and bilateral hippocampal lesions. *Neuropsychologia*, 1965, *3*, 339-351.

Corkin, S. The role of different cerebral structures in somesthetic perception. In E.C. Carteretle & M.P. Friedman (Eds.), *Handbook of perception* (Vol. 6). New York: Academic Press, 1978.

Corkin, S. Milner, B. & Rasmussen, J. Somatosensory threshholds: Contrasting effects of postcentral-gyrus and posterior parietal lobe excisions. *Archives of Neurology*, 1970, *23*, 41-58.

Corsi, P.M. Human memory in the medial temporal region of the brain. Unpublished Ph.D. thesis, McGill University, 1972.

Cranney, J. & Ashton, R. Witelson's dichhaptic task as a measure of hemispheric asymmetry in deaf and hearing populations. *Neuropsychologia*, 1980, *18*, 95-98.

Cratty, B.J. *Movement Behavior and Motor Learning*. London: Henry Kimpton, 1972.

Critchley, M. *The parretal lobes*. New York: Hafner, 1953.

Curry, F.K.W. A comparison of left-handed and right-handed subjects on verbal and non-verbal dichotic listening tasks. *Cortex*, 1967, *3*, 1967.

Curry, F. & Rutherford, D. Recognition and recall of dichotically presented verbal stimuli by right and left-handed persons. *Neuropsychologia*, 1967, *5*, 119-126.

Dee, H.L. Auditory asymmetry and strength of manual preference. *Cortex*, 1971, *7*, 231-245.

Dee, H.L. & Fontenot, D.J. Cerebral dominance and lateral differences in perception and memory. *Neuropsychologia*, 1973, *11*, 167-173.

DeRenzi, E. Nonverbal memory and hemispheric side of lesion. *Neuropsychologia*, 1968, *6*, 181-189.

DeRenzi, E., Faglioni, P. & Scotti, G. Tactile spatial impairment and unilateral cerebral damage. *Journal of Nervous and Mental Disease*, 1968, *146*, 468-475.

DeRenzi, E., Faglioni, P. & Scotti, G. Impairment of memory for position following brain damage. *Cortex*, 1969, *5*, 274-284.

DeRenzi, E., Faglioni, P., & Scotti, G. Hemispheric contribution to exploration of space through the visual and tactile modality. *Cortex*, 1970, *6*, 191-203.

Dimond, S.J. & Beaumont, J.G. (Eds.). *Hemispheric function in the human brain*. New York: Wiley, 1974.

Dodds, A.G. Hemispheric differences in tactuo-spatial processing. *Neuropsychologia*, 1978, *16*, 247-249.

Durnford, M. Visual field depression in visual-spatial perception. Unpublished Ph.D. thesis, University of Western Ontario, 1971.

Faglioni, P., Scotti, G. & Spinnler, H. The performance of brain-damaged patients in spatial localization of visual and tactile stimuli. *Brain*, 1971, *94*, 443-454.

Festinger, L. & Canon, L. Information about spatial location based on knowledge about efference. *Psychology Bulletin*, 1965, *72*, No. 5, 373-384.

Fontenont, J. Visual field differences in the recognition of verbal and nonverbal stimuli in man. *Journal of Comparative and Psychological Psychology*, 1974, 85, No. 3, 564-569.

Fontenont, D.J. & Benton, A.L. Tactile perception of direction in relation to hemispheric locus of lesion. *Neuropsychologia*, 1971, *9*, 83-88.

Gardner, E.B., English, A.G., Flannery, B.M., Harnett, M.B., McCormick, J.K. & Wilhelm, B.B. Shape and recognition accuracy and response latency in a bilateral tactile task. *Neuropsychologia*, 1977, *15*, 607-616.

Gardner, L.P. Experimental data on the problem of sensory lateral dominance in feet and hands. *Psychological Record*, 1942, *5*, 66-124.

Gazzaniga, M., Bogen, J. & Sperry, R.W. Dyspraxia following division of the cerebral commissures. *A.M.A. Archives of Neurology*, 1967, *16*, 606-612.

Gazzaniga, M.S. & Sperry, R.W. Language after section of the cerebral commissures. *Brain*, 1967, *90*, 131-148.

Ghent, L. Developmental changes in tactual threshholds on dominant and non-dominant sides. Journal of Comparative and Physiological Psychology, 1961, 54, 670-673.

Gloning, J., Gloning, K., Haub, G. & Quatember, R. Comparison of verbal behavior in right-handed and non-right-handed patients with anatomically verified lesions of one hemisphere. Cortex, 1969, 5, 41-52.

Goldstein, K. After-effects of brain injuries in the war: Their evaluation and treatment. London: Henemann Ltd., 1942.

Goodglass, H. & Quadfasel, F.A. Language laterality in left-handed aphasics. Brain, 1953, 77, 521-548.

Hannay, H. & Malone, R. Visual field effects and short-term memory for verbal material. Neuropsychologia, 1976, 14, 203-209.

Hannay, J.J., Varney, N.R. & Benton, A.L. Visual localization in patients with unilateral brain disease. Journal of Neurology, Neurosurgery and Psychiatry, 1976, 39, 307-313.

Hardyck, C. & Petrinovich, F. Left-handedness. Psychological Bulletin, May 1977, 84, No. 3, 385-399.

Harnard, S., Doty, R.W., Goldstein, L., Jaynes, J. & Krauthamer, G. (Eds.). Lateralization of the nervous system. New York: Academic Press, 1977.

Harrimman, J. & Castell, L. Manual asymmetry for tactual discrimination. Perceptual and Motor Skills, 1979, 48, 290.

Haslam, D.R. Lateral dominance in the perception of size and pain. Quarterly Journal Experimental Psychology, 1970, 22, 503-507.

Hatta, T. The functional asymmetry of tactile pattern learning in normal subjects. Psychologia, 1978, 21, 83-89.

Hecaen, H. Clincial symptomotology in right and left hemisphere lesions. In V.B. Mountcastle (Ed.) Interhemispheric Relations and Cerebral Dominance. Baltimore: John Hopkins, 1962.

Hecaen, H. & de Ajuriaguerra, J. La problème de las dominance hemispherique et due praxis ches les gauchers los des lesions hemispherique droit et gouches. Journal of Psychiatric Normalacy and Pathology, 1956, 53, 473-486.

Hecaen, H., de Ajuriaguerra, J., Massonnet, D. Les troubles visuoconstructifs par lesion arieto-occipitales droites. Role des perturbations vestibulaires. Encephalé, 1951, 1, 122-179.

Hecaen, H., DeAgostini, M. & Monzon-Montes, A. Cerebral organization in left-handers. Brain and Language, 1981, 12, 261-284.

Hecaen, H. & Piercy, M. Paroxysmal dysphasia and the problems of cerebral dominance. Journal of Neurology, Neurosurgery, and Psychiatry, 1956, 19, 194-201.

Hecaen, H. & Sauguet, J. Cerebral dominance in left-handed subjects. Cortex, 1971, 7, 19-48.

Held, R. & Freedman, J. Plasticity in human sensorimotor control. Science, 1963, 142, 455-560.

Helson, H. Adaptation level theory. New York: Harper & Row, 1964.

Hermelin, B. & O'Connor, N. Functional asymmetry in the reading of braille. Neuropsychologia, 1971, 9, 431-435. (a)

Hermelin, N. & O'Connor, N. Right and left-handed reading of braille, Nature, 1971, 231, 470. (b)

Hines, D. & Satz, P. Superiority of right visual half-fields in right-handers for recall of digits presented at varying rates. Neuropsychologia, 1971, 9, 21-35.

Hines, D. & Satz, P. Cross-modal asymmetries in perception related to asymmetry in cerebral function. Neuropsychologia, 1974, 12, 239-247.

Hines, D., Satz, P. & Clementino, T. Perceptual and memory components of the superior recall of letters from the right visual half-fields. Neuropsychologia, 1973, 11, 175-180.

Inglis, J. & Lawson, J.S. Sex differences in the effects of unilateral brain damage on intelligence. Science, 1981, 212, 693-695.

Jackson, J.H. In J. Taylor (Ed.), Selection of writing of John Hughlings Jackson. London: Hodder and Straughton, 1931.

Jones, B. The role of central monitoring of experience in short-term memory for movement. Journal of Experimental Psychology, 1974, 102, 37-43.

Kimura, D. Cerebral dominance and the perception of verbal stimuli. Canadian Journal of Psychology, 1961, 15, 1966-1971.

Kimura, D. Left-right differences in the perception of melodies. Quarterly Journal of Experimental Psychology, 1964, 16, 255-358.

Kimura, D. Dual function asymmetry of the brain in visual perception. Neuropsychologia, 1966, 4, 275-285.

Kimura, D. Spatial localization in left and right visual fields. Canadian Journal of Psychology, 1969, 23, 445-458.

Kimura, D. & Durnford, M. Normal studies on the function of the right hemisphere in vision. In S.J. Dimond and J.G. Beaumont (Eds.) Hemisphere function in the human brain. New York: Wiley, 1974.

Kirk, R.E. Experimental Design: Procedures for the Behavioral Sciences. Belmont, California: Brooks/Cole, 1968.

Knox, A. & Boone, D. Auditory laterality and tested handedness. Cortex, 1970, 6, 164-173.

Laabs, J. Retention characteristics of different reproduction cues in motor short-term memory. Journal of Experimental Psychology, 1973, 100, No.1, 168-177.

La Breche, T., Manning, A., Goble, W., & Markham, R. Hemispheric specialization for linguistic and nonlinguistic tactual perception in a congenitally deaf population. Cortex, 1977, 13, 184-194.

Lake, D.A. & Bryden, M.P. Handedness and sex differences in hemispheric asymmetry. Brain and Language, 1976, 3, 266-282.

Lashley, K. The problem of serial order in behavior. In L.A. Jeffress (Ed.) Cerebral mechanisms of behavior. New York: Wiley, 1951.

LeDoux, J.E., Wilson, D.H. & Gazzaniga, H.S. Manipulo-spatial aspects of cerebral lateralization clues to the origin of lateralization. Neuropsychologia, 1977, 15, 743-750.

Levin, H. Motor impersistence and propioceptive feedback in patients with unilateral cerebral disease. Neurology, 1973, 23, 833-841.

Levy, J. Possible basis for the evolution of lateral specialization of the human brain. Nature, 1969, 224, 614-615.

Levy, J. & Reid, M. Variations in cerebral organization as a function of handedness, hand posture in writing, and sex. Journal of Experimental Psychology, 1978, 107, 119-144.

Levy, J., Trevarthen, C.B. & Sperry, R.W. Perception of bilateral chimeric figures following hemispheric disconnection. Brain, 1972, 95, 61-78.

Levy-Agresti, J., & Sperry, R.W. Differential perceptual capacities in major and minor hemispheres. Proceedings of the National Academy of Sciences of the United States of America, 1968, 61, 1151.

Lhermitte, F. & Gautier, J.C. Aphasia. In P.J. Vinkin and G.W. Bruyn (Eds.) Handbook of clinical neurology, 4, Amsterdam: North Holland Publishing Company, 1969.

Lloyd, J. & Caldwell, L.S. Accuracy of active and passive positioning of the leg on the basis of kinesthetic cues. Journal of Comparative and Physiological Psychology, 1965, 60, No. 1, 102-106.

Luria, A.R. Traumatic aphasia: It's syndrome, psychology, and treatment. Paris: Mounton, 1970.

Maccoby, E. & Jackin, C. The psychology of sex differences. California: Stamford University Press, 1974.

MacNeilage, P.F. Motor control and serial ordering of speech. Psychological Review, 1972, 77, 183-196.

MacNeilage, P.F. & MacNeilage, L.A. Central processes controlling speech production during sleep and working. In F.J. McGuegan and R.A. Schoonever (Eds.) The Psychophysiology of Thinking. New York: Academic Press, 1973.

Marteniuk, R.G. Further considerations of "Retention characteristics of motor short-term memory cues." A reply to Laabs. Journal of Motor Behavior, 1975, 7, 151-152.

Marteniuk, R.G. & Roy, E.A. The codability of kinesthetic location and distance information. Acta Psychologua, 1972, 36, 471-479.

Marteniuk, R.G., Shields, K.W. & Campbell, S. Amplitude, position, timing, and velocity as cues in reproduction of movement. Perceptual and Motor Skills,1972, 35, 51-58.

McGee, M.G. Laterality, hand preference, and human spatial ability. Perceptual and Motor Skills, 1976, 42, 781-782.

McGlone, J. & Davidson, W. The relation between cerebral speech laterality and spatial ability with special reference to sex and hand preference. Neuropsychologia, 1973, 11, 105-113.

McGlone, J. & Kertesz, A. Sex differences in cerebral processing of visuospatial tasks. Cortex, 1973, 9, 313-320.

McKeever, W., Gill, K. & Van Deventer, A. Letter versus dot stimuli as tools for "splitting the normal brain with reaction time." Quarterly Journal of Experimental Psychology, 1975, 27, 363-373.

McKeever, W.F. & Huling, M.D. Lateral dominance in tachistoscopic work recognition performance obtained with simultaneous bilateral imput. Neuropsychologia, 1971, 9, 15-20.

McKeever, W.F., Van Deventer, A.D. & Suberi, M. Avowed, assessed, and familial handedness and differential hemispheric processing of brief sequential and non-sequential visual stimuli. Neuropsychologia, 1973, 11, 235-238.

Myers, V. & Yates, A.J. Intellectual changes following temporal lobectomy for psychomotor epilepsy. Journal of Neurology, Neurosurgery, and Psychiatry, 1965, 18, 44-52.

Milner, B. Intellectual function of the temporal lobes. Psychological Bulletin, 1954, 51, 42-62.

Milner, B. Laterality effects in audition. In V.B. Mountcastle (Ed.) Interhemispheric relations and cerebral dominance. Baltimore: John Hopkins Press, 1962.

Milner, B. Brain mechanisms suggested by studies of the temporal lobes. In F.L. Darley (Ed.) Brain mechanisms underlying speech and language, New York: Grune and Stratton, 1967.

Milner, B. Visual recognition and recall after right temporal-lobe excision in man. Neuropsychologia, 1968, 6, 191-209.

Milner, B. Hemispheric specialization. Scope and limits. In B. Milner (Ed.) Hemispheric Specialization and Interaction. Cambridge, Massachusettes: MIT Press, 1973.

Milner, B. & Taylor, L.B. Right hemisphere superiority in tactile pattern recognition after cerebral commissurotomy: Evidence of non-verbal memory. Neuropsychologia, 1972, 10, 1-15.

Milner, B. & Teuber, H.L. Alterations of perception and memory in man. Reflections on methods. In L. Wershrantz (Ed.), Analysis of Behavioral Change. New York: Harper and Row, 1968.

Mishkin, M. & Forgays, D.G. Word recognition as a function of retinal locus. Journal of Experimental Psychology, 1952, 43, 43-48.

Mountcastle, V., Pogges, G. & Weiner, G. The relationship of thalamic cell response to peripheral stimuli varied over an intensive continuum. Journal of Neurophysiology, 1963, 26, 807-834.

Mountcastle, V. & Powell, P. Central nervous mechanisms subserving positioning sense and kinesthesis. John Hopkins Hospital Bulletin, 1959, 108, 173-200.

Mourea, T. & Milner, P. Lateral differences in the detection of touched body parts in young children. Developmental Psychology, 1981, 17, 351-356.

Myers, D.H. Right and left-handed counting of braille dots in subjects unaccustomed to braille. British Journal of Psychology, 1976, 67, 407-412.

Nebes, R.D. Dominance of the minor hemisphere in commissurotomized man on a test of figural unification. Brain, 1972, 95, 633-635. .

Nebes, R.D. Superiority of the minor hemisphere in commissurotomized man for the perception of part-whole relations. Cortex, 1971, 7, 333-347.

Nebes, R.D. Hemisphere specialization in commissurotomized man. Psychological Bulletin, 1974, 81, 1-14.

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

Oscar-Berman, J., Rehbein, L., Portfert, A. & Goodglass, H. Dichhaptic hand-order effects with verbal and nonverbal tactile stimulation. Brain and Language, 1978, 6, 323-33.

Paillard, J., & Brouchon, M. Active and passive movements in the calibration of position sense. In S.J. Freedman (Ed.), The neuropsychology of spatially oriented behavior. Homewood, Illinves: Dorsey Press, 1969.

Paillard, J. & Brouchon, M. A proprioceptive contribution to the spatial encoding of a position cues for ballistic movements. Brain Research, 1974, 71, 273-284.

Paterson, A. & Zangwill, O.L. Disorders of visual space perception associated with lesions of the right cerebral hemisphere. Brain, 1944, 67, 331-358.

Phillip, M. & Summers, D. Relationship of kinesthetic perception to motor learning. Research Quarterly, 1954, 25, 456-469.

Provins, K.A. The effect of training and handedness on the performance of two simple motor tasks. Quarterly Journal of Experimental Psychology, 1958, 10, 29-39.

Raizkowski, D. & Kalat, J.W. Reliability and validity of some handedness questionnaire items. Neuropsychologia, 1974, 12, 43-47.

Ray, W., Morell, M., Friedani, A. & Tucker, D. Sex differences and lateral specialization of hemispheric functioning. Neuropsychologia, 1976, 14, 391-395.

Reitan, R.M. Psychological deficits resulting from cerebral lesions in man. In J.M. Warren and K. Akert (Eds.) The frontal granular cortex behavior. New York: McGraw-Hill, 1964.

Rhodes, D.L. & Schwartz, G.E. Lateralized sensitivity to vibrotactile stimulation: Individual differences revealed by interaction of threshhold and signal detection tasks. Neuropsychologia, 1981, 19, 831-835.

Roy, E.A. Spatial cues in memory for movement. Journal of Motor Behavior, 1976, 9, 151-156.

Roy, E.A. Measuring change in motor memory. Journal of Motor Behavior, 1976, 8, 283-287.

Roy, E.A. Role of preselection in memory for movement extent. Journal of Experimental Psychology: Human Learning and Memory, 1978, 4, 307-405.

Rudel, R., Denckler, M. & Hirsch, S. The development of left-hand superiority for deseminating braille configurations. Neurology, 1977, 27, 160-164.

Rudel, R.G., Denckler,M.B. & Spalten, E. The functional asymmetry of braille letter learning in normal sighted children. Neurology, 1974, 24, 733-738.

Russell, D.G. Spatial location cues and movement position. In G. Stelmach (Ed.) Motor Control-Issues and Trends, New York: Academic Press, 1976.

Sarnoff, S.J. & Arrowhead, J.G. Differential spinal block. III. The block of cutaneous and stretch reflexes in the presence of unimpaired position sense. Journal of Neurophysiology, 1947, 10, 205-210.

Satz, P., Achenbach, K., Pattishall, E. & Fennel, E. Order of report, ear asymmetry and handedness in dichhotic listening. Cortex, 1965, 1, 377-396.

Schutz, R. Absolute error. Journal of Motor Behavior, 1974, 6, 299-301.

Schutz, R. & Roy, E. Absolute error: The devil in disguise. Journal of Motor Behavior, 1973, 5, 141-153.

Segalowitz, S.J., & Gruber, F.A. Language development and neurological theory. New York: Academic Press, 1977.

Semmes, J., Weinstein, S., Ghent, L., & Teuber, H.L. Somatosensory changes after penetrating brain wounds in man. Cambridge: Harvard, 1960.

Smith, A. Speech and other functions after left (dominant) hemispherectomy. Journal of Neurology, Neurosurgery, and Psychiatry, 1966, 29, 467-471.

Sperry, R.W. & Gazzaniga, M.S. Language follwing surgical disconnection of the hemispheres. In C.M. Millikan and F.L. Darby (Eds.) Brain Mechanisms Underlying Speech and Language. New York: Green and Stratton, 1967.

Sperry, R.W., Gazzaniga, M.S. & Bogen, J.E. Interhemispheric relationships: The neocortical commissures; syndromes of disconnection. In P.J. Vinkin and G.W. Bruyn (Eds.), Handbook of clinical neurology, 4, Amsterdam: North Holland Publishing Company, 1969.

Stafford, R.E. Sex differences in spatial visualization as evidence of sex-linked inheritance. Perceptual and Motor Skills, 1961, 13, 428.

Stelmach, G.E., Kelso, J.A. & Wallace, S.A. Preselection in short-term motor memory. Journal of Experimental Psychology: Human Learning and Memory, 1975, 1, No. 6, 745-755.

Subirana, A. The prognosis in aphasia in relation to cerebral dominance and handedness. Brain, 1958, 81, 415-425.

Trotman, S. & Hammond, G. Sex differences in task dependent EEG asymmetries. Psychophysiologia, 1979, 16, 429-431.

Umilta, C., Rizzolatti, G., Marze, C.A., Zamboni, G., Franzini, C., Camarda, R. & Berlucchi, G. Hemispheric differences in the discrimination of line orientation. Neuropsychologia, 1974, 12, 165-174.

Varney, N.R. & Benton, A.L. Tactile perception of direction in relation to handedness and familial handedness. Neuropsychologia, 1975, 13, 449-454.

von Holst, E. Relations between the central nervous system and the peripheral organs. British Journal of Animal Behavior, 1954, 2, 89-94.

Wallace, S.A. The coding location: A test of the target hypothesis. Journal of Motor Behavior, 1977, 9, No. 2, 157-169.

Warrington, E.K. Constructional apraxia. In P.J. Vinkin and G.W. Brown (Eds.), Handbook of Clinical Neurology, 4, Amsterdam: North Holland Publishing Company, 1969.

Warrington, E.K. & Rabin, P. Perceptual matching in patients with cerebral lesions. Neuropsychologia, 1970, 8, 475-487.

Weinstein, S. Differences in effects of brain wounds implicating right or left hemispheres. In V.B. Mountcastle (Ed.), *Interhemispheric relations and cerebral dominance*. Baltimore: John Hopkins Press, 1962.

Weinstein, S. The relationship of laterality and cutaneous area to breast-sensitivity in sinistrals and dextrals. *American Journal of Psychology*, 1963, *76*, 475-479.

Weinstein, S. Intensive and extensive aspects of tactile sensitivity as a function of body part, sex and laterality. In D.R. Kenshalo (Ed.), *The skin senses*. Springfield, Illinois: Thomas, 1968.

Weinstein, S. & Sersen, E. Tactual sensitivity as a function of handedness and laterality. *Journal of* Comparative and Physiological Psychology, 1961, *54*, 665-669.

White, M.J. Laterality differences in perception: A review. *Psychological Bulletin*, 1969, *72*, 387-405.

Williams, I.D. & Roy, E.A. Closed-loop control of a ballistic response. *Journal of Motor Behavior*, 1972, *4*, 121-126.

Witelson, S.F. Hemispheric specialization for linguistic and nonlinguistic tactual perception using a dichotomous stimulation technique. *Cortex*, 1974, *10*, 3-17.

Witelson, S.F. Sex and the single hemisphere: Specialisation of the right hemisphere for spatial processing. *Science*, 1976, *193*, 425-427.

Witelson, S.F. Abnormal right hemisphere specialization in developmental dyslexia. In R. Knights and D. Bakker (Eds.) *The neuropsychology of learning disorders: Theoretical approaches*. Baltimore: University Park Press, 1976. (b)

Wolff, B.B. & Jaruik, M.E. Relationship between superficial and deep somatic pain with a note on handedness. *American Journal of Psychology*, 1964, *77*, 589-599.

Zangwill, O.L. Cerebral dominance and its relations to psychological functions. Edinburgh: Olwin and Boyd, 1960.

Zaidel, D. & Sperry, R.W. Performance on the Ravins Colored Progressive Matrues Test by subjects with cerebral commissurotomy. Cortex, 1973, 9, 34-39.

Zurif, E.B. & Bryden, M.P. Familial handedness and left-right differences in auditory and visual perception. Neuropsychologia, 1969, 17, 179-187.