DOES THE RIGHT CEREBRAL HEMISPHERE CONTRIBUTE TO LIMB PRAXIS?

EVIDENCE FROM LIMB APRAXIA FOLLOWING UNILATERAL STROKE

by

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Each experiment in this dissertation has been written in manuscript format; suitable for publication in an APA formatted journal.

ABSTRACT

Five experiments are reported which examine limb praxis, and the frequency and severity of limb apraxia following left or right hemisphere stroke. Apraxia is a disorder of skilled, purposeful action (e.g., picking up a glass, waving goodbye) which cannot be attributed to basic sensory or motor impairments, inattention to commands or poor comprehension. Liepmann's (1908) writings at the turn of the century serve as doctrine for classical approaches to the study of apraxia, and subsequent adherence to the notion that apraxia follows lesions to the left cerebral hemisphere (e.g., Heilman, Rothi, & Velenstein, 1982). However, recent research employing quantitative measurement techniques has shown that apraxia can also be elicited following right hemisphere stroke (Haaland & Flaherty, 1984; Roy, Black, Blair, & Dimeck, 1998). The observation that right hemisphere lesions can also impair praxis served as the foundation for the present research. In two experiments (Experiments 1 and 3) the frequency and severity of apraxia during the pantomime and imitation of transitive (Experiment 1) and intransitive (Experiment 3) limb gestures was evaluated in a sample of patients with unilateral left (LHD) or right hemisphere lesions (RHD). A multi-dimensional error notation system was used to quantify gesture production errors. The results indicated that a significant number of LHD and RHD patients were classified as apraxic, with measures of apraxia severity failing to differentiate between stroke groups. Moreover, using the patterns of apraxia proposed by Roy (1996 [pantomime alone, imitation alone, pantomime and imitation]) it was revealed that LHD does not exclusively impair the selection/evocation stage of gesture production, as indicated by others (e.g., Barbieri & De Renzi, 1988).

Rather, a significant proportion of LHD patients demonstrated impairments in the executive stage of gesture production.

The second experiment served as the basis for differentiating between transitive and intransitive limb gestures in Experiments 1 and 3. In this investigation, a case study involving an individual specifically impaired in the selection/evocation stage of intransitive limb gestures is discussed. Further, this case study provides emergent evidence for parallel and independent systems governing the production of separate gesture forms (transitive vs. intransitive).

In the fourth experiment, a three-dimensional kinematic procedure was developed to examine limb praxis in healthy controls. The results from Experiment 4 provide important methodological detail for examining movement kinematics in unilateral stroke populations. Specifically, identifying a dominant (right) hand advantage for the production of transitive limb gestures.

In the fifth experiment, three-dimensional analyses were employed to examine spatial temporal errors in gesture production following left (N = 4) and right (N = 4) hemisphere stroke. Group results failed to reveal spatial parameterization errors in either stroke group, however, individual patient analyses indicated that one LHD, and one RHD patient demonstrated joint synchronization and temporal coordination errors respectively. These data support previous observational analyses (Experiments 1 and 3) that apraxia can be elicited following right hemisphere stroke.

The results of this research project demonstrate that left or right hemisphere lesions can result in apraxia. Moreover, this research demonstrates that the quantitative assessment of apraxia, combined with careful manipulation of gesture forms (transitive

vs. intransitive) and stimulus modality (pantomime vs. imitation), provide detail critical in extending our knowledge of limb praxis..

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GISÈLE,

AND

MOM AND DAD,

THANK YOU

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GENERAL INTRODUCTION

Limb apraxia represents an impaired ability to generate skilled movements that cannot be attributed to basic sensory or motor disturbances. Instead, apraxia is believed to reflect a disruption to high-level perceptual, cognitive and motor systems that form a distributed praxis network (Rothi, Ochipa, & Heilman., 1991). Liepmann's (1908) writings at the turn of the twentieth century provide the foundation for traditional accounts of limb apraxia. Liepmann proposed that the evolving formation of a skilled action involves a two component action system. Movement formulae, or time-space representations of skilled action represent the first component of this system, with the requisite module(s) necessary for translating movement formulae into action comprising the second (see Figure 1). In such a formulation, Liepmann believed that the genesis of limb apraxia could reflect a disruption to unitary or multiple components of the action system.

Insert Figure 1 about here

In concert with his writings concerning the underlying mechanisms associated with gesture production, Liepmann proposed a neuroanatomical locus for this action system. Liepmann (1905) investigated 83 patients with a right or left brain-lesion, noting that none of his right brain-lesioned patients were apraxic, while approximately one-half of the left brain-lesioned patients were. Based on these findings, Liepmann concluded that the left motor cortex dominates the right in the control of movement praxis for both hands, with the left hemisphere asserting control over the ipsilateral (left) limb via the corpus callosum. More specifically, Liepmann asserted that parietal and frontal regions

within the left hemisphere contain the space-time representations and translation module(s) respectively.

Liepmann's writings regarding the neuroanatomical genesis of limb apraxia serve as his most enduring legacy, as evidenced by a wealth of research supporting left hemisphere dominance of praxis (e.g., Geschwind, 1965; Barbieri & De Renzi, 1988; De Renzi, Piecquro, & Vignolo, 1968; Heilman, Rothi, & Valenstein, 1982). Indeed, the vast number of studies subsequently supporting Liepmann has lead to such pervasive adherence to the notion of left hemisphere dominance for praxis, that several researchers have wholly ignored right hemisphere contributions in praxis control (e.g., Belanger, Duffy, & Coehlo, 1996). However, the exclusive role of the left hemisphere in praxis and limb apraxia has recently been questioned. Mounting evidence suggests that praxis representation may be moderated by variables such as gesture type (Dumont, Ska, & Schiavetto, 1999; Rapscak, Ochipa, Beeson, & Rueben, 1993), stimulus modality (Schnider, Hanlon, Alexander, & Beeson, 1997), and response complexity (Kimura, 1982). Moreover, the work of Haaland and colleagues (Haaland & Flaherty, 1984; Haaland, Harrington, & Knight, 1999) and Roy and colleagues (Roy, Black, Blair, & Dimeck, 1998) has shown that the aforementioned factors in combination with limitations associated with praxis evaluation systems may have obscured right hemisphere contributions to praxis. Hence, quantitative assessment of factors such as gesture type and elicitation modality may further our understanding of the cerebral representation of limb praxis and praxic disorders.

Central to our understanding of limb apraxia is the advent of quantitative techniques for the assessment of the disorder. Traditionally, limb praxis evaluation has

been based upon gesture recognizability (Liepmann, 1908; De Renzi et al., 1968). This type of assessment technique focuses very little upon the details of gesture production, and thus may limit quantification of production errors following right hemisphere stroke. For instance, although a hammering action may be recognized, the movement may be of exaggerated amplitude, or in the incorrect plane of motion; these praxic disorders are not quantified in gesture recognition/evaluation techniques. Indeed, research which has employed quantitative techniques for assessing limb trajectory and gesture production errors following unilateral stroke has shown that right hemisphere lesions can also elicit praxis production errors (Haaland & Flaherty, 1984; Haaland et al., 1999; Roy et al., 1998). Hence, the application of quantitative measurement systems may extend our knowledge of how left and right brain-lesions impact praxis.

Another issue imperative to apraxia research is the methodological approach used in the identification of various praxic disorders. Several different types of apraxia have been identified (see Rothi & Heilman, 1997 for complete review), although ideational and ideomotor apraxia are the two most well known types. The term ideational apraxia encompasses several definitions, reflecting a lack of consensus among researchers as to its precise meaning (Poeck, 1983). The definition adopted in the present research reflects the most widely accepted description of the disorder, that is, a destruction (Heilman et al., 1982), or inability to select/evoke (Barbieri & De Renzi, 1988) the space-time, or memorial representation of an action from semantic memory. The definition of ideomotor apraxia is more widely accepted, representing an impaired ability to translate the space-time representation of learned actions into the appropriate innervatory patterns necessary for overt gesture production (Heilman & Rothi, 1985).

Classical approaches to identifying apraxic types have relied upon the errors observed in gesture production. Ochipa, Rothi, & Heilman (1992) have argued that ideational apraxics exhibit content errors, for example, executing a combing action when asked to pantomime the use of a toothbrush. In contrast, ideomotor apraxics display production, or spatial temporal errors, for example, movements of exaggerated amplitude. Identifying ideational and ideomotor forms of limb apraxia via error type is loosely based on Liepmann's (1908), and more recent (Rothi et al., 1991/1997) two stage models of gesture production. As such, content errors are believed to underlie disruptions to the first stage of gesture production, representing a failure to correctly select/evoke the correct representation of an action from memory. In contrast, the production errors associated with ideomotor apraxia follow disruptions to the second stage of gesture production where the innervatory patterns necessary for overt performance are transcribed.

Another approach used in identifying apraxic types is the manipulation of elicitation modalities. Gestural pantomime and imitation are elicitation modalities in which participants respond to a verbal command (pantomime), or replicate an action modelled by an experimenter (imitation). Impaired performance in response to verbal command (pantomime) is thought to reflect a deficit in the first stage of gesture production, or a failure in accessing or evoking the representation of the action from memory (De Renzi & Luchelli, 1988). Impaired gestural imitation is thought to underlie an executive impairment; a disorder of the second stage of action production (Goldenberg, 1996).

While the two approaches discussed above have provided relevant information toward our understanding of limb apraxia, each is limited in its ability to accurately specify whether an individual is specifically impaired by a response selection or executive impairment. This limitation stems from the failure of each approach to assess production errors across pantomime and imitation modalities (see Roy, 1996 for complete review). For example, when pantomime and imitation performance are examined in isolation, as is the case for the two techniques described above, impaired performance to imitation alone, or the type of errors observed in this elicitation modality, do not exclusively indicate an executive disorder as hypothesized by Goldenberg (1996). Instead, impaired imitation may reflect an inability to analyze visual gestural information, or translating this information into movement (conduction apraxia; Heath, Westwood, Roy, & Black, 2000; Ochipa, Rothi, & Heilman, 1994). Moreover, identifying a selection/evocation disorder based on gestural pantomime is not sufficient information for identifying an ideational form of apraxia, as the individual may also be impaired when imitating a gesture, indicative of an executive impairment (ideomotor apraxia). To accommodate these limitations, Roy (1996) has proposed a model of apraxia, in which the performance of an individual patient is evaluated concurrently in pantomime and imitation contexts. Subsequently, performance patterns across elicitation modalities can be assessed leading to the identification of ideational, ideomotor and conduction (visual/imitative) forms of apraxia.

The first pattern of apraxia described by Roy (1996; see model depicted in Figure 2) is one in which performance is impaired in pantomime alone, with deficits not concurrently observed in the imitation context. This pattern is thought to reflect an

impaired ability to access or select/evoke the appropriate representation of the learned action from memory. An executive deficit cannot be attributed to this pattern, as similar deficits are not observed in the imitation condition. The second pattern is one in which performance is impaired to imitation but not pantomime. In this pattern, the underlying deficit reflects an impaired ability to analyze visual gestural information, or translate this information into movement. The preserved ability to pantomime a gesture in this pattern suggests that the selection/evocation and executive stages of production are intact. The final pattern is one in which performance is impaired concurrently to pantomime and imitation. In this case, the individual is able to select the appropriate action from memory, and knows what the action looks like, but is unable to transcribe the relevant innervatory patterns, a final common path for all gestures on their way to action. The pattern analyses described by Roy may provide a better understanding of the specialized roles of the cerebral hemispheres in movement praxis, since the model is able to identify the specific stage, and hence mechanisms underlying praxis impairments.

Insert Figure 2 about here

Roy's model of apraxia may provide the relevant methodological framework for identifying the neuroanatomical correlates of limb praxis. Indeed, classical understanding about the anatomy of apraxia (ideational and ideomotor) follows closely the original writings of Liepmann (1920) and Geschwind (1968), and their views concerning left hemisphere dominance for praxis. In both schemes, the modality of eliciting gesture production was an important consideration in the expression of a particular apraxic subtype. In particular, damage to Wernicke's area was thought to destroy the visuokinesthetic engrams responsible for the formulation of learned, skilled

action, thus resulting in an ideational form of limb apraxia. In contrast, infarctions involving white matter connections, typically the arcuate fasiculus, and/or their terminal connections to supplementary (Heilman et al., 1982) or motor cortex were thought to impair the transcoding of the time-space engrams of learned action, resulting in an ideomotor form of apraxia. However, evidence supporting this view has not been garnered from neuroimaging studies of apraxia. Indeed, three large neuroimaging studies (Alexander, et al., 1992; Basso, Luzzatti, & Spinner, 1980; Kertesz, Ferro & Shewan, 1984) failed to report a specific neuroanatomical region associated with either ideomotor or ideational limb apraxia (see also De Renzi & Luchelli, 1988). Moreover, several case studies have reported ideomotor apraxia following purely subcortical lesions (e.g., Agostoni, Colletti, & Orlando, 1983; Alexander, Naeser, & Palumbo, 1987). Hence, evidence from neuroimaging data do not conclusively support Liepmann or Geschwind's conceptualisation of the neuroanatomical sequelae responsible for limb apraxia.

The ability to identify a precise neuroanatomical region critical for praxis may be tempered by two elements. In the first case, the position that a specific cortical region (i.e., inferior parietal lobule) entirely controls the formulation of complex actions such as hammering a nail or picking up a cup of water does not fully appreciate the complexity of these acts. For instance, recent anatomical and functional studies have identified in primates a series of segregated parietofrontal circuits working in parallel for the coordination of reaching and grasping movements (Wise, Boussaoud, Johnson, & Caminiti, 1997). Indeed, the two components associated with reaching and grasping (transport and grasp components) are subserved by parallel systems. The parietofrontal circuits subserving the transport (reaching) phase are believed to originate in the superior

parietal lobe and dorsal regions of the premotor cortex, whereas inferior parietal and ventral regions of the premotor cortex are believed to subserve the grasping component (Lacquaniti, Guigon, Bianchi, Ferraina, & Caminiti, 1995). Leiguarda and Marsden (2000) proposed that apraxia (ideomotor) is related to disruptions of diffuse parietofrontal circuits and their subcortical connections. Thus, the diffuse representation of learned actions and their cognitive-motor interactions may preclude a definitive localization of the neuroanatomical sequelae involved in praxis following acquired brain injury.

The second element critical to our understanding of the neuroanatomical correlates of limb apraxia, and central to the present investigation, is the identification of specific apraxic subtypes. Indeed, previous neuroimaging studies have failed to distinguish between ideational and ideomotor apraxic patients in their samples due to their one-dimensional evaluation of the disorder. In such cases the assessment of apraxia is restricted to one stimulus modality (e.g., pantomime or imitation). For example, Kertesz et al. (1984) restricted their assessment of apraxia to a pantomime condition, thus it is unclear whether the patients included in this sample were similarly impaired to imitation. As discussed above, using pantomime and imitation modalities in isolation does not provide sufficient data for the identification of a particular apraxic subtype, thus it is likely that the sample of patients employed by Kertesz et al. included a heterogeneous group of ideational and ideomotor apraxics. Such a methodology may hinder the identification of the neuroanatomical correlates of apraxia, as the cortical/subcortical regions responsible for selection/evocation (ideational apraxia) and response execution (ideomotor apraxia) are likely dissociable. Indeed, identifying and recruiting specific apraxic subtypes (e.g., ideomotor) via the pattern analyses described

by Roy (1996; see above) may provide the requisite methodology for disseminating the neural correlates of limb praxis. Hence, the present investigation provides a behavioural paradigm to be employed for the selection of patients in future neuroimaging studies of apraxia.

One final element relevant to apraxia research is the impact of gesture forms on the expression of the disorder. Transitive limb (tool based; e.g., hammering a nail, picking up a cup), intransitive (expressive/communicative content; e.g., waving goodbye, saluting an army officer), and non-representational (novel hand postures) gesture are employed in limb praxis batteries. Several investigators have failed to consider whether different gesture forms differentially contribute to the genesis of limb apraxia. For instance, De Renzi and colleagues (e.g., Barbieri & De Renzi, 1988; De Renzi et al., 1968) employed transitive limb gestures when evaluating gestural pantomime, while intransitive limb gestures were used to assess gestural imitation. Even more confounding is the fact that several researchers have not differentiated between gesture forms within an elicitation modality. In this scenario, transitive and intransitive limb gestures are used interchangeably to assess praxis errors within pantomime or imitation contexts (e.g., Alexander et al., 1992).

Evidence from optic aphasia research (Beauvois & Saillant, 1985; Shallice, 1987) as well as recent case study of apraxia (Dumont et al., 1999) has demonstrated that multiple semantic and response output systems underlie separate gesture forms (transitive vs. intransitive). Hence, those studies that have not systematically differentiated between gesture forms may have limited our understanding of the frequency and severity of praxic disorders. Moreover, differentiating between transitive and intransitive limb gestures

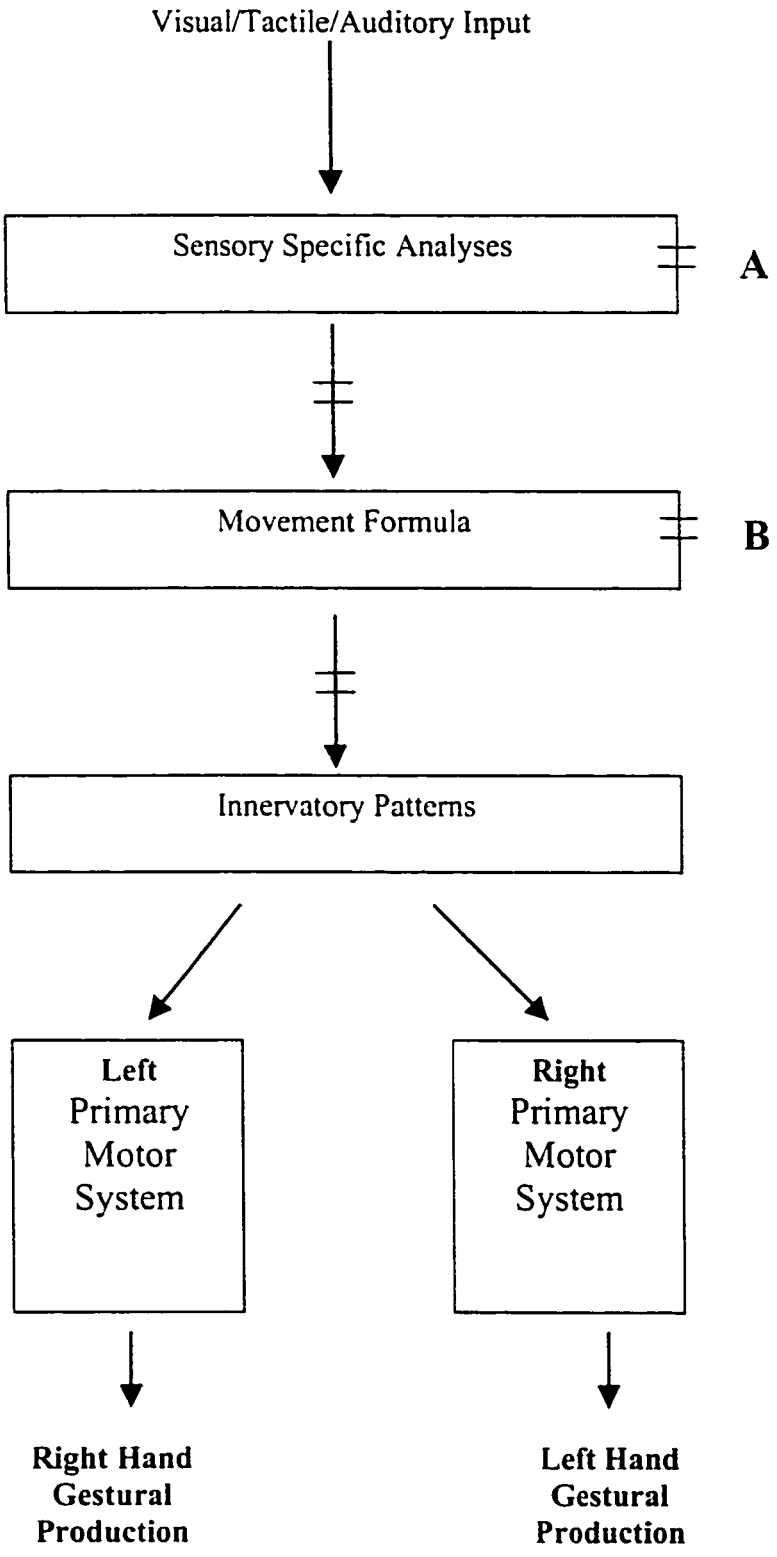
may enhance our understanding of whether separate gesture forms differentially contribute to the expression of apraxia following left or right hemisphere stroke.

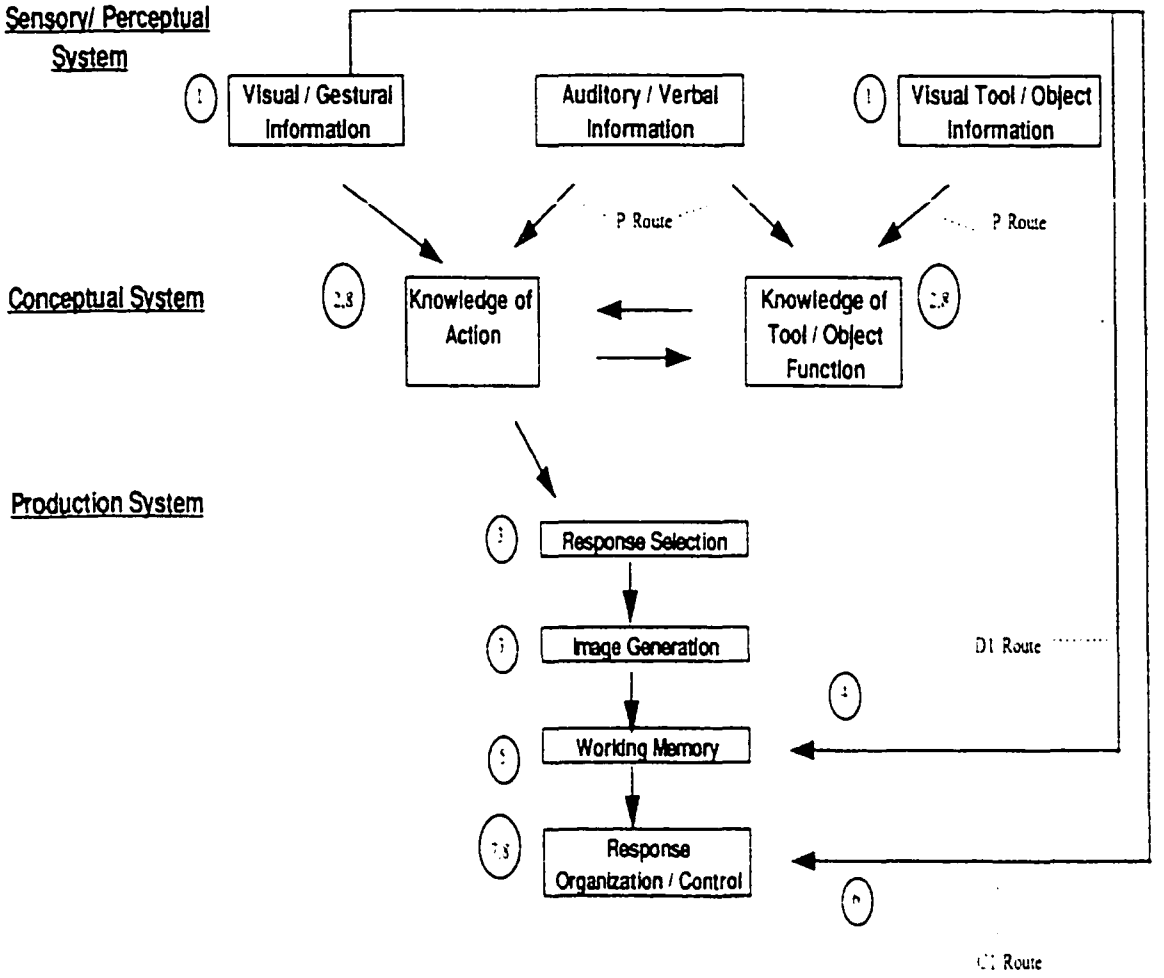
The primary goal of the following experiments was to apply quantitative assessment techniques to the study of limb apraxia following left or right hemisphere stroke to determine the cerebral representation of limb praxis. In the first three experiments, multi-dimensional observation analyses were employed to quantify the frequency. and typology of apraxia following left or right hemisphere stroke. Issues such as stimulus modality, and gesture type are addressed in these experiments to determine whether such factors differentially contribute to the expression of the disorder. Further, Experiments 1 and 3 entail the first group investigations to examine the patterns of apraxia described by Roy (1996). In addition to observational analysis, a three-dimensional kinematic analyses procedure was developed, and applied to the examination of limb praxis in the dominant and non-dominant limbs of healthy participants to examine limb praxis in this population (Experiment 4). Experiment 4 provided the methodological devices necessary for applying three-dimensional analyses in unilateral stroke populations. Finally, Experiment 5 employed kinematic analyses to identify specific spatial-temporal impairments in gesture production following unilateral left or right hemisphere stroke.

Figure Captions

Figure 1. Liepmann's conceptualisation of praxis processing. Arrows with crossed lines represent stages of praxis processing Liepmann believed could be impaired following left hemisphere lesions. Movement formulae (A) represent the first stage in this praxis network, and the module(s) transcribing the movement formulae into innervatory patterns (B) comprise the second.

Figure 2. Roy's (1996) neurobehavioural model of limb praxis and praxic disorders. The patterns of apraxia discussed in the present research are represented in this model (3, 6, 7). The first pattern is one in which pantomime but not imitation performance is impaired (3). For this pattern, a disruption to the response selection, or image generation stage is indicated. The second pattern, impaired imitation but not pantomime performance (6) reflects an impaired ability to analyze or translate visual gestural information into movement. The final pattern (7) represents a disruption to the executive, or response organization/control stage of processing. Indeed, performance decrements to pantomime and imitation reflect a deficit at this stage of processing as it represents the final common pathway for all gesture on their way to action.


Visual/Tactile/Auditory Input
Sensory Specific Analyses
A
Movement Formula
B
Innervatory Patterns
Left Primary Motor System
Right Primary Motor System
Right Hand Gestural Production
Left Hand Gestural Production


Sensory/ Perceptual System
Visual / Gestural Information
Auditory / Verbal Information
Visual Tool / Object Information
P Route
P Route
Conceptual System
Knowledge of Action
Knowledge of Tool / Object Function
Production System
Response Selection
Image Generation
DT Route
Working Memory
Response Organization / Control

EXPERIMENT ONE

ABSTRACT

The present study was designed to examine the frequency and severity of apraxia in patients with left or right hemisphere stroke in both pantomime and imitation conditions and to compare the frequency of apraxia in each stroke group across the three patterns of apraxia described in Roy's model (Roy, 1996). Ninety-nine stroke patients and 15 age-matched healthy adults performed eight transitive gestures to pantomime and to imitation. Gestural performance was quantified as accuracy on five performance dimensions and a composite score, an arithmetic combination of the five performance dimensions used as an index of overall accuracy. Analyses revealed a comparable proportion of patients in each stroke group were classified as apraxic, and the severity of the apraxia in these two apraxic stroke groups was also equivalent. Accuracy in the pantomime condition was lower than in the imitation condition, but the frequency and severity of apraxia in these two conditions was comparable in the two stroke groups. Analyses of the patterns of apraxia (pantomime alone, imitation alone or apraxia in both conditions) revealed a higher frequency of apraxia in both stroke groups for the pattern reflecting apraxia in both conditions, indicating that a disruption at the movement execution stage of gesture performance was most common.

EXPERIMENT ONE

Limb apraxia is a movement disorder usually associated with lesions to the left cerebral hemisphere which cannot be accounted for by weakness, sensory loss, poor coordination of movement, poor comprehension, or inattention to commands (Rothi and Heilman, 1997). One of the earliest observations about apraxia was that impairments could be seen under some performance conditions but not others. For example, Liepmann (1908) distinguished between performance to command (or pantomime), when the patient must generate the gesture from memory, and imitation, where the patient must copy a gesture demonstrated by the examiner. Liepmann suggested that impairments to pantomime reflected a disruption in the engram or motor program for the action or gesture, while impairments to imitation reflected an inability to implement, execute or control the gestural movements. Over the ensuing years many studies have compared performance of gestures in both conditions, noting that impairments are more severe when pantomiming gestures (Alexander, Baker, Naeser, Kaplan, & Palumbo, 1992; Lehmkuhl, Poeck, & Wilmes, 1983; Poeck, Lehmkuhl, & Wilmes, 1982; Schnider, Hanlon, Alexander, & Benson, 1997; Watson Fleet, Rothi & Heilman, 1986), but a double dissociation has also been observed with some patients being more impaired on imitation (Barbieri & De Renzi, 1988; De Renzi, Faglioni, & Sargato, 1982; Ochipa, Rothi, & Heilman, 1994).

In a series of studies comparing performance in pantomime and imitation conditions De Renzi (Barbieri & De Renzi, 1988; De Renzi & Lucchelli, 1988; De Renzi et al., 1982; De Renzi, Motti, & Nichelli, 1980) found a dissociation in these performance conditions between patients with left-hemisphere damage (LHD) and those with right-hemisphere damage (RHD). De Renzi (Barbieri & De Renzi, 1988) primarily quantified

apraxia based on the frequency or proportion of patients who fell below a performance cutoff score defined as the lowest score in a group of age-matched non-brain-damaged adults (controls). While a higher proportion of patients with LHD were apraxic in both conditions, the difference in frequency was larger in the pantomime condition. De Renzi (Barbieri & De Renzi, 1988) further examined patients who demonstrated a greater impairment in one condition or the other. An equal proportion of patients in each brain-damaged group were more impaired on imitation than pantomime. In contrast, a significantly higher proportion of patients with LHD were more impaired on pantomime than imitation. Consistent with the findings that pantomime and imitation can be dissociated, De Renzi (Barbieri & De Renzi, 1988; De Renzi et al., 1980) showed that performance in these two conditions was not correlated and suggested that they engaged different processes underlying praxis. Like Liepmann (1908), De Renzi thought that pantomime reflected ideational processes involved in evoking or generating a gesture from memory, while imitation reflected the ability to execute the movements involved in performing the gesture. De Renzi reasoned that the higher frequency of patients with LHD showing a greater impairment on pantomime than imitation reflected the dominant role played by the left hemisphere in the ideational component of gesture performance.

More recent accounts of apraxia have extended these studies by De Renzi and others, and suggest that apraxia may arise from disruptions to various stages of gesture performance. In their initial formulation of this notion, Roy and Square (1985) argued that apraxia may result from a disruption in a conceptual system and/or a production system. The conceptual system is thought to contain knowledge about actions, objects and tools, and knowledge relevant to movement sequencing. Production systems are

involved in the execution of action, and may include stored motor programs and innervatory patterns (Rothi, Ochipa & Heilman, 1991, 1997).

Building on this model of apraxia, Roy and Hall (1992) made specific predictions about the types of impairment that might be observed following disruptions to various stages in gestural performance. Pantomiming gestures is thought to place demands on the ideational system, as the performer must generate a gesture from memory based on representations of tools and actions. Imitating gestures is thought to require visual analysis of gestural information, and may completely bypass the ideational system. Both routes to action are thought to map onto a later stage in the production system responsible for movement execution.

More recently Roy (1996) referred to the three possible combinations of apraxia across pantomime and imitation as patterns of apraxia and suggested that each pattern could reflect a disruption at a particular stage in gestural performance. The pattern in which apraxia is present in pantomime but not imitation may reflect disruptions in the ideational system, affecting image generation or response selection. Apraxia in the imitation condition alone is thought to reflect a disruption in the ability to analyze the visual gestural information presented by the examiner, or in the translation of this visual gestural information into movement. Apraxia in both conditions is thought to reflect a selective disruption at a later stage in gestural performance involving movement execution.

The present study was designed to examine the frequency and severity of apraxia in patients with left or right hemisphere stroke in both pantomime and imitation, and to compare the frequency of apraxia in each stroke group across the three patterns of apraxia

described in Roy's model (Roy, 1996). The frequency and severity of apraxia was expected to be greater for the patients with LHD, particularly in the pantomime condition. Further, De Renzi's findings (Barbieri & De Renzi, 1988) predict the frequency of apraxia should be much higher for patients with LHD in the pattern of apraxia reflecting disruptions in ideational processes, that is, apraxia on pantomime alone. An equal frequency of apraxia was expected in the pattern in which imitation alone is impaired.

One problem with many investigations of apraxia is that the analysis of gestural performance appeared insensitive to subtle apraxic impairments which may have lead to an underestimation of the frequency and degree of apraxia, particularly in the patients with RHD. For example, De Renzi (Barbieri & De Renzi, 1988), using a scoring system which focused very little on the details of movement execution, found the frequency of apraxia in his RHD patients when pantomiming gestures to be at 13 percent. Haaland and Flaherty (1984) and more recently Schnider et al. (1997), using more detailed error analyses, found much greater apraxic impairments in their patients with RHD. For example, Schnider at al (1997) found that 45 percent (5/11) of patients with RHD fell in the apraxic range when pantomiming and imitating meaningful gestures. Recent work by Roy et al. (1998) supports these observations. Using a detailed analysis of pantomime performance across five dimensions, Roy et al. found that RHD patients were significantly less accurate than controls, and the frequency of apraxia in these patients was 30 percent. The present investigation was designed to extend Roy et al's work by employing this same detailed analysis system to examine gestural performance in both pantomime and imitation.

METHOD

Participants

Ninety-nine consecutive patients with a single unilateral hemispheric stroke, 46 lateralized to the left hemisphere (LHD), and 53 lateralized to the right (RHD), and 15 healthy adults with no history of neurologic or neuromuscular disorders served as participants in the study (see Table 1). All stroke patients met the inclusion criteria which were a unilateral hemispheric stroke and sufficient comprehension and stamina to complete the assessment. The control group matched as closely as possible the age and gender distribution in the stroke groups. All participants were right-handed. Consent to participate in this study was obtained from all participants or their proxy. The stroke diagnosis was confirmed by the presence of an appropriate lesion on CT, or by a clinically appropriate focal perfusion abnormality seen on ^{99}Tc-HMPAO-SPECT scan images obtained on a single-head GE gamma camera.

Analyses comparing the three groups revealed no significant differences in age. In addition the two stroke groups did not differ in the time of apraxia assessment from stroke onset.

Insert Table 1 about here

Gestural Tasks and Performance Scoring

Participants were required to pantomime and imitate eight transitive gestures which had been examined in a previous study of gestural pantomime (Roy et al, 1998). In the pantomime condition participants were shown each tool and asked to pretend to use it in performing a particular action. For example, the request for the hammer was, "show me how you would use this to pound a nail here" (examiner points to a location

directly in front of the participant). In the imitation condition the examiner demonstrated the gesture while the participants attempted to imitate the examiner's performance. The examiner continued to demonstrate the gesture during the patient's attempt at imitation. The pantomime condition was always performed first in order to avoid providing cues to the participants as to how each gesture was performed.

As noted elsewhere, (Roy et al., 1998) the dimensions of repetitiveness and spatial location relative to the body (e.g., gesture toward or on the body versus away from the body) contribute to the complexity of the gesture. Hence, of the sample of gestures employed, four reflected non-repetitive movements performed toward (eat a spoonful of soup, put on glasses) or away from the body (pick up a ball, use a key to open a lock), and the other four were repetitive gestures performed toward (brush teeth, comb hair) or away from the body (saw wood, hammer a nail).

The stroke patients used their ipsilesional hand to perform gestures, while control participants used both hands with half using their right hand first. The performance of each participant was videotaped and scored on the basis of five performance dimensions: orientation of the hand, action (the movement characteristics of the gesture), the posture of the hand, plane of movement of the hand, and location of the hand in space relative to the body. These performance dimensions were developed in previous work (Roy, Square, Adams, & Friesen, 1985; Roy et al, 1998) and are based on movement features important in manual signing (Stokoe, 1972). Each dimension was rated on a 3-point scale reflecting the degree of accuracy as follows: 2 (correct), 1 (distorted), and 0 (incorrect). Within each of the performance dimensions a set of three features were defined which the rater used to determine whether performance on the dimensions should

be rated as 2, 1, or 0. If all the features were present, performance on the dimension was rated as 2. If two features were present, performance was rated as 1. Performance was rated as 0 if one or none of the features was present. Performance on each dimension was expressed as a percentage of the total possible score across the eight gestures. A composite score, the percentage of the total possible score across all dimensions and gestures, was also calculated. Gestural performance was scored on imitation and pantomime from the participants' videotaped performance using the procedures which have been shown to exhibit high inter-rater reliability (Roy et al, 1998).

Aphasia Assessment

Speech and language function was assessed in all patients with LHD on the Western Aphasia Battery (Kertesz, 1979). The overall severity of aphasia was reflected in the Aphasia Quotient (AQ) with a lower score reflecting a more severe impairment.

Data Analysis

Gestural performance was quantified as accuracy on five performance dimensions and a composite score, an arithmetic combination of the five performance dimensions. The composite score was used as an index of the overall accuracy in performing the gestures. Analyses of the correlation between each performance dimension and the composite score, corrected for contamination (Magnusson, 1966, p. 212), revealed that each performance dimension was significantly and positively correlated with the composite score ($p < .01$), indicating that all performance dimensions were reliable predictors of the composite score.

Using the above measures, one set of analyses involved univariate analyses of variance (ANOVA) and focused on the composite score, while a second set using

multivariate analyses of variance (MANOVA) compared performance across the five performance dimensions. A partial least squares procedure (LSD < .05) examined significant effects involving greater than two means.

RESULTS

Performance of Control Participants

Analyses of the control participants revealed no hand differences in performance on the composite score, $F(1, 14) < 1$, or on any of the performance dimensions ($p > .05$). Hence, subsequent analyses pooled the left and right hand data of control participants (Table 2). There was, however, a significant effect for performance condition. Participants exhibited lower overall accuracy in the pantomime relative to the imitation condition as reflected in significantly lower composite scores, $F(1, 14) = 25.43$, $p < .001$. The MANOVA revealed that this reduced accuracy for pantomime was seen across all performance dimensions, $F(1, 14) = 17.79$, $p < .01$.

Insert Table 2 about here

Comparisons Between the Control and Stroke Groups

The pooled left/right hand composite score data of control participants was compared with the ipsilesional hand performance of the stroke groups in a 3 group (control, LHD, RHD) by 2 condition (pantomime, imitation) mixed factor ANOVA. In addition, a 3 group (control, LHD, RHD) by 2 condition (pantomime, imitation) by 5 dimension (location, posture, action, plane, orientation) MANOVA examined the group and condition effects across the five performance dimensions. For the composite score, main effects were seen for group, $F(2, 111) = 6.15$, $p < .01$, and condition, $F(1, 111) = 19.89$, $p < .001$. The participants with LHD were significantly less accurate than the

control but not the RHD group (see Figure 1). Performance accuracy was also significantly lower in the pantomime condition. The MANOVA demonstrated main effects for group, $F(2, 111) = 6.45$, $p < .01$, condition, $F(1, 111) = 17.25$, $p < .001$, and dimension, $F(4, 444) = 26.84$, $p < .001$, as well as a group by dimension interaction, $F(8, 444) = 4.36$, $p < .001$. This interaction indicated that the patients with LHD were significantly less accurate on location and posture dimensions than RHD patients who were in turn more impaired than controls. Further, the patients with LHD were impaired relative to control participants on action and plane dimensions, with RHD patients not differing from either group. The final dimension, orientation, did not reveal significant group differences (see Figure 2).

Insert Table 3 and Figures 1 and 2 about here

We also examined the correlation between pantomime and imitation performance as reflected in the composite scores. There was a significant correlation for all groups with the correlation for the patients with LHD ($r = .900$, $p < .01$) being significantly higher than that for the patients with RHD ($r = .498$, $p < .01$) and the controls ($r = .581$, $p < .05$).

Frequency of Apraxia

The relative frequency of apraxia in each stroke group for each performance condition was assessed by developing a cutoff score based on the mean composite score of the control participants in each performance condition (see Roy et al., 1998). The first cutoff score was equal to one standard deviation below the composite mean (I), and the second cutoff score was equal to two standard deviations below the composite mean (II). The cutoff scores were subsequently used to classify patients within each stroke group as:

non-apraxic (less than score I), borderline apraxic (between scores I and II), or apraxic (greater than score II).

Analyses of the frequency of participants in each category in the pantomime condition revealed a higher proportion of patients with LHD in the apraxic category, and the difference between stroke groups was significant, $\chi^2 = 4.01$, $p = .045$ (Table 4). In the imitation condition the distribution of patients in the two stroke groups did not differ significantly across the two categories, $\chi^2 = 0.98$, $p = .322$.

Insert Table 4 about here

Comparison Between Apraxic and Non-apraxic Groups

The preceding analyses examined the frequency of apraxia in each stroke group in the pantomime and imitation conditions. The following analyses examined which performance dimensions best discriminated between the patients classified as apraxic from those classified as non-apraxic in each stroke group for each performance condition (see Tables 5 and 6). For the patients with LHD there was a main effect of group (apraxic vs. non-apraxic) for both pantomime, $F(1, 44) = 30.79$, $p < .001$, and imitation, $F(1, 44) = 25.92$, $p < .001$), conditions and a group by dimension interaction for both pantomime, $F(4, 176) = 8.55$, $p < .001$, and imitation, $F(4, 176) = 6.70$, $p < .001$. Similarly for the patients with RHD there were main effects of group in both the pantomime, $F(1, 51) = 47.21$, $p < .001$, and imitation, $F(1, 51) = 30.44$, $p < .001$), conditions and group by dimension interactions in the pantomime, $F(4, 204) = 3.59$, $p < .01$, and imitation, $F(4, 204) = 12.27$, $p < .001$, conditions. In both stroke groups the interaction demonstrated that the apraxics were less accurate than the non-apraxics on all performance dimensions, but this difference was largest for the posture dimension.

Insert Tables 5 and 6 about here

Between Hemisphere Comparison of Apraxic Severity

These analyses focused only on the patients classified as apraxic and asked whether the degree of apraxic impairment as indexed by the composite score and individual performance dimensions differed between the stroke groups (see apraxic patients in Tables 5 and 6). Analyses of the composite scores revealed no difference between the stroke groups in the pantomime condition, $F(1, 35) = 1.02$, $p = .320$, or the imitation condition, $F(1, 53) = .333$, $p = .566$. The MANOVA also revealed no group effect for either the pantomime condition, $F(1, 35) = 1.75$, $p = .195$, or the imitation condition, $F(1, 53) = .333$, $p = .566$, indicating that the stroke groups did not differ on any performance dimension. There was, however, a significant effect for dimension in both the pantomime, $F(4, 140) = 25.97$, $p < .001$, and the imitation, $F(4, 212) = 42.13$, $p < .001$, conditions which showed both stroke groups exhibited significantly lower accuracy on the posture dimension.

Another approach to examining the severity of the apraxic impairment in the two stroke groups is to compare the number of performance dimensions on which each patient is impaired, with a greater number of impaired performance dimensions indicating a greater apraxic impairment. In a recent study of apraxia (Roy et al, 1998) patients were divided into two groups, one reflecting patients who exhibited an impairment on two or fewer performance dimensions and the other reflecting patients who were impaired on three or more dimensions. In the present analysis the average performance of patients categorized as non-apraxic in the pantomime and imitation conditions was used to define whether performance on a particular dimension was impaired. The two standard

deviation rule used in defining apraxia was used to determine if performance was impaired on each dimension. Performance scores which fell more than two standard deviations below the mean for that dimension (separately for LHD and RHD groups) were classified as impaired. The results for pantomime and imitation were compared separately (see Table 7).

Insert Table 7 about here

The pantomime data indicated that a higher proportion of patients in the right stroke group exhibited impairments on two or fewer dimensions, while a greater proportion of LHD patients were impaired on three or more dimensions ($\chi^2 = 4.23$, p=.04). For the imitation condition, the same pattern was observed but the difference in the relative distribution of patients in the two stroke groups was not significant, $\chi^2 = 1.33$, $p = .249$.

Patterns of Apraxia

In accord with Roy (1996), three patterns of apraxia were defined based on the combination of apraxic impairments in the two performance conditions (see Table 8): apraxia present in pantomime but not imitation (P_AI_{NA}), in imitation but not pantomime ($P_{NA}I_A$) or in both pantomime and imitation (P_AI_A). Patients who fell into these three patterns were identified from the cutoff scores used to define apraxic categories (i.e., non-apraxic, borderline apraxic and apraxic) in a previous analysis (see Frequency of Apraxia). Patients who fell in the apraxic category in the pantomime or imitation condition alone were assigned to the first and second patterns, respectively. Patients who fell in the apraxic category in both conditions were assigned to the third pattern. The number of patients in each group who fell into each of these categories was then

examined. The results (Table 8) revealed that approximately the same proportion of patients in each group fell in the first two patterns, while a greater proportion of the patients with LHD fell in the third category.

Insert Table 8 about here

We also compared performance accuracy between the two stroke groups within each pattern of apraxia (see Table 8 for composite scores of each group in each pattern of apraxia). Analyses comparing imitation performance in the pattern reflecting apraxia on imitation alone revealed no significant effect of group, $F(1, 21) = .523$, $p = .478$. Clearly, there was also no difference between the stroke groups in pantomime performance in the pattern reflecting apraxia in pantomime alone. Finally, analyses of the pattern reflecting apraxia in both pantomime and imitation using a 2 (stroke group) by 2 (pantomime versus imitation) ANOVA also revealed no effect for group, $F(1, 30) = .520$, $p = .477$, but a significant effect for performance condition, $F(1, 30) = 22.17$, $p < .001$, which revealed less accurate performance in the pantomime condition.

Apraxia and Aphasia in the Participants with LHD

Analyses of the AQ scores for the patients with LHD on the Western Aphasia Battery reveal that 48 percent (21/44) of the patients were aphasic[1]. All of these patients with aphasia could be classified into different aphasic types (see Table 9) with the largest number being of the anomic (43 percent or 9/21) or the Broca's (24 percent or 5/21) type. These findings suggest that our patients with LHD may have had relatively mild strokes.

To examine the relationship between apraxia and aphasia, the frequency of apraxia in the patients with aphasia was compared to patients without aphasia. These analyses revealed a much higher frequency of apraxia among the patients with aphasia

(57 percent or 12/21 for pantomime and 76 percent or 16/21 for imitation) than among the patients without aphasia (35 percent or 8/23 for pantomime and 43 percent or 10/23 for imitation), and the frequency of apraxia among the patients with aphasia averaged across performance conditions was 67 percent, a value comparable to that reported in the literature (e.g., Goldenberg, 1996; Lehmkuhl et al., 1983; Wang & Goodglass, 1992).

Insert Table 9 about here

These findings suggest a clear relationship between aphasia and apraxia. Analyses of the relationship between apraxia, and aphasia as reflected in the AQ score, a measure of the overall severity of aphasia, support this finding in that the AQ was correlated significantly with the composite scores for gestural pantomime ($r = .62$, $p < .01$) and imitation ($r=.53$, $p < .01$). In concert with these correlations the apraxic patients exhibited significantly lower aphasia quotients than the non-apraxic patients for both the pantomime condition (apraxic AQ = 71.04; non-apraxic AQ = 90.54), $F(1, 42) = 25.57$, $p < .001$, and the imitation condition (apraxic AQ = 76.07; non-apraxic AQ = 90.50), $F(1, 41) = 6.87$, $p < .02$). Overall, these analyses demonstrate a close relationship between limb apraxia and aphasia as others have found (e.g., Kertesz, Ferro, & Schewan, 1984; Lehmkuhl et al., 1983).

DISCUSSION

Left versus Right Hemisphere Stroke and Apraxia

The primary goal of this experiment was to examine the frequency and severity of apraxia associated with the pantomime and imitation of transitive limb gestures in a sample of patients with left or right hemisphere stroke. A priori it was hypothesized that both the frequency and severity of apraxia would be greater in those patients with LHD.

Examining the proportion of patients classified as apraxic to pantomime, the data indicate that the proportion of LHD patients in this group was significantly greater than those with RHD, a finding well noted in apraxia research (e.g., Rothi & Heilman, 1997). However, this difference was not borne out in the imitation condition, as the proportion of LHD and RHD apraxic patients was equivalent (cf. Haaland & Flaherty, 1984). As for the accuracy data, the overall measure of performance accuracy (composite score) revealed that LHD patients were significantly less accurate than controls, however, they did not differ with their RHD counterparts in either the pantomime or imitation conditions.

In concert, the above findings imply that left hemisphere stroke does not cause greater impairments in praxis. How can these results be reconciled given the plethora of evidence indicating greater impairment following LHD? Two hypotheses have been forwarded to address this concern. The first states that the time of post stroke assessment may have differed between LHD and RHD groups, such that if the time since stroke were shorter for the RHD group, then they would have had less time to recover from the acute cognitive and motor deficits stemming from stroke. However, analyses comparing the time since stroke for both stroke groups, and those patients classified as apraxic revealed no difference in the time of assessment.

An alternative hypothesis is that the precision afforded by the multi-dimensional error notation system may have afforded greater sensitivity in detecting movement impairments associated with RHD. Indeed, previous studies employing detailed error analysis systems such as that used in the present investigation have found impairments with RHD (e.g., Haaland & Flaherty, 1984; Schnider et al., 1997). In contrast, more precise kinematic techniques have failed to show impairments in patients with RHD (e.g.,

Poizner, Merians, Clark, Macauley, Rothi, & Heilman, 1998). This discrepancy may be due to the fact that these kinematic studies have typically examined only a small number of patients (e.g., N = 3, Clark, Merians, Kothari, Poizner, Macauley, Rothi, & Heilman, 1994) and, the LHD included in these studies are selected based on their clinical diagnosis of limb apraxia. Patients with RHD are not similarly selected. Finally the studies conducted by Poizner and colleagues (e.g., Poizner et al., 1998) have exclusively relied on comparing the pooled (left/right hand) performance of control participants to the ipsilesional limb of LHD and RHD stroke groups. Recent work by Heath (Experiment 4), examining the production of transitive limb gestures in healthy right hand dominant adults has demonstrated that manual asymmetries are elicited during the production these gestures. Specifically the effectiveness and consistency of left hand trajectory was less than that of the dominant right hand. Thus, Poizner's inability to detect performance deficits in RHD patients may relate to the fact that inappropriate hand contrasts were employed.

In the proceeding sections the frequency and severity of apraxia will be discussed separately for the pantomime and imitation conditions. Following this, the patterns of apraxia outlined by Roy (1996), and identified in our sample of lateralized stroke patients will be considered to highlight the frequency and specific gestural deficits associated with each pattern.

Performance Conditions and Apraxia

Pantomiming a gesture requires that an appropriate representation of the action be evoked/selected from memory. Failure on this task is believed to reflect an impaired ability to generate or access this knowledge (Rothi, Ochipa, & Heilman, 1997), or

generating the appropriate visual image of the gesture (Roy & Hall, 1992). Previous investigations have found that LHD results in greater impairments to gestural pantomime, a deficit believed to reflect left hemisphere dominance for the ideational components of gesture production (De Renzi, Piecquro, & Vignolo, 1968; Barbieri & De Renzi, 1988). The present findings demonstrate that a significantly greater proportion of LHD patients were classified as apraxic during the pantomime of gestures, while the overall severity of the disorder did not differ between LHD and RHD patients. Therefore, although LHD more frequently results in apraxia when memory demands guide performance, the severity of the disorder is equally marked regardless of the hemisphere impaired. This latter finding corresponds to recent work by Roy et al. (1998) noting that left or right hemisphere damage equally impaired gesture production. In contrast, the work of Schnider et al. (1997) indicated that RHD patients were not impaired relative to age-matched controls, while LHD patients were significantly impaired in this condition. The present results contrast those of Schnider et al., and indicate that apraxia impairs gesture performance regardless of the side of lesion. This discrepancy may relate to the sensitivity of their error notation system. In Schnider et al's investigation, RHD and age-matched controls performed at near ceiling levels, while performance of our controls and RHD patients did not reach ceiling performance. Further, Schnider et al. (1997) did not classify individual patients as apraxic or non-apraxic, thus it is impossible to know whether the sample of RHD patients (N=11) in their study actually included individuals with apraxia.

Performance in the imitation condition revealed that an equal number of LHD and RHD patients were classified as apraxic and, that the severity of the deficit equally

impaired LHD and RHD apraxic patients. These results are parsimonious with the work of De Renzi et al. (1982) who examined the frequency of apraxia in this condition, and that of Haaland and Flaherty (1984) who examined the severity of the disorder via an error notation system similar to that used in the present investigation. Indeed, De Renzi et al. noted that a relatively equal proportion of LHD and RHD patients were apraxic to imitation, while Haaland and Flaherty observed that LHD and RHD patients did not differ in the total number of errors committed during gestural imitation. In sum, the present results support the notion that damage to either hemisphere disrupts the praxis functions associated with gestural imitation.

Patterns of Apraxia

Pantomime Dissociated from Imitation. The notion that LHD alone selectively impairs the ideational processes associated with gesture performance was not borne out in our examination of the first pattern of apraxia: apraxia to pantomime alone. A priori it was predicted that the proportion of patients classified as apraxic in the pantomime condition alone would be significantly greater in the LHD stroke group (see Table 8). This hypothesis was based on a considerable body of research which has consistently reported that LHD selectively impairs the ideational processes involved in gesture production (e.g., Barbieri & De Renzi, 1988; De Renzi et al., 1968). Indeed, in their report, Barbieri and De Renzi noted that more LHD (12) patients than RHD (2) demonstrated a dissociation in which apraxia was greater on pantomime than imitation. In contrast, our data reveal that the proportion of patients showing a similar dissociation (e.g., apraxia in pantomime alone) was approximately the same in the two stroke groups (LHD = 2 or 5 %, RHD = 3 or 6%).

The discrepancy between the present data and that of Barbieri and De Renzi (1988) may relate to the manner in which the dissociation was defined. In their study, Barbieri and De Renzi did not require patients to be apraxic to pantomime alone. Instead, the pattern was defined such that the difference between pantomime and imitation performance was greater than that seen in controls. In contrast, the present study classified patients within this pattern only if their performance in the pantomime condition fell within the apraxic range. Given the differences between the two investigations, it is possible that a number of the patients with LHD showing this pattern in Barbieri and De Renzi's study may have actually been apraxic in both conditions, but were simply more impaired in pantomime than imitation. This explanation is explored in greater detail in the section examining those individuals who demonstrated the third pattern of apraxia; apraxic to pantomime and imitation. Briefly, these results demonstrated a significantly larger number of LHD patients in this pattern (Table 8), suggesting that some of the patients in Barbieri and De Renzi's study who showed the dissociation between pantomime and imitation may have actually be apraxic on both conditions. This notion is based on the present data which found that only in this subgroup did LHD patients out number those with RHD. In contrast to Barbieri and De Renzi, the present results suggest that damage to the left hemisphere does not selectively impair the ideational components of gesture production, but may involve significant disruptions of the latter or executive stages of gesture production.

Imitation Dissociated from Pantomime. The second pattern of apraxia described by Roy (1996) is one in which apraxia is observed in imitation but not pantomime. Numerous case reports have recorded this pattern (e.g., Merians, Clark, Poizner, Macauley, Rothi, &

Heilman, 1997; Ochipa et al., 1994; see also Heath, Experiment 3), however, the present investigation provides the first group study investigating this selective pattern of apraxia. In our sample of lateralized stroke patients, it would appear that disruptions at this stage of gesture production (reflecting disruptions in the analysis of visual gestural information or in the translation of visual gestural information into movement) occur with approximately equal frequency following left or right stroke. This finding is congruous with that of Barbieri and De Renzi (1988) who also found that the proportion of LHD and RHD demonstrating this pattern of apraxia was equal. Further, the degree of the apraxic impairment was found to be equal in both stroke groups. Using both frequency and severity measures, it appears that disruptions in visual gestural analysis or its translation into movement can arise from damage to either hemisphere.

Roy (1996) proposed that the pattern of apraxia reflecting impaired performance on imitation alone is indicative of an impaired ability to analyze visual gestural information, or in the translation of this information into movement. This hypothesis is in contrast to that of De Renzi and colleagues (Barbieri & De Renzi, 1988; De Renzi et al., 1980) who proposed that this pattern is likely indicative of an executive disorder. Evidence in favour of the latter explanation is scant. Specifically, Roy and Square (1994) have argued that such an executive disorder would also lead to apraxia in pantomime, a consideration not reported in De Renzi's model.

Indeed, several explanations have been proposed to account for the impaired ability to imitate gestures. Goldenberg and Hagmann (1997) reported two cased in which LHD patients were impaired at imitating meaningless, but not meaningful gestures. Further, Goldenberg and Hagmann reported that although LHD and RHD patients were

similarly impaired at imitating the distal elements of non-representational gestures, LHD patients were considerably more impaired at imitating the proximal features associated with the gestures. Moreover, Goldenberg (1996) noted that LHD patients were not only impaired at imitating gestures (non-representational), but also in moving the hand and arm of a manikin into the gestural configuration demonstrated by an examiner. Based on these data, Goldenberg proposed that the impaired ability to imitate a gesture (meaningful and meaningless) is the result of an impaired knowledge related to body schemata.

Goldenberg's (1996) proposal suggests that imitating gestures does not involve a direct route to movement execution, rather one through a component involving knowledge of body schema. This schema then would appear to be more important at directing the arm (proximal) as opposed to the hand and fingers (distal), since it was only the proximal features that were selectively impaired in patients with LHD. Hence, imitation may place not only emphasis on visual gestural processes but also intact knowledge of body schema. The multi dimensional error notation system used in the present investigations allowed a direct examination of Goldenberg's body schema hypothesis. Recall that Goldenberg observed that the proximal elements of gesture production (e.g. arm position) were more impaired in LHD patients. In the present analyses the location and posture dimensions are roughly analogous to the proximal and distal aspects of movement respectively. Given Goldenberg's findings, one would predict that our patients with LHD would be more impaired on the location dimension relative to their RHD counterparts. The present analyses do not entirely support this prediction, as LHD patients were more impaired than controls on posture and location dimensions.

While we are unable to definitively determine the nature of the performance decrement in both apraxic stroke groups, further work will examine the patient's performance on a gesture recognition/discrimination task. In this context, it may be possible to determine whether the performance of individual patients is specifically related to impaired visual gestural discrimination (e.g., unable to discriminate and perform gesture) or impaired knowledge of body schema (e.g., able to discriminate/recognize gesture but unable to perform appropriate gesture).

Concurrent Apraxia on Pantomime and Imitation. The final group of patients, were those classified in the apraxic range in both pantomime and imitation. This pattern is thought to reflect damage to the latter or executive stages of gesture production, underlying a motor control impairment. In the present investigation, this pattern of apraxia occurred more frequently in the LHD patients, although the severity of the deficit was equal among both stroke groups. As we have noted above, a plethora of research has indicated that apraxia following LHD is indicative of an impairment in the ideational processes associated with gesture formation (e.g., Alexander et al., 1992; Barbieri & De Renzi, 1988; Belanger, Duffy, & Coehlo., 1996; De Renzi et al., 1968; De Renzi, 1985; McDonald, Tate, & Rigby, 1994; Schnider et al., 1997). Unfortunately, a majority of these studies have not examined the concurrent performance of individuals in pantomime and imitation conditions, thus they are unable to wholly conclude that the nature of the disorder is related strictly to an ideational deficit. The one study reported in the literature that attempted to quantify whether LHD or RHD patients were more impaired in a pantomime or imitation condition, is the work of Barbieri and De Renzi (1988). Recall that Barbieri and De Renzi examined whether the performance of individual patients was

more impaired on pantomime or imitation. Thus, the basic experimental protocol is considerably different than the present investigation, where a clear dissociation between apraxic versus non-apraxic performance was determined. Despite these differences, Barbieri and De Renzi observed that the proportion of LHD patients with an apraxia of equal magnitude in both conditions was fifty-four percent, a value which corresponds to the present finding of forty-three percent. For RHD patients, Barbieri and De Renzi observed twenty-four percent in this category, while the present results indicated that twenty-three percent of RHD patients were classified in this category. In conjunction, these results highlight two important findings in apraxia research. Firstly, the results indicate that LHD as opposed to RHD is more likely to result in an impaired ability to imitate and pantomime gestures, a pattern Roy (1996) has interpreted to reflect deficits in the latter stages of gesture production. This notion is furthered strengthened by a stronger correlation between the pantomime and imitation conditions for the LHD stroke group. The second issue relates to the proportion of patients within the LHD group exhibiting this pattern. Specifically, a larger proportion of LHD patients were classified as apraxic to both pantomime and imitation (43 percent) than the other two apraxic categories (5 percent for pantomime alone and 17 percent for imitation alone). These data further substantiate the claim that the occurrence of apraxia in LHD is not strictly related to an ideational disorder as reported by others (e.g., Alexander et al., 1992; De Renzi et al., 1968; De Renzi, 1985; Heilman & Rothi, 1979). Instead the results suggest that LHD apraxic patients are more frequently impaired in the executive processes of gesture production.

CONCLUSIONS

The present results mandate that future apraxia research explore co-jointly pantomime and imitation performance in order to more fully ascertain the locus of gesture production deficits in individual patients. Future work is directed at examining this issue in different types of gestures (e.g., intransitive, meaningless) to clarify whether individual patients are impaired globally in gesture production, or whether their deficits are isolable to a unique characteristics associated with specific gesture types. Future research using the procedures described in the present research will further clarify whether the expression of apraxia is related to semantic constructs of gesture production, or the executive components.

Footnotes

[1]The Western Aphasia Battery was not administered to two of the patients with LHD due to time limitations in their availability for testing, hence their data are not included in subsequent analyses involving AQ data or aphasic categorization.

Table 1

Participant Characteristics

Group	Age			Test Onset (Days Since Stroke)	
	N	M	sd	M	sd
Control	15	68.45	10.01	--	--
LHD	46	71.40	12.70	74.60	76.10
RHD	53	69.20	13.40	71.20	60.50

Table 2

Gestural Performance of Control Participants

	pantomime				imitation			
	Left hand		Right hand		Left Hand		Right Hand	
	M	sd	M	sd	M	sd	M	sd
Orientation	94.58	8.14	94.58	8.80	98.21	5.16	96.67	7.03
Action	96.61	4.05	97.92	3.05	98.66	2.60	97.08	3.23
Posture	94.11	6.02	93.27	6.45	97.77	4.66	97.92	3.05
Plane	97.92	3.86	97.92	3.86	98.21	2.93	99.17	2.20
Location	97.86	3.14	95.77	3.10	99.27	0.23	99.10	0.30
Composite	95.71	3.58	95.64	1.98	98.57	1.61	98.17	1.63

Table 3. Composite Score Distribution of LHD, RHD and Control Participants Across Performance Conditions

	Pantomime			Imitation		
Score	Control	LHD	RHD	Control	LHD	RHD
97-100	4	5	5	12	11	20
94-96.9	9	10	13	2	9	15
91-93.9	1	9	20	1	10	5
88-90.9	1	8	5	-	6	5
85-87.9	-	3	3	-	5	3
82-84.9	-	4	2	-	1	1
79-81.9	-	1	1	-	-	1
76-78.9	-	-	3	-	2	1
73-75.9	-	-	-	-	-	1
70-72.9	-	3	-	-	-	-
67-69.9	-	1	-	-	-	-
64-66.9	-	-	-	-	-	-
61-63.9	-	-	1	-	-	1
58-60.9	-	-	-	-	1	-
55-57.9	-	-	-	-	-	-
52-54.9	-	1	-	-	-	-
49-51.9	-	-	-	-	-	-
46-48.9	-	-	-	-	-	-
43-45.9	-	-	-	-	-	-
40-42.9	-	1	-	-	-	-
37-39.9	-	-	-	-	-	-

Table 4

Apraxia Severity as a Function of Stroke Group

Group	**Gestural Condition**	
	Pantomime	Imitation
LHD		
Apraxic	22 (48%)	28 (61%)
Borderline	6 (13%)	7 (15%)
Non-apraxic	18 (39%)	11 (24%)
RHD		
Apraxic	15 (28%)	27 (51%)
Borderline	14 (26%)	6 (11%)
Non-apraxic	24 (46%)	20 (46%)

Table 5

Gestural Performance of LHD Participants Classified as Apraxic and Non-apraxic

	Apraxic				Non-apraxic			
	pantomime		imitation		pantomime		imitation	
	M	sd	M	sd	M	sd	M	sd
Orientation	83.81	16.44	92.18	8.94	96.09	5.47	92.18	8.94
Action	81.73	12.89	89.28	8.13	93.60	6.37	96.52	3.19
Posture	64.12	17.30	76.33	13.64	90.81	6.43	94.09	3.99
Plane	87.78	16.08	93.97	10.95	98.17	3.90	99.33	2.02
Location	81.20	14.90	87.72	9.39	95.23	4.64	87.72	9.39
Composite	79.73	13.08	87.00	7.84	94.78	2.28	97.43	1.24

Table 6

Gestural Performance of RHD Participants Classified as Apraxic and Non-apraxic

	Apraxic				Non-apraxic			
	pantomime		imitation		pantomime		imitation	
	M	sd	M	sd	M	sd	M	sd
Orientation	84.94	8.38	92.12	7.47	96.38	6.43	97.83	4.30
Action	87.02	8.29	88.88	11.41	92.73	5.53	96.76	3.87
Posture	74.58	14.65	78.47	15.24	89.30	7.39	96.60	3.66
Plane	90.00	8.77	94.90	7.36	95.81	5.50	98.07	3.43
Location	87.08	10.15	91.20	7.20	96.49	4.85	99.03	2.29
Composite	83.48	7.19	89.12	7.82	94.14	2.13	97.66	1.08

Table 7

Number of Performance Dimensions Impaired in each Apraxic Stroke Group

	2 = <		> = 3	
Group	Pantomime	Imitation	Pantomime	Imitation
LHD	31 (67.4%)	27 (58.7%)	15 (32.6%)	19 (41.3%)
RHD	45 (84.9%)	37 (69.8%)	8 (15.1%)	16 (30.2%)

Table 8

Frequency and Composite Score Accuracy Data for Patients with LHD or RHD in Each Apraxic Category

Apraxic Pattern	LHD			RHD		
	Frequency (%)	Pantomime Accuracy	Imitation Accuracy	Frequency (%)	Pantomime Accuracy	Imitation Accuracy
P_{NA} I_{NA}	16 (35)	95.58	97.57	23 (43)	94.57	97.63
P_{A} I_{NA}	2 (5)	87.50	96.25	3 (6)	87.91	97.91
P_{NA} I_{A}	8 (17)	93.19	92.81	15 (28)	93.50	90.50
P_{A} I_{A}	20 (43)	78.95	85.93	12 (23)	82.38	87.39

P = Pantomime
I = Imitation
NA = Non-apraxic
A = Apraxic

Table 9

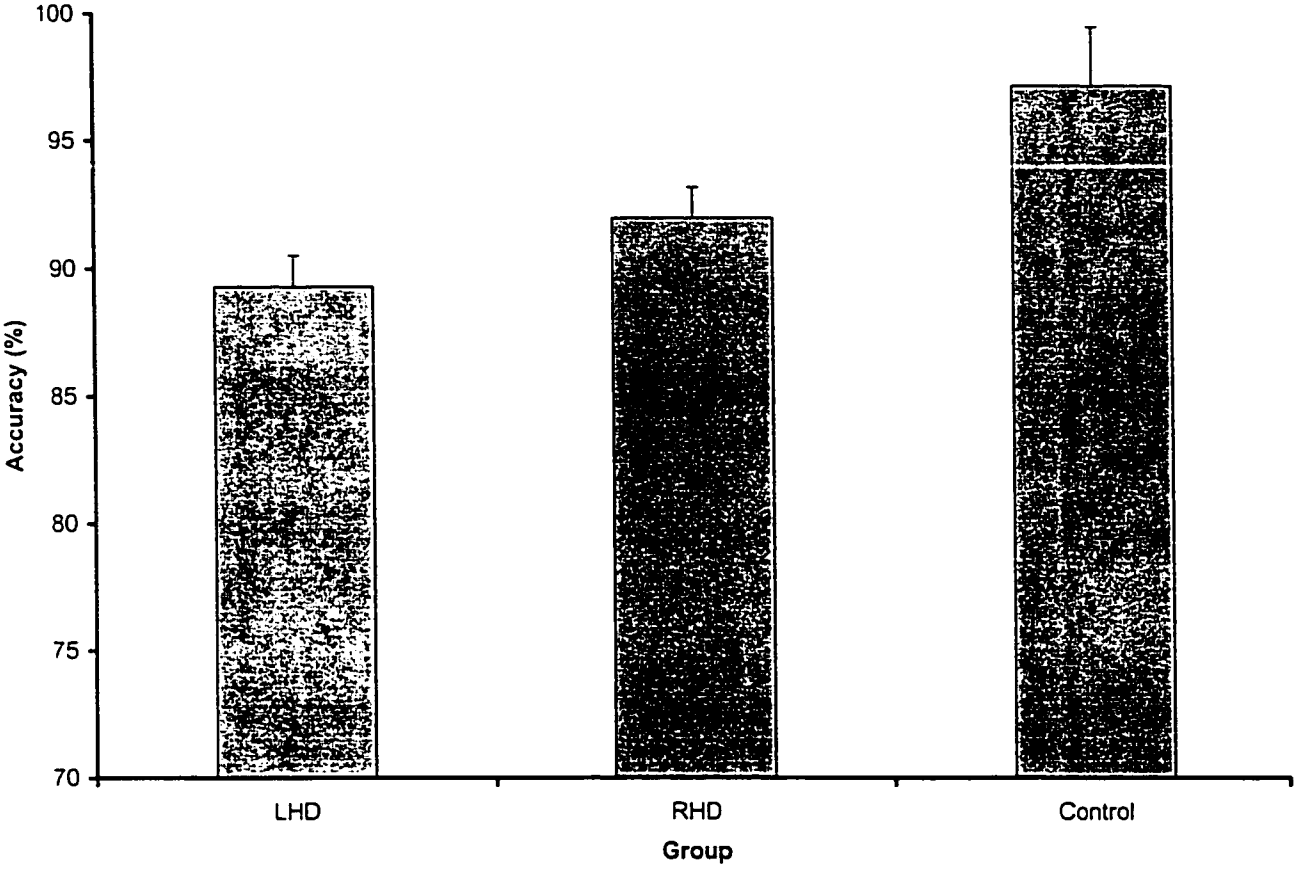
Left Hemisphere Group Aphasia Classification

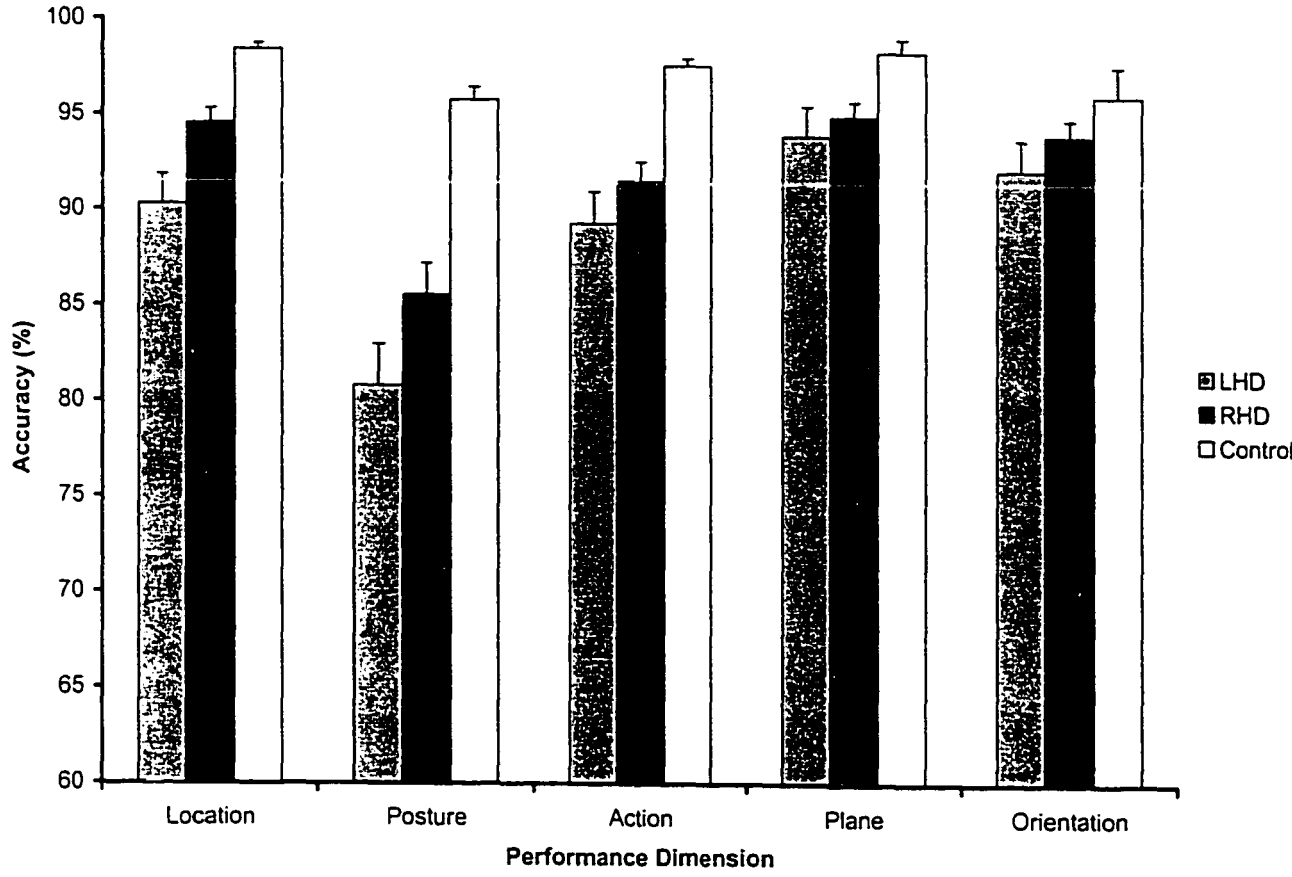
Aphasia	Normal	Broca's	Wernicke's	Global	Anomic	Conduction	Trans Sensory
LHD	23 (52%)	5 (11%)	2 (5%)	2 (5%)	9 (20%)	1 (2%)	2 (5%)

Figure Captions

Figure 1. Average composite score for patients with LHD and RHD and for controls.

Figure 2. Accuracy across performance dimensions for both stroke groups and controls


100
95
90
85
80
75
70
Accuracy (%)
LHD
RHD
Control
Group


100
95
90
85
80
75
70
65
60
Accuracy (%)
Location
Posture
Action
Plane
Orientation
Performance Dimension
LHD
RHD
Control

EXPERIMENT TWO

ABSTRACT

A patient (KF) who following a unilateral stroke demonstrated a unique form of ideational limb apraxia is reported. Clinical assessment examined KF's conceptual, ideational and executive stages of gesture production. Transitive (tool based; e.g. hammering a nail), intransitive (symbolic; e.g. waving goodbye), and non-representational (meaningless hand postures) gestures were employed in the praxis battery. The results revealed a specific deficit in KF's ability to produce intransitive gestures in response to verbal command, indicating that although conceptually able to identify intransitive limb gestures, he was unable to select/evoke this knowledge when verbally cued to produce these gestures. This case study provides empirical support for parallel systems supporting the production of transitive and intransitive gestures.

EXPERIMENT TWO

Traditional cognitive neuropsychological models of gesture production propose two stages (Rothi, Ochipa, & Heilman, 1997; Roy & Square, 1985): (1) a conceptual stage, involving information relevant to tool use and mechanical problem solving abilities, and (2) a production or executive stage, which includes selection/evocation of the movement formulae responsible for learned, skilled, purposeful actions, and the requisite module(s) necessary for the translation of this information into action. These models have proven invaluable for understanding limb apraxia, a disorder of skilled movement that cannot be attributed to ataxia, weakness, sensory loss, poor comprehension, or inattention to commands (Heilman & Rothi, 1985). However, recent three-stage models Roy (1996) provide a new framework for understanding the genesis of apraxia. Roy's model proposes a mutually exclusive distinction between the stage responsible for selecting/evoking the movement formulae responsible for skilled actions, and the translation of this information into action, thus incorporating a hierarchy of (1) conceptual, (2) selection/evocation and (3) production stages. This formulation affords an opportunity to clearly distinguish between conceptual, ideational (selection/evocation deficit) and ideomotor (production deficit) forms of apraxia.

Recently Dumont, Ska, & Schiavetto (1999) reported an individual uniquely impaired when producing transitive (tool based; e.g., hammering a nail), but not intransitive (expressive/communicative; e.g., waving goodbye) limb gestures; pointing toward a gesture-specific form of apraxia. The aim of the present investigation was to determine whether the opposite dissociation can be elucidated; that is, a specific impairment in the production of intransitive limb gestures. Further, Roy's (1996) model

of gesture production was employed to resolve whether a gesture-specific form of apraxia can be linked to a deficit in the selection/evocation or ideational stage of production.

Liepmann (1920) defined ideational apraxia as an impaired ability to perform tasks requiring a sequence of serial acts with tools or objects. Poeck (1983; Lehmkuhl, Poeck, & Willmes, 1983) extended this notion, adding that ideational apraxia is a sequencing disorder in the conceptual organization of sequential actions. In such a formulation, when making a pot of coffee, a patient with ideational apraxia may have difficulty performing the familiar act in the proper sequence. In contrast to Poeck's view of ideational apraxia, several investigators (De Renzi, 1985; Heilman, Rothi, & Valenstein, 1982; Roy, Black, Blair, & Dimeck, 1998) have observed an impaired ability to perform a single gesture in response to verbal command (e.g., pantomime), suggesting that ideational apraxia is not a disorder of the sequential organization of familiar actions. Rather, the complexity associated with producing a series of gestures or actions, may simply produce a condition favouring the appearance of such an ideational apraxia. Thus, De Renzi (1985) proposed that a pure form of ideational apraxia reflects a disorder in selecting/evoking the representation of a gesture from semantic memory. This view is similar to Heilman and colleagues (Heilman et al., 1982) who have argued that ideational apraxia results from a destruction of, or inability to access visuokinesthetic engrams responsible for learned, skilled, purposeful actions. Indeed, both views acknowledge that ideational apraxia represents a loss of knowledge, or the ability to access knowledge related to tool and/or object use.

One problem with this definition of ideational apraxia is that it is limited to impairments of learned, skilled actions involving tools and/or objects, hence intransitive

gestures are not accounted for. Recent work (Heath, Experiment 3) has shown that the ability to select/evoke intransitive gestures can also be impaired following stroke, indicating that impaired selection/evocation is not limited to gestures featuring tools and/or objects, but all actions involving a learned, stored representation. In the present investigation an inclusive definition of ideational apraxia is adopted, encompassing a failure to select/evoke transitive and/or intransitive (symbolic) gestures from semantic memory.

Such an inclusive definition of ideational apraxia permits an opportunity to evaluate whether the processes underlying the selection/evocation of transitive and intransitive gestures are dissociable from one another. Transitive limb gestures involve the use of tools (e.g., knife) and/or objects (e.g. bread), whereas intransitive limb gestures (e.g., waving goodbye) convey expressive or communicative content. While recent neuro-imaging research has provided tentative evidence supporting the notion that transitive limb gestures are functionally represented in a unique region of cerebral space (Grafton, Fadiga, Arbib, & Rizzolati, 1997), the representation of intransitive limb gestures is unknown. Dumont et al. (1999) have reported behavioural evidence of a dissociation between gesture forms. In their case study, patient PF demonstrated apraxic deficits while pantomiming and imitating transitive limb gestures, and when actually manipulating the tool associated with the gesture. Surprisingly, PF's production of intransitive and non-representation gestures was unimpaired. Dumont et al's novel finding of a selective apraxia based on gesture type provides the first evidence that separate systems underlie the production of different gesture forms.

The present research sought to determine whether the opposite pattern is observable (e.g., apraxic to intransitive gestures only), and whether this dissociation can be limited to a stage of gesture production; specifically, the selection/evocation stage. If transitive and intransitive gestures are supported by functionally distinct processes, then it would seem plausible to observe a selective form of ideational apraxia, in which the selection/evocation of one gesture type is impaired, while sparing the other.

The above hypothesis was tested using Roy's (1996) model of gesture production that provides a series of testable hypotheses for examining disruptions at various stages in the evolving production of an action or gesture. This model provides a methodology for identifying specific forms of apraxia. For instance, a conceptual apraxia arises from deficits in the early stages of gesture formulation, and can be identified when an individual demonstrates impairments in identifying or understanding the elements associated with tool and/or object properties, or an inability to correctly discriminate between different gestures. Similarly, deficits in analyzing visual gestural information, or translating this information into movement can impair the early stages of gesture production. This form of apraxia is observed when an individual is selectively impaired imitating, but not pantomiming gestures.

In the later stages of gesture production, impairments in selection/evocation (ideational apraxia), or a deficit in response organization and control (ideomotor apraxia) can be identified using Roy's (1996) model. A deficit in response selection/evocation should be seen when imitation performance and conceptual knowledge are intact, but pantomime is impaired. In this pattern, an individual knows what the gesture looks like, but has difficulty in translating what they know into action, representing a form of

ideational apraxia. In contrast, a deficit in response organization and control produces deficits in pantomime and imitation performance, without impairments in conceptual knowledge. The failure to produce gestures in this case results from a deficit in the final common pathway to action, and is indicative of an ideomotor apraxia. A gesture-specific form of apraxia limited to a specific stage of gesture production can be elucidated when the integrity of each stage of gesture production is evaluated independently for transitive and intransitive limb gestures.

In the present investigation a right-handed male with a right subcortical infarct who was unimpaired for each stage (conceptual, selection/evocation, production) of transitive limb gesture production is reported. Similarly, his conceptual knowledge, and praxis executive stage for intransitive limb gesture was unimpaired. It was a deficit in the selection/evocation of intransitive limb gestures that identified this gesture-specific form of ideational apraxia.

Case Report

KF was sixty-five years old when he was referred to the Stroke Care Unit of Sunnybrook and Women's Health Sciences Centre after a right hemisphere infarct. He is a right-handed man with 13 years of formal education, with a history of mild hypertension and a previous myocardial infarct 15 months prior to admission.

KF experienced sudden onset of left arm weakness, without other associated neurological symptoms. Except for minor weakness in the contralesional limb, tone was normal in all extremities, and no further motor or sensory disorders were observed. A computed tomographic scan on day 7 revealed a large subcortical basal ganglia infarction in the territory of the right middle cerebral artery (Figure 1).

Insert Figure 1 about here

General Neuropsychological Examination

KF was oriented and alert for all evaluations, which occurred 42 days following stroke onset. His performance on the Mini Mental Status Exam was maximal (30/30). Similarly, his performance on a neglect battery (0/100; a lower score representing more accurate performance) demonstrated no deficits in visual-spatial or hemi-attentional processes (Black, Martin, & Szalai, 1990). Motor performance, as assessed using the Grooved Pegboard Task (right-hand only), was within the normal range, yielding an average performance time of 84 seconds in the placement or 'in' phase, and 26 seconds in the removal or 'out' phase. As part of our larger study examining limb praxis, the Western Aphasia Battery (WAB; Kertesz, 1979) was administered to stroke patients with left hemisphere damage, and right hemisphere damaged participants demonstrating language impairments. At the time of assessment, neither KF nor his family members reported any significant changes in his language abilities, hence assessment on the WAB was not included as part of KF's neuropsychological work-up.

Neuropsychological Evaluation of Apraxia

A battery of tests was administered to examine the patterns of apraxia discussed in Roy's (1996) model of gesture production.

Conceptual Knowledge Assessment

The conceptual apraxia battery included nine tests to examine tool naming, tool identification and tool-action naming. Additionally, a gesture recognition test was administered to assess gesture recognition and discrimination. KF's performance was compared to that of a group of 30 age-matched control participants. The mean age of

these participants was 68 years (range = 44 – 82, sd = 10), with a mean level of formal education equal to 15.1 years.

The first three tests examined participants naming abilities. In the Tool Naming Test (1) participants were shown a tool and asked to properly name the tool; the Tool Function Test (2) required participants to name the function of an observed tool (e.g., when shown a saw, participants responded correctly by saying "it is used to cut wood"). The Tool Action Test (3) required the naming of a tool based on its action. For instance, participants were asked to name the tool used for driving a nail ("hammer").

Tool identification included four tests (4-7). The Tool Identification Test (4) involved pointing to the correct tool named by the experimenter from among five foils. For the Tool Function Identification Test (5) participants were required to select a tool from a set of five foils based on the tools function (e.g., "show me the tool used to drive a nail"). In the Action Identification (6) and Tool-Action Identification (7) tests participants observed a split screen monitor depicting the examiner performing two gestures. For the Action Identification Test participants were asked to point to the appropriate screen depicting the action (e.g., "point to the person who is hammering"), whereas in the Tool-Action Identification Test participants were required to select the appropriate image associated with the action of a tool (e.g., "point to person driving a nail").

The final test, Gesture Recognition (8), required participants to identify from the split-screen monitor the image described by the experimenter (e.g., "point to the person waving goodbye").

A total of eight transitive gestures were included in the conceptual apraxia tests: 1 through 7. In addition to the 8 transitive gestures, the Gesture Recognition Test included 8 intransitive gestures.

KF's performance on the conceptual praxis battery was maximal, achieving 100% accuracy in each of the naming, identification and recognition tests.

Limb Praxis Assessment

Limb praxis was evaluated using a multi-dimensional error notation system (see Roy, Square, Adams, & Friesen, 1985). Gestural performance was videotaped and later evaluated on five performance dimensions (location, posture, action, plane, orientation) which were used to calculate a composite score reflecting overall accuracy across the five performance dimensions. Each dimension was evaluated independently and scored as: correct (2), partially correct (1), or incorrect (0). For these classifications, elements critical to each dimension were identified in advance, and the scores on each dimension reflected the degree to which each element was present. KF's composite score was evaluated relative to the 30 age-matched controls reported above. KF's performance on each limb praxis test was classified as non-apraxic (z-score > -1), borderline (z-score of less than or equal to -1 but less than -2) and apraxic (z-score equal to or less than -2). KF's contralesional (right) limb was evaluated relative to the dominant (right) limb of the 30 participants who served as age-matched controls.

Transitive Gestures

Transitive limb gestures (N = 8) were examined in six conditions. In the first, or Pantomime Test [P.T.], gestures were produced in response to verbal command (e.g., "show me how to use a hammer"). In the second (Pantomime Picture Test [P.Pi.]), a

picture depicting a tool was shown (e.g., hammer) and the participant was instructed to perform the action associated with the picture. The third test involved producing gestures while manipulating the tool associated with the action (Tool-Use Test [P.TU.]). The Pantomime by Function Test [P.F.], involved performing a gesture in response to a verbal description of the action associated with a tool (e.g., "show me how to drive a nail"). The final tests, Imitation Concurrent [IC.-T.] and Imitation Delayed [ID.-T.], required that a gesture demonstrated by the examiner be copied by the participant, either concurrently, or following a five second delay period.

KF demonstrated that he could select/evoke a transitive gesture from memory (P.T. z-score = -0.67), and produce gestures accurately when shown a picture of the tool (P.Pi. z-score = -0.09), when provided with the actual tool (P.TU. z-score = -0.33) and when described the action of a tool (P.F. z-score = -0.08). Similarly, KF's performance on Concurrent Imitation (z-score = -1.01) and Delayed Imitation (z-score = 0.99) tests was largely unimpaired (see Figure 2).

Intransitive Gestures

Intransitive gestures (N = 8) were assessed in a Pantomime Test (e.g., "show me how to wave goodbye" [P.I.]), and Concurrent [IC.-I.] and Delayed [ID.-I.] Imitation Tests. KF demonstrated an impaired ability to pantomime intransitive gestures (P.I. z-score = -2.70), however his performance was not impaired in either of the imitation conditions (IC.-I. z-score = 0.45; ID.-I. z-score = -0.56) (Figure 2).

Insert Figure 2 about here

Non-representational Gestures

KF's concurrent imitation (Concurrent Imitation [IC.-NR.] z-score = 0.02) and delayed imitation (Delayed Imitation [ID.-NR.] z-score = -0.20) of non-representational gestures was unimpaired (Figure 2).

DISCUSSION

The case study of KF presents a unique form of apraxia, demonstrating an individual with a specific impairment in the selection/evocation of intransitive limb gestures. KF's performance of transitive limb gestures which tapped his conceptual, ideational and production systems was unimpaired. Moreover, KF was unimpaired while imitating transitive, intransitive and non-representational gestures. It was the pantomime of intransitive gestures that KF demonstrated apraxic performance, suggesting a specific deficit in the selection/evocation of intransitive limb gestures.

Recall that Roy's (1996) model of gesture production provides a series of hypotheses for identifying patterns of apraxia. Using this approach, KF's apraxia could not be attributed to a deficit in the conceptual stage of production, as he was able to correctly name, identify and perform the actions and functions associated with transitive limb gestures, and was able to correctly discriminate between intransitive gestures. Similarly, deficits in the analysis of visual gestural information, or the translation of this information into movement does not describe KF's impairment, as his ability to discriminate between different gestures, in conjunction with his imitation of transitive, intransitive, and non-representational gestures was not affected.

Examining the later stages of gesture production identified a deficit in KF's selection/evocation stage of gesture production. Most interestingly, KF's

selection/evocation deficit was specific to intransitive gestures, as he was wholly able to pantomime transitive limb gestures. This deficit could not be attributed to an executive impairment, as impairments at this stage would also impact gestural imitation. Thus, the current findings suggest that separate systems underlie the selection/evocation of transitive and intransitive limb gestures.

The observation that the ideational stage (selection/evocation) of gesture production can be impaired by a specific gesture form (intransitive gestures) is not readily accounted for by Roy's (1996) model, as a distinction between gesture forms is not considered. This consideration is not well documented in other models of apraxia (Rothi et al., 1997). According to Rothi et al's model of apraxia, KF's impaired ability to pantomime intransitive gestures would result from a disconnection between action semantics and the verbal (action) output lexicon. In this formulation, a disconnection between stored conceptual knowledge of learned, skilled actions and the motor programs responsible for translation of this information into action results in an impaired ability to pantomime gestures. However, similar to Roy's model, Rothi et al's formulation is unable to explain KF's specific impairment in pantomiming intransitive gestures, as an explicit distinction between the formulation of transitive and intransitive gestures is not considered. The present results suggest that both models should incorporate parallel systems for the production of different gesture forms.

Further support for the assertion that parallel systems underlie different gesture forms stems from the recent observations of Dumont et al. (1999). Recall that in their case study patient PF was impaired strictly in the production of transitive limb gestures across multiple modalities (pantomime, imitation, use of objects, and photographs). PF's

ability to discriminate and comprehend the conceptual information contained in transitive gestures, as well as his ability to pantomime intransitive and imitate intransitive and non-representational gestures was unimpaired. Dumont et al. proposed that PF's deficits arose because his "transitive postural and movement representations are disconnected from the motor association areas" (p. 455). Dumont et al's proposal was based on the fact that Rothi et al's model was unable to attribute PF's disorder to: (1) an impairment in accessing action semantics (conceptual knowledge of transitive gestures), in light of his spared ability to name and recognize tools, or (2) a deficit in his output action lexicon (production disorder), since he was able to imitate intransitive and non-representational gestures. However, Dumont et al's explanation does not entirely account for PF's inability to imitate transitive limb gestures. Indeed, 'transitive postural representations' are not required for imitating gestures, as the imitation of gestures can involve a direct route to action, bypassing the need for conceptual knowledge of the gesture (Heath, Westwood, Roy, & Black, 2000). In conjunction with the present case study of KF, we propose an alternative account for the pattern of apraxia described by Dumont et al. Specifically, we attribute PF's pattern of apraxia to impairments in an action output lexicon dedicated to the production of transitive limb gestures. This account explains PF's unimpaired performance of intransitive and non-representational gestures, since a separate action output lexicon would support the organization and control of these gestures on their way to action. Similarly, if parallel systems are incorporated into Roy's model, than PF's apraxia could be attributed an executive stage of gesture production dedicated to transitive limb gestures.

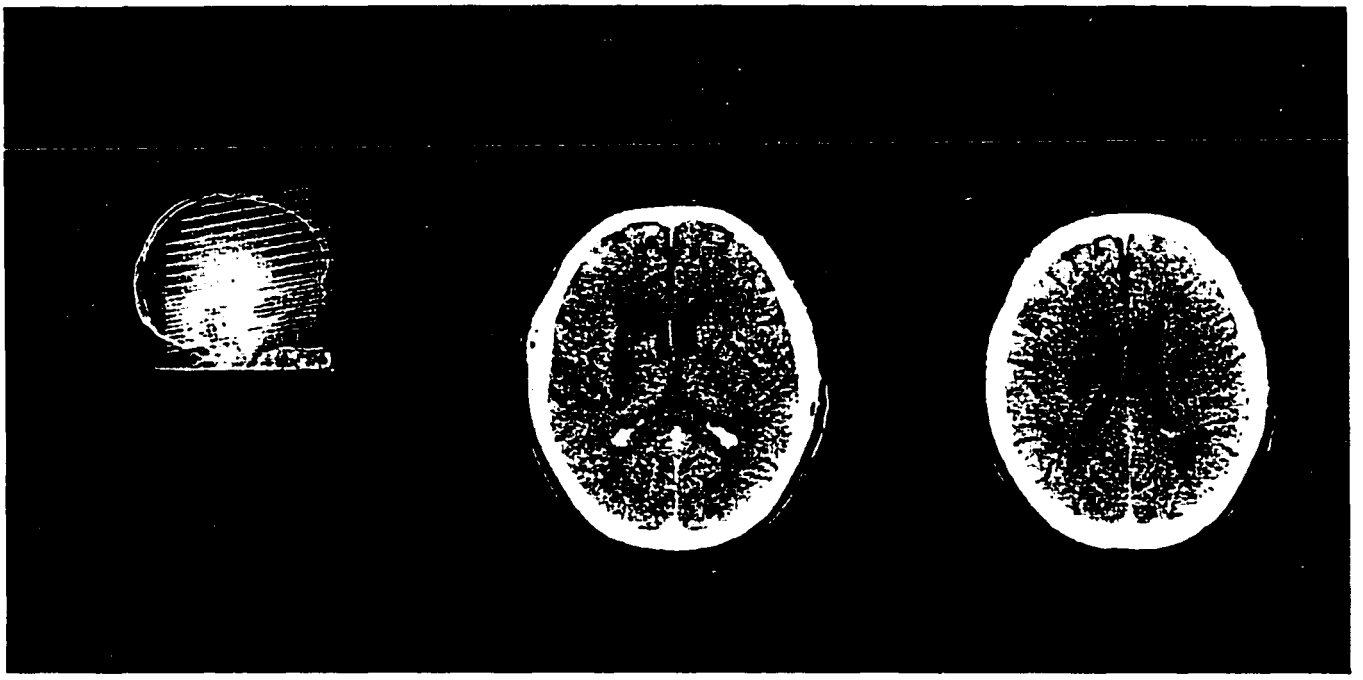
The inclusion of separate processing systems governing the formulation of transitive and intransitive gestures can explain PF's gesture-specific form of apraxia, and the gesture-specific pattern exhibited by KF in the present investigation. Further, the fact that KF demonstrated a deficit in the selection/evocation stage, whereas PF exhibited a deficit in the production stage of gesture production, suggests that each stage of gesture production is supported by parallel transitive and intransitive systems.

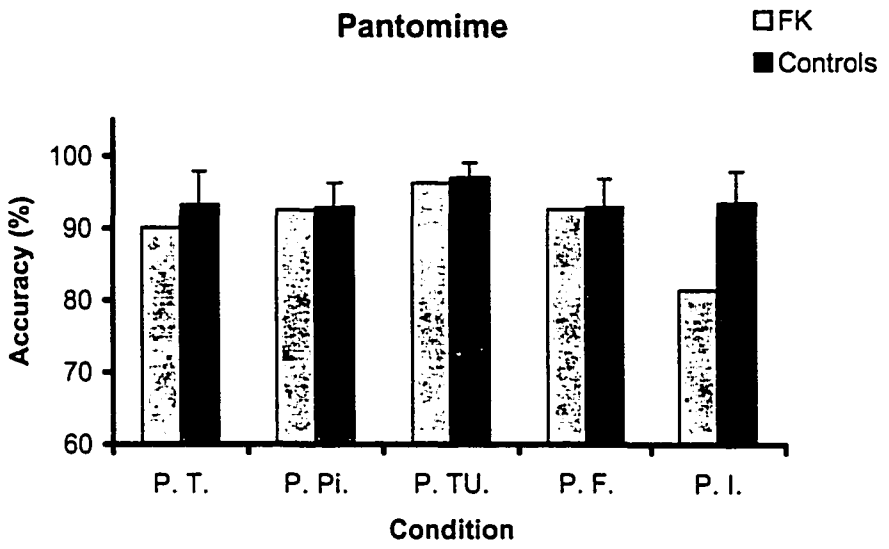
The present results provide evidence that the selection/evocation of different gesture forms is mediated by similar yet functionally distinct processes. Interestingly, KF's pantomime of intransitive gestures was impaired in the absence of similar deficits for transitive gestures. As noted by several researchers (Clark, Merians, Kothari, Poizner, Macauley, Rothi, & Heilman, 1994; Poizner, Clark, Merians, Macauley, Rothi, & Heilman, 1998), transitive limb gestures involve interactions between tools/objects and movement effectors (arm and hand), and are more 'complex' than intransitive gestures. However, KF's data suggests that it was the content and not complexity of the gesture that contributed to his form of apraxia. Conceivably, the distinction between different gesture forms could be further examined via neuro-imaging research in non-clinical populations. Grafton et al. (1997) observed that the left dorsal prefrontal cortex was preferentially activated when individuals silently named transitive gestures, or observed the production of these gestures. A similar paradigm could be used to determine whether separate cortical regions exist for intransitive gestures. In vivo evidence, coupled with the present findings and those of Dumont et al. (1999) would provide convergent support for parallel stages of gesture production.

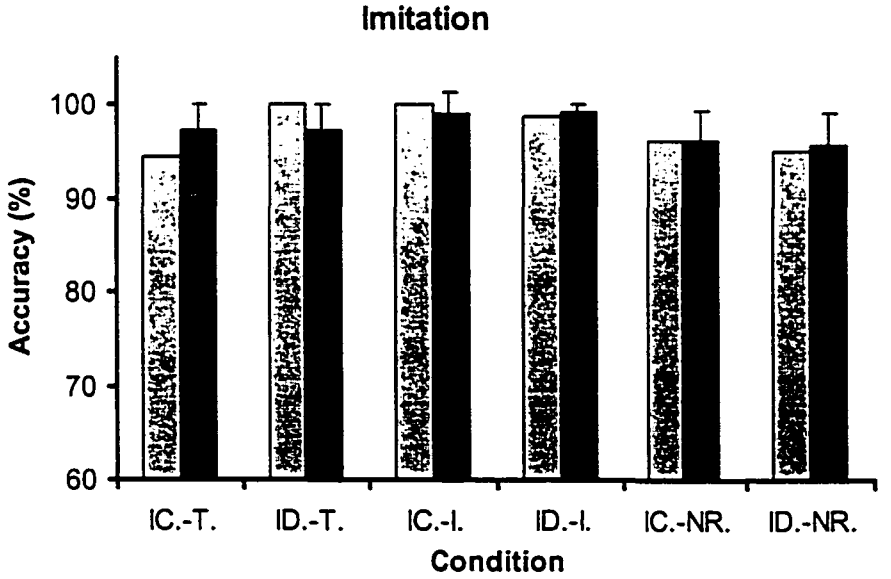
Figure Captions

Figure 1. An axial CT scan in the first week post stroke showed a large right subcortical hypodense region involving the head of the caudate, internal capsule, putamen and globus pallidus extending upward in the centrum semiovale.

Figure 2. Pantomime (top) and imitation (bottom) accuracy of FK, and average performance of age-matched controls.




Pantomime
FK
Controls
Accuracy (%)
100
90
80
70
60
P. T.
P. Pi.
P. TU.
P. F.
P. I.
Condition


Imitation
Accuracy (%)
100
90
80
70
60
IC.-T.
ID.-T.
IC.-I.
ID.-I.
IC.-NR.
ID.-NR.
Condition

EXPERIMENT THREE

ABSTRACT

Apraxia is the loss of the ability to perform learned, skilled movements correctly, and is frequently attributed to left hemisphere damage (Heilman and Rothi, 1985). Recent work by Roy and colleagues (e.g., Roy, Black, Blair & Dimeck, 1998) has questioned the exclusive involvement of the left hemisphere in apraxia. In their analyses, the frequency and severity of apraxia associated with the production of transitive limb gestures did not differ between patients with left or right hemisphere damage. In the present investigation, the frequency and severity of limb apraxia associated with intransitive limb gestures was examined in patients with left or right hemisphere stroke. The occurrence of apraxia during the production of intransitive limb gestures is not well documented, and the expressive/communicative nature of these gestures may result in a pattern of apraxia different to that observed for transitive gestures. One hundred and nineteen consecutive stroke patients (LHD = 57, RHD = 62) and 20 healthy age-matched controls performed eight intransitive gestures to pantomime and imitation. Performance was quantified via a multi-dimensional error notation system, providing detail pertaining to specific elements of performance (e.g., location), and a composite score, an arithmetic combination of the performance dimensions reflecting overall accuracy. Analyses of pantomime and imitation performance revealed an equal proportion of apraxic patients in both stroke groups, and, the severity of apraxia in these groups was also equivalent. In addition, analyses of the patterns of apraxia described by Roy (1996) revealed a higher frequency of apraxia in both stroke groups for the pattern reflecting apraxia in pantomime alone,

indicating that a disruption in the selection/evocation stage of gesture performance was most common.

EXPERIMENT THREE

Limb apraxia represents an inability to perform learned, skilled, purposeful actions such as showing someone how to wave goodbye, which cannot be attributed to weakness, ataxia, sensory loss, poor language comprehension or inattention to commands (Heilman & Rothi, 1985; Roy, 1985). Historically apraxia has been linked to damage of the left cerebral hemisphere in right-handed individuals (e.g., Liepmann, 1905; Geschwind, 1965). Indeed, considerable empirical evidence has substantiated this claim, however more recent work has shown that this notion may be subsumed by methodological considerations such as measurement precision (Haaland and Flaherty, 1984; Heath, Experiment 1; Roy, Black, Blair, & Dimeck, 1998), stimulus modality (Schnider, Hanlon, Alexander, & Benson, 1997), and gesture type (Goldenberg, 1996). Thus, the current challenge facing apraxia research is the application of appropriate methodologies and measurement systems sensitive to the deficits underlying the genesis of apraxia.

Apraxia can be observed when a gesture is produced in response to a verbal command (pantomime), and/or when a gesture demonstrated by an examiner is to be imitated. Many accounts of apraxia follow Liepmann's (1908) original formulation of two stages in the production of limb gestures. In the earliest stage, the appropriate representation of the gesture is evoked/selected from long term memory. The final stage involves translating the memorial representation into an appropriate motor act. Indeed, the basic tenets of Liepmann's two stage model of gesture production are prevalent in modern neuropsychological accounts of apraxia (e.g., Rothi, Ochipa, & Heilman, 1991,

1997; Roy and Hall, 1992; Roy and Square, 1994; Roy, 1996), and have provided testable hypotheses for understanding the cerebral organization of praxis.

In a series of studies comparing performance in pantomime and imitation conditions, De Renzi (Barbieri and De Renzi, 1988; De Renzi and Lucchelli, 1988; De Renzi, Motti, & Nichelli, 1980; De Renzi, Faglioni, & Sorgato, 1982) reported that LHD patients were significantly impaired relative to their RHD counterparts when producing gestures in response to verbal command. During imitation, RHD patients committed more gesture production errors, although their impairment in this condition was less severe than that seen in LHD patients. Further, De Renzi (Barbieri and De Renzi, 1988) examined patients who demonstrated a greater impairment in one condition or the other (pantomime vs. imitation) to determine the stage of gesture impairment associated with apraxia. These results indicated that although an equal proportion of LHD and RHD patients were more impaired to imitation than pantomime, a significantly higher proportion of LHD patients demonstrated the reverse dissociation, that is, greater impairment to pantomime. In concert with Liepmann's (1908) original report, De Renzi's findings suggest that the higher frequency of LHD patients demonstrating a greater impairment to pantomime than imitation reflects the selective role of the left hemisphere in the ideational (selection/evocation) components of gesture formulation.

The adherence to De Renzi's (1985) notion that apraxia is a left hemisphere disorder is reflected in a large body of current research (e.g., Belanger, Duffy, & Coehlo, 1996; Clark, Merians, Kothari, Poizner, Macauley, Rothi, & Heilman, 1994; McDonald, Tate, & Rigby, 1994) which have failed to consider the right hemisphere's role in praxis. One problem with this approach of not examining gesture performance following RHD is

that De Renzi's initial studies are based on qualitative measures of performance such as whether the gesture was correct on the first, second or third trial (Barbieri and De Renzi, 1988; De Renzi et al., 1980). This type of measurement system focuses very little on the details of movement execution, and hence may not be sensitive to quantifying apraxic deficits arising from RHD. Indeed, studies examining multiple dimensions of gesture production have noted significant performance disruptions following RHD (e.g., Haaland and Flaherty, 1984; Roy et al., 1998; in press). Haaland and Flaherty (1984) examined errors in gesture production using a multi-dimensional error notation system that provided information regarding arm and hand position, as well as hand posture and orientation. In their study, patients with LHD or RHD were compared with age-matched controls. Comparisons of the three groups revealed that healthy adults made significantly fewer errors than each stroke group, while the total number of errors between the two stroke groups did not differ. This novel finding suggests that damage to either hemisphere influences gesture production. How can these findings be reconciled given the plethora of evidence indicating the exclusive role of the left hemisphere in apraxia? The notion that damage to either hemisphere equally influences performance may be attributable to the fact that Haaland and Flaherty required patients to imitate gestures, mitigating the argument that the analysis of visual gestural information is mediated by the right and left hemisphere. Alternatively, their multi-dimensional error notation system may have enabled the detection of apraxic deficits not readily identified by more clinical tests of apraxia. This latter explanation is parsimonious with the more recent research of Roy and colleagues (Roy et al., 1998) and Heath (Experiment 1) who have employed a multi-dimensional error notation system in their assessment of apraxia.

In their initial analyses, Roy et al., (1998) examined the frequency and severity of apraxia following LHD or RHD. Patients were required to pantomime eight transitive limb gestures and performance was scored on five dimensions thought to be critical in gesture production. The results indicated that 54% of LHD and 30% of RHD patients were apraxic. While the percentage of apraxic patients with LHD or RHD was not significantly different, the nature of the apraxic deficit, as represented in the performance dimensions indicated that apraxia was differentially represented in LHD and RHD apraxic patients. For LHD patients, significantly poorer performance was demonstrated on the action dimension (i.e. exaggerated movement amplitude), suggesting impairments in the planning or formulation of movement trajectories. In contrast, RHD patients with apraxia were more impaired on the spatial dimensions of gesture production (i.e. location; position of the hand relative to the body). These findings do not support De Renzi's (1985) contention that damage to the left hemisphere alone results in an impaired ability to pantomime gestures, and suggests that each hemisphere may impart information critical for the formulation of a purposeful limb gesture.

Following Roy et al's (1998) work, Heath (Experiment 1) examined the performance of LHD or RHD patients during the production of transitive limb gestures in both pantomime and imitation contexts. Analyses revealed a proportionately greater number of LHD patients impaired in the pantomime condition, although the severity of the apraxic disorder did not differentiate between the two stroke groups. In the imitation condition, both the frequency and severity of apraxia was equal among LHD and RHD patients. Moreover, performance of patients across pantomime and imitation conditions permitted analysis of the specific patterns of apraxia exhibited by each patient.

Based on Roy's (1996) neuropsychological model of apraxia, three distinct patterns of apraxia were identified and examined. The first pattern, in which apraxia is present in pantomime but not imitation (P_A I_{NA}), is believed to reflect the impaired ability to select/evoke the appropriate response from memory (Roy and Hall, 1992). It is this pattern of apraxia that Liepmann (1908) believed to reflect loss of knowledge, or ability to access the movement formulae responsible for learned, skilled actions. Further, it is this pattern of apraxia that De Renzi (1985) has attributed specifically to LHD (see De Renzi, Piecquro, & Vignolo, 1968). In the second pattern, apraxia is observed on imitation but not pantomime (P_{NA} I_A), and may reflect disruptions in visual gestural analyses, or the translation of this information into movement. The final pattern, apraxia in both pantomime and imitation (P_A I_A), is thought to arise from a disruption in the later stages of gesture performance involving movement execution. The results of Heath (Experiment 1) provide the first group findings to examine simultaneously the frequency and severity of LHD and RHD patients in each pattern of apraxia. Surprisingly, the percentage of patients who were apraxic in pantomime alone was considerably low, and the frequency and overall severity of the deficit among LHD (5%) and RHD (6%) patients did not differ. Consistent with previous work examining apraxia to imitation, Heath reported an equal percentage of LHD (18%) and RHD (23%) in the second pattern, apraxic to imitation alone. It was the final pattern of apraxia that differentiated between stroke groups, as a majority of LHD (43%) patients were apraxic to both pantomime and imitation, and this number was significantly greater than RHD (23%) patients. These results suggest that the inability to pantomime a gesture following LHD may not exclusively reflect De Renzi's notion of an impaired ability to select/evoke the

appropriate gesture from semantic memory, rather, the results of Heath point toward a disruption in the later stage of the gesture production system, responsible for the organization and control of both pantomimed and imitated actions.

A further question remaining in the apraxia literature relates to understanding the expression of apraxia during the production of intransitive limb gestures in lateralized stroke patients. The majority of apraxia studies have focussed on the performance of transitive gestures (e.g., Foundas, Henchey, Gilmore, Fennell, & Heilman, 1995; McDonald et al., 1994), which involve manipulating tools and/or objects. Several studies have employed transitive, intransitive and non-representational gestures in their apraxia batteries; however, the distinction between gesture type was not addressed in their experimental analyses (Alexander, Baker, Naeser, Kaplan, & Palumbo, 1992; Barbieri and De Renzi, 1988). The paucity of research that has differentiated between gesture type has produced novel findings, namely the interaction of gesture type and stimulus modality (Belanger et al. 1996; Schnider et al., 1997). In their analyses, Schnider et al. failed to observe significant differences between LHD and RHD patients during the pantomime of intransitive gestures, implying that the selection/evocation of intransitive gestures can be equally impaired following left or right hemisphere damage. Indeed, intransitive gestures involve representational movements and tend to convey communicative/expressive content (e.g., waving goodbye). According to Rapcsak and colleagues (Rapscak, Ochipa, Beeson, & Rubens, 1993) intransitive "context-dependent" gestures are mediated by left and right hemisphere praxis systems, while abstract gestures (e.g., transitive) involving tool-object relations are believed to be lateralized to the left hemisphere. According to this type of explanation it should then be possible for the

contralesional hemisphere to mediate the formulation of intransitive gestures following unilateral insult.

The assertion that transitive and intransitive gestures are mediated by separate processes is bolstered by the recent work of Dumont, Ska, & Schiavetto (1999), and Heath (Experiment 2), each has reported selective forms of apraxia based on gesture type. Dumont et al. described a patient uniquely impaired during the production of transitive, but not intransitive or non-representational gestures. Conversely, Heath reported an individual, who was impaired when producing intransitive limb gestures, but was not impaired when producing transitive and non-representational gestures. These studies provide support for the notion that separate processes underlie the production of transitive and intransitive gestures. Given these findings, the present investigation examined the pantomime and imitation of intransitive gestures in a large sample of unilateral stroke patients to determine if the frequency and severity of apraxia associated with these gestures is different from that observed in studies employing transitive gestures (e.g., Heath, Experiment 1). Further, the patterns of apraxia described in Roy's (1996) model will be examined to determine if various stages of gesture production are differentially affected in lateralized stroke patients.

Method

Participants

One-hundred and nineteen consecutive patients with a single unilateral stroke, 57 lateralized to the left hemisphere (LHD) and 62 lateralized to the right (RHD) participated in this study. All right-handed patients without prior history of stroke were included, except for severely impaired patients who could not be instructed or modelled

for appropriate limb praxis assessment. Lesion sites were confirmed by the presence of an appropriate lesion CT, or by a clinically appropriate focal perfusion abnormality seen on ^{99}Tc-HMPAO-SPECT scan images obtained on a single-head GE gamma camera. In addition, twenty right-handed participants without history of neurologic or neuromuscular disorders served as controls. Control participants were selected to match as closely as possible the age and gender composition of the stroke groups (Table 1).

Insert Table 1 about here

All participants were right-handed as reported in their consent form, or as indicated by consent from their proxy. Subject's consent was obtained according to the declaration of Helsinki, and the study was approved by the Office of Human Research, University of Waterloo.

Gestural Task

Participants were required to pantomime or imitate eight intransitive limb gestures. In the pantomime condition, participants were asked to perform a familiar intransitive gesture to command. For example, for the 'salute' task, the request was "show me how you would salute an army officer". In the imitation condition, the examiner demonstrated the gesture and the participant attempted to imitate the performance. This demonstration was continued if the patient indicated subsequent attempts to replicate. For each participant the pantomime condition was performed prior to imitation in order to avoid providing cues as to the correct manner in which to perform the gesture.

Previous work by Roy et al. (1998) has demonstrated that the spatial and temporal dimensions of movement contribute to the overall complexity of the task. For instance,

the dimensions of repetitiveness and spatial location relative to the body (e.g., gesture toward or on the body, versus away from the body) may be differentially influenced by limb apraxia. Hence, the sample of gestures employed in the present task included non-repetitive movements performed toward the body (salute) or away from the body (okay sign), and the other four were repetitive gestures performed toward (crazy) or away from the body (wave goodbye). Control participants used their left and right hand, with half beginning with their right. For each stroke group, patients used their ipsilesional hand.

Performance Scoring

The performance of each participant was videotaped and scored on the basis of five performance dimensions which have been extended from previous work (see Roy, Square, Adams, & Friesen, 1985 for complete details), and are important features in manual signing (Stokoe, 1972). The performance dimensions included: **orientation** of the hand (rotation of the palm of the hand relative to the patient's arm or position), **action** (dynamic characteristics of hand movement through space), the **posture** of the hand (position or shape of the limb structure), **plane** of movement of the hand (the plane through which the movement normally occurs), and **location** of the hand (spatial location of the limb structure relative to the body). The videotaped performance of each participant was observed on five separate occasions, with separate dimensions scored per observation. One experienced researcher evaluated all subjects, and was blind to the experimental group of each subject during videotaped assessment. Each dimension was rated on a 3-point scale reflecting the degree of accuracy as follows: 2 (correct), 1 (distorted), 0 (incorrect). Within each performance dimension three unique features were defined which allowed the observer to determine if the dimension should be rated as 2, 1,

or 0. If each feature was present the performance was rated 2. If two features were present, performance was rated 1. A rating of 0 was given if one or less of the defined features were present. Each dimension was subsequently expressed as a percentage of the total possible score across the eight gestures. Finally, a **composite** score, representing overall movement accuracy was derived from the scores across the five dimensions. As noted elsewhere, the videotaped scoring procedure has demonstrated a high inter-rater reliability (see Roy et al., 1998).

Aphasia and Neglect Assessment

Speech and language function was assessed for each patient with LHD on the Western Aphasia Battery (Kertesz, 1979). The overall severity of aphasia was reflected in the Aphasia Quotient (AQ; max. = 100), with a higher score reflecting a more severe impairment.

All patients were administered a neglect battery consisting of line bi-section, line and figure cancellation, drawing from memory, and copying a clock and a daisy. These tasks were previously standardized and each patient received a score (max. = 100) with a higher score reflecting a more severe impairment (Black, Martin, & Szalai, 1990).

Data Analysis

The present analyses were designed to examine concurrently the frequency and severity of apraxia associated with unilateral cerebral damage. Previous investigations have typically focussed on addressing these issues separately (e.g., severity), and thus, are unable to determine if the lateralization of apraxic frequency and severity are co-related.

Data related to the severity of apraxia were reflected in the five performance dimensions and the composite score, an arithmetic derivative of the performance dimensions, which we have interpreted as a reflection of overall accuracy in gestural performance. Using these measures, one set of analyses involved a univariate analysis of variance (ANOVA) that focussed on the composite score. For the five performance dimensions a multivariate analysis of variance (MANOVA, Pillai's Trace, $p < .05$) was employed to compare the pattern of performance across each dimension. Fisher-Hayter ($p < .05$) and Bonferroni post-hoc procedures were employed to examine significant effects involving more than two means.

The correlation of each performance dimension with the composite score revealed a significant and positive correlation ($p < .05$) for each participant group and gestural condition. These results then, suggest that each performance dimension is a reliable predictor of overall accuracy as assessed by the composite score[1].

Results

Left and Right Hand Performance of Control Participants

A major issue associated with comparing upper limb performance in persons with unilateral cerebral damage is the influence of pre-morbid manual asymmetries. Typically LHD patients perform gestures with their non-dominant (left) hand due to the severity of contralateral hemiparesis, whereas RHD patients perform the task with their dominant (right) hand. Thus, group differences may not entirely reflect the influence of stroke laterality, rather, the underlying performance impairment may be indicative of the co-joint influence of stroke and premorbid manual performance asymmetries. To address this issue, the present investigation examined the left and right-hand performance of

control participants to determine if manual asymmetries influenced performance accuracy. The results indicated that the left and right hand of control participants did not differ in accuracy as assessed by the composite score, $F(1,19) = 1.79$, $p > .05$, or individual performance dimensions, $F(1,19) = 1.78$, $p > .05$ (Table 2). Hence, subsequent interpretations of LHD and RHD group results are attributed to the effect of stroke.

Insert Table 2 about here

In addition to addressing left/right hand differences, the above analysis examined whether gestural condition influenced accuracy. The results of the composite score analysis, $F(1,19) = 35.44$, $p < .001$, and performance dimensions, $F(1, 19) = 35.44$, $p < .001$, revealed that participants were less accurate during pantomime as opposed to imitation. As well, the dimension of orientation was less accurate than the other performance dimensions, $F(4, 76) = 9.13$, $p < .01$.

Comparison Between Control, Left and Right Hemisphere Stroke Groups

Prior to examining the frequency data related to limb apraxia, the accuracy scores of individuals in both stroke groups and control participants were assessed to determine whether unilateral cerebral damage resulted in a global deficit in gesture production (Figures 1 and 2; see also Table 3 for distribution of scores in the three groups). The composite score results were examined via a 3 group (control, LHD, RHD) x condition (pantomime, imitation) ANOVA, while a 3 group (control, LHD, RHD) x condition (pantomime, imitation) x 5 dimension (location, posture, action, plane, orientation) MANOVA assessed treatment effects involving the performance dimensions. The highest order interaction for the composite score, group x gesture, $F(2, 136) = 101.25$, $p < .001$, indicated that both stroke groups were equally impaired relative to the control group

in the pantomime condition. However, during imitation, only the LHD group was significantly impaired relative to the control group. Further, the multivariate analysis revealed a three-way interaction involving group, gesture and dimension, $F(8, 544) = 5.61$, $p < .001$. The interaction (see Figure 1 and 2) suggested that control participants were more accurate relative to both stroke groups on all performance dimensions, with the exception of orientation in the pantomime condition. Both stroke groups generally performed at the same level of accuracy in the pantomime condition, although LHD patients were more impaired on the action dimension. For the imitation data, group performance did not differ on the dimensions of location, plane, and orientation, while both stroke groups were impaired relative to controls on the posture dimension. On the action dimension, the LHD group demonstrated significant performance impairments relative to RHD and control participants.

Insert Figure 1 and 2 and Table 3 about here

Apraxic Classification

Previous investigations have relied on a range of techniques to classify individuals as either apraxic or non-apraxic. De Renzi et al. (1968) classified individuals as apraxic if their performance score fell below the lowest value achieved by a control participant. In contrast, the present investigation classified patients as either apraxic or non-apraxic if their composite score differed quantitatively from the group performance of control participants. A two-standard deviation rule permitted the identification of three categories of patients: apraxic, borderline, and non-apraxic. Patients were classified separately for the pantomime and imitation conditions. A cut-off score based on the mean composite score for control participants was employed for the apraxic

designation[2]. The first cutoff score was equal to one standard deviation below the composite mean (I), and the second cutoff score was equal to two standard deviations below the composite mean (II). Cutoff scores were subsequently used to classify patients within each stroke group as non apraxic (greater than score 1), borderline (between score 1 and II), or apraxic (less than score II).

LHD and RHD Apraxic Frequency and Severity Data to Gestural Pantomime

Table 4 presents the frequency of apraxic, borderline and non-apraxic patients in the pantomime condition. If apraxia is a disorder related primarily to left cerebral damage then we would expect a higher proportion of LHD patients in the apraxic category, and a lower proportion RHD patients in the same category. This argument was not borne out in the present results. The proportion of patients observed in the apraxic category (LHD = .68, RHD = .64) was remarkably similar, $\chi^2 = 4.09$, $p = .129$. One might speculate that although the frequency of the apraxic impairment was relatively similar, the overall severity of the deficit would be greater in LHD patients. To address this possibility the accuracy data of apraxic and non-apraxic participants in both stroke groups were compared.

Insert Table 4 about here

The accuracy scores of LHD and RHD apraxic and non-apraxic patients were compared to examine the possibility of a stroke group (LHD vs. RHD) by apraxia classification (apraxic vs. non-apraxic) interaction (see Tables 5 and 6). The composite score data failed to demonstrate a significant effect for stroke group or a stroke group by apraxic classification interaction, $F < 1$. Analyses of the performance dimension revealed a stroke group by dimension, $F(4, 115) = 10.72$, $p < .001$, and apraxia classification by

dimension interactions, $F(4, 115) = 6.16$, $p < .001$. As noted previously, the stroke group by dimension interaction indicated that LHD patients were impaired on the action dimension, while the apraxia classification by dimension interaction demonstrated that apraxic patients were significantly more accurate on the location than actior. dimension.

Insert Table 5 and 6 about here

Correlative data examining composite score results (pantomime and imitation) were instructive in inferring the nature of the movement deficit. LHD and RHD apraxic patients exhibited significant correlations between their composite scores (LHD, $r = .56$, $p < .001$; RHD, $r = .54$, $p < .001$) underscoring the possibility of a common mechanism underlying the movement deficit.

LHD and RHD Apraxic Frequency and Severity Data to Gestural Imitation

The imitation of intransitive gestures provides a valuable opportunity for examining whether the left or right hemisphere is preferentially lateralized for the visual analysis of intransitive gestures. Once again, we report frequency and severity data concurrently.

As expressed in Table 4, the proportion of LHD and RHD (LHD = .38, RHD = .37) patients with apraxia is equal, and the difference in this distribution was not significant, $\chi^2 = 2.49$, $p < .288$. Further the severity data failed to indicate significant differences between LHD and RHD patients, or demonstrate a stroke group by apraxic classification interaction, $F < 1$. Analysis of the performance dimensions indicated that stroke and apraxic groups were differentially impaired on several performance dimensions (see Tables 5 and 6). Specifically a three-way interaction between stroke group, apraxia classification and dimension, $F(4, 115) = 6.94$, $p < .001$, indicated that

LHD apraxic patients were significantly impaired on the action dimension, while RHD apraxic patients were impaired on the posture dimension.

Correlative data involving composite score results (pantomime and imitation) for LHD and RHD apraxic participants indicated a significant correlation between scores for the LHD ($r = .58$, $p < .01$) but not the RHD group ($r = .17$, $p > .05$).

Categorization of Apraxia

Following Roy (1996), stroke participants were classified individually based on their performance across pantomime and imitation conditions. Three patterns of apraxia were identified. Patients who fell in the apraxic condition for pantomime only were assigned to the first pattern (P_A I_{NA}), patients who fell in the apraxic range for imitation only were assigned to the second pattern (P_{NA} I_A). Those patients apraxic in both pantomime and imitation were assigned to the third pattern (P_A I_A). The frequency of patients in each of these groups was examined and the results are presented in Table 7. The results indicated a relatively equal number of LHD and RHD patients represented in each pattern of apraxia.

Insert Table 7 about here

The benefit of employing the above classification system was that different apraxic categories could be compared with one another, thus providing a method for identifying the apraxic category with the most profound deficit. The first set of analyses involved comparing the pantomime scores of individuals classified as apraxic in both conditions with those apraxic in pantomime alone, (2 group (LHD, RHD) x 2 apraxia type (P_A I_{NA}, P_A I_{NA}). The composite score results indicated that those participants apraxic in both conditions were more impaired than those apraxic to pantomime alone,

$F(1, 75) = 15.07$, $p < .001$, however, a group by apraxia classification interaction that approached significance, $F(1, 75) = 3.65$, $p = .06$, suggested that RHD patients classified as apraxic to both conditions were more impaired relative to their LHD counterparts, whereas LHD and RHD patients classified as impaired to pantomime alone were equally impaired. To address whether the production disorder was related to a specific element of gesture production a 2 group (LHD, RHD) x 2 apraxic type ($P_{A\ NA}$, $P_A\ I_A$) by 5 dimension (location, posture, action, plane, orientation) MANOVA was performed. These results revealed a main effect for apraxia classification, $F(1,75) = 14.42$, $p < .001$, such that patients apraxic in both pantomime and imitation were more impaired than those apraxic to pantomime alone. Further, a group by dimension interaction was revealed, $F(4, 75) = 6.65$, $p < .001$, demonstrating that RHD patients were significantly less accurate than LHD patients on the dimensions of location, posture, and orientation. It was only on the action demonstration that LHD patients demonstrated a significant decrement in performance relative to the other performance dimensions. These results suggest that apraxia following RHD is a result of a multidimensional impairment in gesture production, while LHD selectively impaired the action dimension of gesture production (see Figure 3).

Insert Figure 3 about here

A second set of comparisons examined the imitation scores of patients apraxic in both conditions with those apraxic on imitation alone. The composite score analysis failed to exhibit any significant effects or interactions ($F < 1$), while the analysis examining performance dimensions revealed a group by dimension interaction, $F(4, 35) = 4.15$, $p < .004$. The group by dimension interaction indicated that accuracy in the two

stroke groups differed only on the action dimension, with the LHD group being more impaired (see Figure 4).

Insert Figure 4 about here

Performance Impairments Associated with Apraxia

Another approach to examine the severity of apraxic impairments in the two stroke groups is to compare the number of performance dimensions on which each patient is impaired, with a greater number of impaired performance dimensions indicating a greater apraxic impairment. Patients were divided into two groups, one reflecting patients who exhibited an impairment on two or fewer performance dimensions, and the other reflecting patients who exhibited impairments on three or more dimensions. A mean value for each performance dimensions was calculated from those patients classified as non-apraxic in both pantomime and imitation (separately for LHD and RHD groups). Subsequently the two standard deviation rule was used to determine if performance was impaired on an individual dimension.

The pantomime data revealed an equal proportion of LHD (.54) and RHD (.55) impaired on greater than two performance dimensions (see Table 8) categories; $\chi^2 = 0.02$, $p = .96$, and is in accord with the frequency and severity data reported previously. Data pertaining to the imitation condition indicated a higher frequency of LHD (.81) and RHD (.82) patients demonstrating performance impairments on two or fewer dimensions, $\chi^2 = 0.048$, $p = .83$.

Insert Table 8 about here

The Relationship Between Apraxia and Neglect in LHD and RHD Patients

The present results indicated that the neglect scores of RHD patients were significantly greater than their LHD counterparts, ($p < .01$). Moreover, the imitation composite score for the RHD group was the only measure significantly correlated with neglect scores ($r = -.31$). In light of these findings is it possible that hemi-attentional or visual spatial neglect contributed to group differences in accuracy? The results do not support this contention given that LHD and RHD patients classified as apraxic in both gestural conditions (P_A I_A) did not differ in their neglect scores, ($p > .05$). As well, the considerable number of RHD patients classified as apraxic to pantomime alone cannot be attributed to neglect. Thus, the apraxic deficits observed in RHD patients can be attributed to deficits in praxis production, and not hemi-attentional or visual-spatial neglect.

The Relationship Between Apraxia and Aphasia in Patients with LHD

Analyses of the AQ scores on the Western Aphasia Battery revealed that 43 percent $(23/54)^3$ of the patients were aphasic. All of these patients with aphasia could be classified into different aphasic types (Table 9) with the largest number being of the anomic (39 percent or 9/23) or the Broca's (26 percent or 6/23) type. These findings suggest that our patients with LHD may have had relatively mild strokes.

Insert Table 9 about here

The relationship between apraxia and aphasia was first examined by comparing the frequency of apraxia in the patients with aphasia to that in the patients without aphasia. These analyses revealed a much higher frequency of aphasia among patients classified as apraxic to pantomime (83 percent or 19/23 for apraxic) than among aphasic

patients without apraxia in this condition (17 percent or 4/23). A similar finding for the imitation condition was not elucidated, as the number of aphasic patients classified as apraxic (48 percent or 11/23) did not differ from number of aphasic patients without apraxia in this condition (52 percent or 12/23).

The measure of overall aphasia severity (AQ) demonstrated that patients classified as apraxic to pantomime (apraxic AQ = 80.10; non-apraxic AQ = 93.48, $F(1,52) = 4.73$, $p < .04$) were impaired relative to their non-apraxic counterparts. In contrast, patients classified as apraxic to imitation did not differ from the non-apraxic group (apraxic AQ = 80.56; non-apraxic AQ = 87.10, $F(1,53) = 1.31$, $p = .29$). Similarly, the relationship between apraxia and aphasia indicated that the AQ was significantly correlated with the composite score for pantomime ($r = .39$, $p = .01$) but not imitation ($r = .16$, $p = .23$). These findings suggest a relationship between speech/language and apraxia in the pantomime but not imitation condition (Kertesz, Ferro, & Shewan, 1984; Lehmkuhl, Poeck, Wilmes, 1983; Square-Storer, Roy, & Hogg, 1990). These results suggest that a strong relationship exists between the pantomime of an intransitive gesture and aphasia.

DISCUSSION

The design of this study was based on the assumption that performing a gesture to verbal command requires the retrieval of the gesture from semantic memory, whereas imitation of the same gesture demands the visual analysis of gestural information and its translation into movement. The work of De Renzi and colleagues (e.g.., De Renzi et al., 1968; see also Roy, 1985) has pointedly demonstrated that the occurrence and overall severity of apraxia to pantomime is particularly marked following LHD. In contrast, the

present results suggest that the frequency and severity of apraxia during the pantomime of intransitive limb gestures is similar following left or right hemisphere damage. Further, as demonstrated elsewhere (e.g., Haaland and Flaherty, 1984; Heath, Experiment 1), the frequency and severity of apraxia during gestural imitation was found to be similar.

The frequency and severity data separately for pantomime and imitation conditions will be discussed first. Following this, the patterns of apraxia discussed by Roy (1996) and identified in this sample of lateralized stroke patients will be outlined to highlight the frequency and specific gestural deficits associated with each pattern. Moreover, the performance dimensions impaired in each stroke group will be discussed to assess the specific contributions of the left and right hemisphere to gesture production.

Pantomime and Apraxia

Recall that pantomiming a gesture is thought to require the selection/evocation of an appropriate memorial representation of the action from semantic memory; thus, failure in this task is believed to reflect an inability to access this knowledge (Rothi et al., 1997), generating the relevant visual image of the gesture (Roy and Hall, 1992; see also Roy, 1996) or selecting the appropriate response (De Renzi, 1985). Previous investigations examining the frequency of this disorder have typically assessed the performance of transitive limb gestures (e.g., Barbieri and De Renzi, 1988; De Renzi et al., 1968; Foundas et al., 1995; Roy et al., 1998, in press), while those investigations that have assessed the severity of apraxia during the pantomime of intransitive gestures have not included frequency data (e.g., Belanger et al., 1996; Schnider et al., 1997). The

present investigation examined concurrently the frequency and severity of apraxia related to the pantomime of intransitive gestures.

A significant percentage of LHD (68%) and RHD (64%) patients were found to be apraxic to pantomime, suggesting that the integrity of the ideational (selection/evocation) stage of gesture production is not selectively impaired by left hemisphere damage. The frequency data then, do not concur with those of De Renzi and colleagues (De Renzi et al., 1968; Barbieri and De Renzi, 1988) who have consistently reported a significantly greater number of LHD patients apraxic in this condition (see also Alexander et al., 1992). In fact, in his original study, De Renzi (De Renzi et al., 1968) failed to observe a single case of RHD that resulted in performance classified as apraxic. The discrepancy between the present work and that of De Renzi et al. (1968) may relate to fact that De Renzi's patients performed transitive gestures. Similarly, Alexander et al. (1992) who included both transitive and intransitive gestures failed to observe apraxic performance in his sample of RHD patients. It is plausible that De Renzi and Alexander et al. did not observe apraxic performance in RHD patients due to the former examining exclusively the performance of transitive gestures, while the latter did not examine whether the occurrence of apraxia differed on the basis of gesture type. Indeed, the distinction between intransitive and transitive gestures may play an integral role in explaining the discrepancy, and will be explored in greater detail during subsequent sections detailing the patterns of apraxia.

Alternatively, the discrepancy between our findings and those of De Renzi (De Renzi et al., 1968) may relate to the precision afforded by our multi-dimensional error notation system. In previous work examining transitive gestures (Roy et al. 1998), the

occurrence of apraxia in the pantomime condition was found to be similar among left and right hemisphere stroke patients. While Heath noted that the number of LHD (48%) patients demonstrating apraxic performance to pantomime was greater than the RHD group (28%), it is evident in both cases that a significant number of patients with RHD were apraxic in this condition. Presumably, the scoring system used by De Renzi and colleagues (e.g., Barbieri and De Renzi, 1988) was not as sensitive as ours in quantifying disruption in gesture performance as their system involved only the analysis of gesture recognizability, where the precise characteristics of performance are much less clearly defined.

Support for the hypothesis that the error notation system used in the present investigation was more sensitive in characterizing the effects of unilateral damage on gesture production stems directly from the accuracy data. As noted above, the frequency data indicated an equal proportion of LHD and RHD patients were classified as apraxic, and, the overall accuracy (composite score) of gesture production did not differ between the two apraxic stroke groups. This finding is consistent with the work of Schnider et al. (1997) who reported that LHD and RHD patients were equally impaired when pantomiming intransitive gestures. Moreover, the multi-dimensional error notation system identified specific elements impaired in gesture formation. This analysis revealed that LHD patients exhibited less accurate performance on the action dimension (e.g., exaggerated movement amplitude, non-fluid movements), while RHD patients were globally impaired in gesture production.

The overriding deficit exhibited by LHD patients on the action dimension, particularly 'non-fluid' movements and movements of 'exaggerated' amplitude points to

the importance of the left hemisphere in controlling the spatial-temporal elements of movement. This coincides with a wealth of performance and kinematic data indicating that the left hemisphere regulates the neuromuscular synergies associated with the programming and control of movement amplitude and force production (Clark et al., 1994; Kimura, 1982; Haaland, Harrington, & Knight, 1999; Poizner, Mack, Verfaellie, Rothi, & Heilman, 1990; Poizner, Merians, Clark, Macauley, Rothi, & Heilman, 1998; Wyke, 1967; 1971). For RHD patients, the present findings did not provide a definitive locus for the movement deficits. At present we our employing kinematic and kinetic analyses (Heath, Experiments 4 and 5; see also Hermsdorfer, Mai, Spatt, Marquardt, Veltkamp, & Goldenberg, 1996; Clark et al., 1994) to explore in greater detail the origin of movement deficits in apraxic patients with LHD or RHD. The ultimate goal of this line of research is to determine whether unique deficits are associated with LHD or RHD apraxia.

Imitation and Apraxia

The imitation of a gesture requires the analysis of visual gestural information and the translation of this information into movement. In our sample of lateralized stroke patients an equal proportion of LHD (38%) and RHD (37%) patients were found to be apraxic in this condition. These data support those of Barbieri and De Renzi (1988) and Heath (Experiment 1) which noted a relatively equal percentage of LHD and RHD patients apraxic in this condition (see also Haaland and Flaherty, 1984; De Renzi et al., 1982). As well, comparison of the composite scores (overall accuracy) revealed that both stroke groups were equally impaired by the apraxic disorder.

Analysis of the individual performance dimensions provided an index as to which aspect of gesture production was impaired in LHD and RHD apraxic patients. In accord with the pantomime data, LHD patients with apraxia were found to be significantly impaired on the action dimension relative to their non-apraxic counterparts, whereas RHD patients were particularly impaired on the action, plane, and notably posture dimensions. The observation that the spatial dimensions of gesture production were more impaired in RHD apraxic patients is consistent with the work of Haaland and Flaherty (1984) and their assertion that the movement deficits associated with representative movements (e.g., intransitive gestures) may be quite different in LHD and RHD populations.

While the frequency data generally concur with previous research examining the frequency of apraxia during gestural imitation, the observation that RHD patients were as impaired as their LHD apraxic counterparts is a novel finding. In their work examining the performance of LHD and RHD patients during the imitation of intransitive gestures, Schnider et al. (1997) noted that only LHD patients were impaired relative to control subjects when intransitive gestures were imitated, RHD patients were not similarly impaired. Moreover, Belanger et al. (1996) failed to observe performance differences between LHD and age-matched controls in this condition, and concluded that the inclusion of a condition involving the imitation of intransitive gestures has "limited value in the differential diagnosis and appraisal of limb apraxia" (p. 401). The discrepancy between the present results and those of Belanger et al. (1996) and Schnider et al. (1997) may relate to several elements. Firstly, the number of RHD patients employed by Schnider et al. was relatively small (N = 11), and therefore may have lacked sufficient

power to detect movement deficits associated with apraxia in RHD patients. Secondly, Schnider et al. did not distinguish between apraxic and non-apraxic patients in their study. Belanger et al. did classify patients as being apraxic if their performance on any task in their apraxia battery (including transitive and intransitive gestures performed to pantomime or imitation) fell within an apraxic range of performance. Recall that in the present study patients were classified as apraxic separately for the pantomime and imitation of intransitive gestures. Thus, Schnider et al. and Belanger et al. may have failed to report results congruent with the present study because their analyses did not specifically focus on the performance impairments associated with *apraxia* in their imitation conditions alone.

Patterns of Apraxia

The preceding sections examined frequency and severity data for pantomime and imitation conditions separately. However, a more appropriate method for understanding the mechanisms underlying apraxia may be through examining the patterns of apraxia proposed by Roy (1996). In this scheme, patients are classified based on their performance in both stimulus modalities co-jointly.

Pantomime Dissociated from Imitation

The first pattern of apraxia (see Roy, 1996) involves apraxic performance to pantomime but not imitation (P_A I_{NA}). In the present investigation the clearest evidence arguing against the selective role of the left hemisphere in the pantomime of a gesture stems from the equal proportion of LHD (22 or 38 percent) and RHD (26 or 42 percent) patients in this category. Barbieri and De Renzi (1988) observed a higher frequency of LHD (12) than RHD (2) patients that demonstrated this pattern, while Heath (Experiment

1) noted an equal distribution; albeit a considerably lower frequency relative to the present results (LHD = 2 or 5 percent, RHD = 3 or 6 percent).

The discrepancy between the present findings and those mentioned above may relate to the type of gesture performed (Barbieri and De Renzi, 1988; Heath, Experiment 1) and/or the manner in which the pattern was defined (Barbieri and De Renzi, 1988). Recall that in the present investigation this pattern was based on a clear dissociation, such that a patient's performance fell in the apraxic range only in the pantomime condition. In contrast, Barbieri and De Renzi classified patients in this category if the difference between imitation and use of objects (pantomime) test was larger than that seen in controls. The fact that Barbieri and De Renzi reported a larger number of LHD patients in this condition (pantomime more impaired than imitation) may reflect the fact that patients in Barbieri and De Renzi's sample were apraxic in both conditions, but were just more impaired on pantomime than imitation. Support for this view is seen in previous work examining transitive gestures (Heath, Experiment 1), indicating a lower proportion of LHD patients in the pantomime alone condition, compared to a large number of LHD patients apraxic in both pantomime and imitation (LHD = 20 or 43 percent; RHD = 12 or 23 percent). Thus, Barbieri and De Renzi's patients may not have been impaired by an ideational disorder, rather, the genesis of the disorder may have involved a significant disruption to the executive stage of gesture production.

A further distinction between the present results and those of Barbieri and De Renzi (1988), and Heath (Experiment 1) relates to the type of gesture performed, and the method in which the response was elicited. Heath. employed transitive gestures and found a small proportion of LHD (5%) and RHD patients (6%) in this category. In the

present experiment a significantly greater number of LHD (38%) and RHD (42%) patients demonstrated this pattern. This difference may be related to the different action semantic systems underlying the production of transitive and intransitive gestures (see Heath, Experiment 2; Rothi et al., 1997; Roy and Square, 1994; Roy, 1996).

Pantomiming a transitive gesture involves not only the ability to select/evoke the memorial representation of a gesture from semantic memory, but also the ability to perceive function from structure (conceptual knowledge) based on the tool's visual affordances (Goldenberg and Hagmann, 1997). In an investigation examining this relationship, Goldenberg and Hagmann required LHD and RHD patients to pantomime the use of familiar tools, and in a separate condition, tested the ability of the same patients to select and apply a novel tool in a mechanical problem solving task. The inclusion of both conditions allowed the investigators to identify patients in whom novel tool selection was impaired and the pantomime of tool actions was normal, as well as patients demonstrating the reverse dissociation. Goldenberg and Hagmann observed both patterns, demonstrating that the ability to utilize familiar tools can be associated with the retrieval of instructions from semantic memory, or through the visual affordances pertaining to the tool's structure. In a previous analysis of transitive gestures (Heath, Experiment 1) patients were briefly shown the tool associated with the gesture prior to each trial (see also Barbieri and De Renzi, 1988). Thus, patients were provided the opportunity of accurately pantomiming the gesture based on their ability to select/evoke the appropriate action from memory, and/or their ability to perform the action based on the mechanical affordances provided by vision of the tool used in the action. In the present investigation, a verbal cue alone was used to elicit the pantomime response, thus

patients relied solely on the ability to select/evoke the appropriate response from semantic memory. Thus, the higher frequency of patients demonstrating this pattern of apraxia relative to previous research (Heath, Experiment 1) may have occurred due to the fact that patients were not afforded the opportunity to utilize multiple cues for accurate gesture production, instead pantomime performance in the present investigation relied solely upon the evocation of a gesture from semantic memory.

A second issue relating to this pattern of apraxia is why an equal proportion of LHD and RHD patients were impaired in selecting/evoking the memory for intransitive gesture (see also Heath, Experiment 1). Ample research has demonstrated that LHD impairs the ability to perform gestures and gestural sequences from memory (Jason, 1983, 1985, 1986; Roy, 1981; Roy, Square, Hogg, & Adams, 1991; see also Roy and Square, 1994 for a review). In more recent work Roy (Roy et al., 1998) has speculated that the RHD may contribute to limb apraxia due to several factors including interhemispheric interference, lesion size, or bilateral representation of movement praxis. The present findings indicate that two novel elements contributed to the equal proportion of LHD and RHD patients in this pattern. As indicated previously, the sensitivity of the analysis system may have permitted the quantification of movement deficits not readily quantifiable by more clinical tests of apraxia. Secondly, the large number of LHD and RHD patients in this pattern of apraxia indicates that unlike transitive limb gestures, the production of intransitive limb gestures is more likely to be impaired following stroke to either hemisphere. This notion, supports Dumont et al., (1999) and Heath (Experiment 2) who have argued that parallel systems underlie the production of intransitive and transitive limb gestures.

Imitation Dissociated from Pantomime

The second pattern of apraxia is one in which apraxia is seen on imitation but not pantomime (P_{NA} I_A). A limited number of cases demonstrating this pattern have been reported (Mehler, 1987; Merians, Clark, Poizner, Macauley, Rothi, & Heilman, 1997; Ochipa, Rothi, & Heilman, 1994; Roy et al., 1998). Ochipa et al. reported a single case in which pantomiming gestures was superior to imitation, despite the fact the patient was able to verbally discriminate (label) gestures. To account for this selective form of apraxia which Ochipa et al. coined "conduction apraxia", a distinction between gesture production and reception, as well as a non-lexical route to action for the imitation of gestures was proposed. More specifically, this pattern of apraxia may reflect impaired visual gestural analysis and/or the translation of this information into movement. In the present investigation this pattern was infrequent (LHD = 5 or 9 percent, RHD = 3 or 5 percent), and the overall accuracy (composite score) data indicated that apraxic patients in both stroke groups were equally impaired. However, as indicated previously, the dimensions of performance were instructive in differentiating between the specific movement deficits in each group. Specifically, LHD patients were most impaired on the action dimension, while the performance of RHD apraxic patients were equally impaired in each performance dimension. Using both measures (frequency and accuracy), it appears that disruption at this stage occurs infrequently, resulting from a specific impairment in LHD patients (action dimension) while RHD patients are globally impaired.

The observation that left and right hemisphere patients are equally impaired in the imitation of gestures has been documented by numerous researchers (De Renzi et al.

1980; Haaland and Flaherty, 1984; Heath, Experiment 1). However, the fact that this pattern of apraxia (apraxic to imitation alone) accounted minimally for the total number of patients classified as apraxic in the imitation condition suggests that the majority of patients impaired to imitation were not selectively impaired in visual gestural analysis or its translation into movement. Rather, the nature of their movement deficit is likely linked to impairments at the executive stage of gesture production. This idea will be extended in the following section examining the frequency and severity of apraxia in those patients classified as apraxic in both pantomime and imitation. Indeed, the low number of RHD patients demonstrating this pattern of apraxia speaks to a deficit in gesture production, and not impairments associated with visual-spatial neglect.

Despite the small number of patients within this category, the fact that this pattern can arise points toward an interesting dissociation not definitively explained by many neuropsychological models of apraxia (Rothi et al., 1991, 1997; Roy and Hall, 1992). As indicated above, this pattern is believed to reflect a disruption in visual gestural analysis or its translation into movement. In contrast, Barbieri and De Renzi (1988) have attributed this pattern to an executive deficit. The latter explanation seems unlikely given that an executive impairment should also hinder performance in the pantomime condition.

Goldenberg (1996) has further argued against Barbieri and De Renzi's (1988) position that impaired gesture imitation is indicative of a deficit of motor execution. In his study LHD and RHD patients imitated non-representational gestures. Performance was scored on the basis of hand and finger postures. The results demonstrated that the LHD and RHD patients were equally impaired for finger configuration, whereas

defective imitation of hand position was exclusive to the LHD group. Based on these findings Goldenberg has argued that the impaired ability to imitate a gesture is not likely to reflect deficits in motor execution since impairments in motor execution should affect all aspects of gesture production to the same extent. Instead, Goldenberg's results, indicating that hand postures of LHD patients are more impaired than finger position, suggests that LHD patients may have difficulty imitating gestures due to defective knowledge regarding the schemata of the human body. In contrast, data for RHD patients suggest defective visuo-spatial analysis.

In the present study the low frequency of patients in this pattern of apraxia (imitation alone) did not permit meaningful analyses, however examination of the mean scores for the performance dimensions do not support Goldenberg's position. Our LHD patients performed flawlessly on the location dimension, which is roughly analogous to Goldenberg's "hand position". In contrast, our data point toward a disorder in the action dimension, suggesting that these individuals are able to infer global detail pertaining to gesture production, but are impaired in the dynamical elements of gesture production. RHD patients demonstrated global impairments in gesture production, indicative of a more general impairment in praxis.

While we are unable to definitively determine the nature of the performance decrement in both apraxic stroke groups, future work is aimed at extending the notion that this pattern of apraxia reflects impaired visual gestural analyses, or the translation of this information into movement. In this context, patients will be assessed on a gesture recognition/discrimination task in conjunction with their pantomime and imitation

performance. Patients demonstrating impaired imitation in the absence of pantomime and gesture recognition/discrimination deficits would support the above hypothesis.

Concurrent Apraxia on Pantomime and Imitation

The final pattern of apraxia reflects the co-occurrence of an apraxic deficit in both pantomime and imitation conditions (P_A I_A). The pantomime and imitation of a gesture is thought to rely upon the same common route to action, hence apraxic performance in both conditions is indicative of an impaired executive stage of production. The occurrence of this pattern was only slightly greater in LHD patients (LHD = 30%, RHD = 22%). This high co-occurrence coincides with the finding that the pantomime and imitation scores of LHD patients were significantly correlated, and for those RHD patients classified as apraxic to pantomime. Further, these results support the hypothesis proposed by Roy (1996) that the co-occurrence of apraxia in both conditions represents a disruption to the later stage in the production system which controls the innervatory patterns for movement.

The present findings provide tentative support for previous work reporting that 40% of LHD and 22% of RHD patients were apraxic in both conditions (Heath, Experiment 1), as well as that of Barbieri and De Renzi (1988; LHD = 54%, RHD = 24%) who also demonstrated that the co-occurrence of apraxia was greater in LHD patients. Our future work is aimed at extending these results via kinematic and kinetic analyses, in order to examine the specific spatial-temporal elements impaired in LHD or RHD patients with this pattern of apraxia. Indeed, Poizner and colleagues (Poizner et al., 1998) have examined the performance of LHD and RHD patients using kinematic analyses, but have failed to observe abnormal kinematic profiles in RHD patients.

However, these null findings may be due to the fact that their LHD patients are selected on basis of their clinical diagnosis of ideomotor apraxia, whereas RHD patients are not. Further, Poizner et al. did not systematically examine the influence of premorbid manual asymmetries in their assessment of LHD and RHD patients. Recent work by Heath (Experiment 4) has shown that manual performance asymmetries are elicited during the production of transitive limb gestures in healthy adults. In this paradigm participants were required to produce transitive limb gestures with their dominant (right) or non-dominant (left) hand. The results indicated that the spatial path and consistency of the non-dominant hand was significantly less than that of the dominant hand. Extended to the apraxia literature, it is probable that previous kinematic work has failed to report movement deficits in RHD patients due to the fact the ipsilesional (right) limb of RHD patients is compared to the pooled left/right performance of control participants. This type of comparison may underestimate apraxic deficits in RHD patients. If direct limb comparisons are made, it may be possible to employ kinematics and kinetics to quantify the precise movement deficits associated with apraxia and RHD. Future work will employ kinematic analyses to examine LHD and RHD patients with clinical diagnosis of apraxia; the ipsilesional limb (right) of RHD patients will be contrasted with the dominant hand (right) of age-matched controls. Correspondingly, the ipsilesional limb (left) of LHD patients will be compared to the non-dominant limb (left) of control participants.

CONCLUSIONS

The present findings revealed that impairments in pantomiming intransitive limb gestures was not restricted to LHD, suggesting that the failure to select/evoke an

intransitive limb gesture from memory can be equally impaired following stroke to either hemisphere. These results provide the first evidence from a group study to support the notion that the selection/evocation processes associated with intransitive limb gestures may be different from those associated with transitive limb gestures (Heath, Experiment 2; Rapcsak et al., 1993). Additionally, apraxic performance to gestural imitation could not be attributed to impaired visual gestural analysis in the majority of LHD or RHD patients. Instead, these patients were concurrently impaired in gestural pantomime, suggesting deficits in the executive stage of gesture production.

Footnotes

[1]Significant correlations between each performance dimension and composite score were revealed following correction for contamination (Magnusson, 1966, p. 212).

[2]The composite score derived for cut-off performance for apraxic patients was based on the pooled left and right hand performance of control participants.

[3]Time limitations did not permit administration of the Western Aphasia Battery to three LHD patients, and their data are not included in subsequent analyses involving AQ data or aphasic categorization.

Table 1

Participant Characteristics

Group	Age			Test Onset (Days Since Stroke)	
	N	M	sd	M	sd
Control	20	68.45	10.01	--	--
LHD	57	70.10	15.86	72.36	70.16
RHD	62	69.37	12.61	75.61	74.78

Table 2

Gestural Performance of Control Participants

	Pantomime				Imitation			
	Left hand		Right hand		Left Hand		Right Hand	
	M	sd	M	sd	M	sd	M	sd
Orientation	94.58	8.14	94.58	8.80	98.21	5.16	96.67	7.03
Action	96.61	4.05	97.92	3.05	98.66	2.60	97.08	3.23
Posture	94.11	6.02	93.27	6.45	97.77	4.66	97.92	3.05
Plane	97.92	3.86	97.92	3.86	98.21	2.93	99.17	2.20
Location	97.86	3.14	95.77	3.10	100	0.00	100	0.00
Composite	95.71	3.58	95.64	1.98	98.57	1.61	98.17	1.63

Table 3. Composite Score Distribution of LHD, RHD and Control Participants Across Performance Conditions

	Pantomime			Imitation		
Score	Control	LHD	RHD	Control	LHD	RHD
97-100	6	5	9	18	22	36
94-96.9	5	4	5	2	21	15
91-93.9	5	1	2	-	5	3
88-90.9	4	4	4	-	3	3
85-87.9	-	4	2	-	2	1
82-84.9	-	2	6	-	2	2
79-81.9	-	7	4	-	-	1
76-78.9	-	11	8	-	-	1
73-75.9	-	4	5	-	1	-
70-72.9	-	5	3	-	1	-
67-69.9	-	3	3	-	-	-
64-66.9	-	2	2	-	-	-
61-63.9	-	2	3	-	-	-
58-60.9	-	-	-	-		-
55-57.9	-	1	1	-	-	-
52-54.9	-	-	-	-	-	-
49-51.9	-	-	-	-	-	-
46-48.9	-	-	1	-	-	-
43-45.9	-	1	1	-	-	-
40-42.9	-		1	-	-	-
37-39.9	-	1	2	-	-	-

Table 4

Apraxia Severity as a Function of Stroke Group

Group	Gestural Condition	
	Pantomime	Imitation
LHD		
Apraxic	39 (68%)	22 (38%)
Borderline	5 (9%)	5 (9%)
Non-apraxic	13 (23%)	30 (53%)
RHD		
Apraxic	40 (64%)	17 (37%)
Borderline	13 (21%)	10 (16%)
Non-apraxic	9 (15%)	35 (57%)

Table 5

Gestural Performance of LHD Participants Classified as Apraxic and Non-apraxic

	Apraxic				Non-apraxic			
	Pantomime		Imitation		Pantomime		Imitation	
	M	sd	M	sd	M	sd	M	sd
Location	79.46	13.83	95.73	7.05	97.56	4.85	99.28	2.01
Posture	74.38	13.97	90.34	10.69	94.09	6.23	95.37	4.87
Action	59.77	14.67	76.70	9.67	82.63	14.30	95.00	6.21
Plane	68.53	14.08	89.77	11.97	90.27	11.78	99.99	0.33
Orientation	80.31	10.87	95.45	7.00	96.52	6.85	99.46	2.33
Composite	72.33	12.36	89.60	7.04	92.77	4.72	97.82	1.56

Table 6

Gestural Performance of RHD Participants Classified as Apraxic and Non-apraxic

	Apraxic				Non-apraxic			
	Pantomime		Imitation		Pantomime		Imitation	
	M	sd	M	sd	M	sd	M	sd
Location	73.32	16.65	95.22	5.19	97.15	5.00	99.58	1.57
Posture	68.95	20.32	82.24	8.27	88.75	9.21	94.82	5.90
Action	63.22	15.50	87.50	8.83	91.19	10.32	97.96	4.83
Plane	66.25	16.06	88.97	13.89	98.57	3.82	99.99	0.33
Orientation	74.91	16.08	94.80	6.72	96.26	5.00	99.42	1.86
Composite	69.33	15.72	89.74	5.62	94.39	4.49	98.35	1.38

Table 7

Frequency and Composite Score Accuracy Data for Patients with LHD or RHD in Each Apraxic Category

Apraxic Pattern	LHD			RHD		
	Frequency (%)	Pantomime Accuracy	Imitation Accuracy	Frequency (%)	Pantomime Accuracy	Imitation Accuracy
P_{NA} I_{NA}	13 (23)	93.17	98.171	19 (31)	92.72	98.26
P_{A} I_{NA}	22 (38)	74.89	97.61	26 (42)	75.36	98.42
P_{NA} I_{A}	5 (9)	91.75	92.00	3 (5)	94.10	90.83
P_{A} I_{A}	17 (30)	69.01	88.89	14 (22)	58.21	89.51

P = Pantomime
I = Imitation
NA = Non-apraxic
A = Apraxic

Table 8

Number of Performance Dimensions Impaired in each Stroke Group

	2 = <		> = 3	
Group	Pantomime	Imitation	Pantomime	Imitation
LHD	26 (46%)	46 (81%)	31 (54%)	11 (19%)
RHD	28 (45%)	51 (82%)	34(55%)	11 (18%)

Table 9

Left Hemisphere Group Aphasia Classification

Aphasia	Normal	Broca's	Wernicke's	Global	Anomic	Conduction	Trans Sensory
LHD	31(57%)	6 (11%)	2 (3.5%)	1 (2%)	9 (14%)	3 (6%)	2 (3.5%)

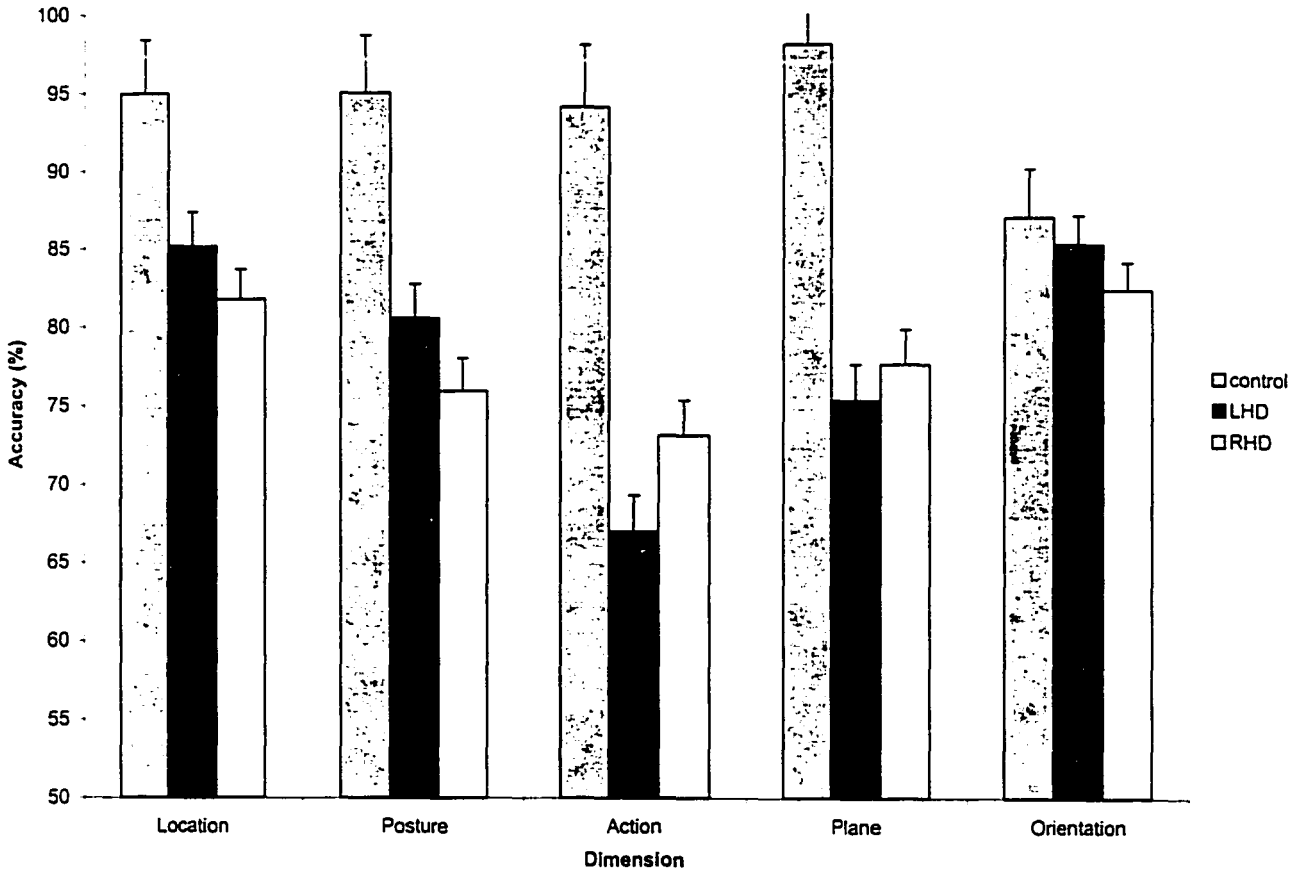
Figure Captions

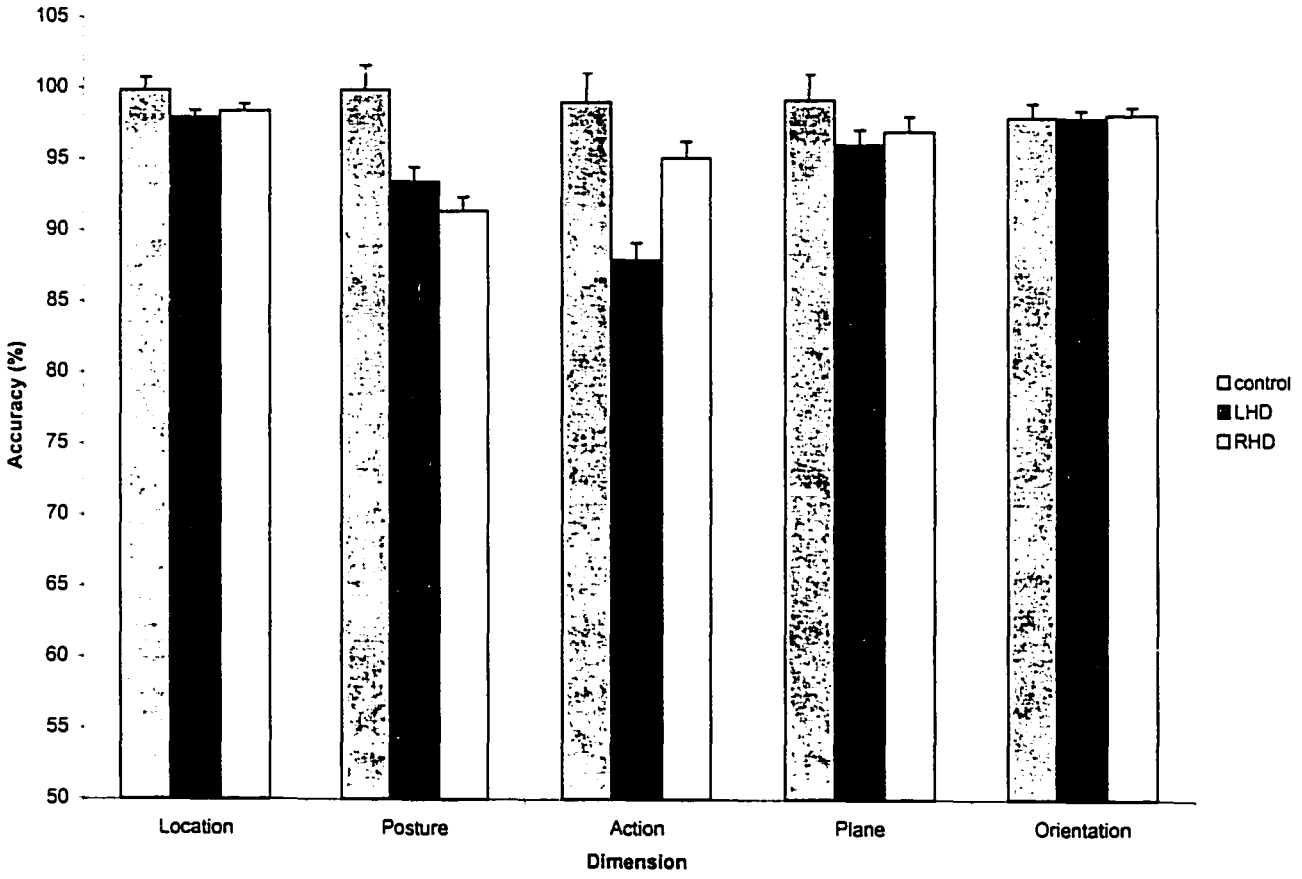
Figure 1. Average pantomime accuracy (%) across performance dimensions for both stroke groups and control participants.

Figure 2. Average imitation accuracy (%) across performance dimensions for both stroke groups and control participants.

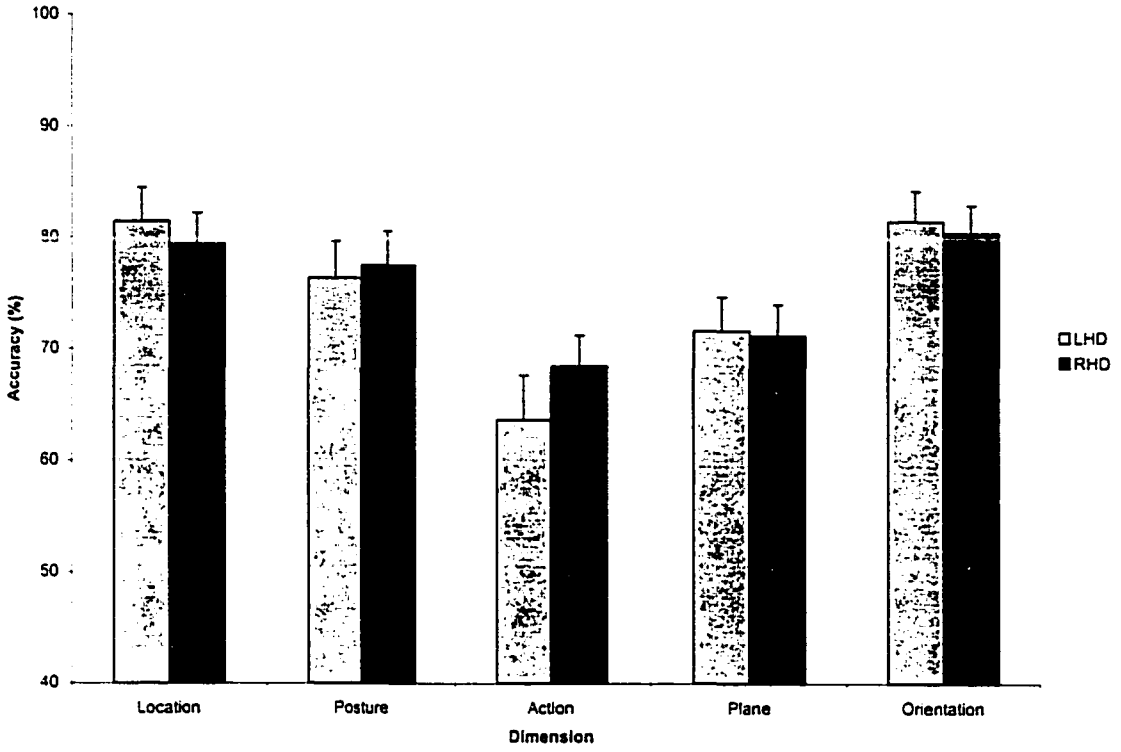
Figure 3. Average pantomime accuracy (%) across performance dimensions for LHD and RHD patients classified apraxic to pantomime alone (top) and apraxic to pantomime and imitation concurrently (bottom).

Figure 4. Average imitation accuracy (%) across performance dimensions for LHD and RHD patients classified apraxic to imitation alone (top) and apraxic to pantomime and imitation concurrently (bottom).

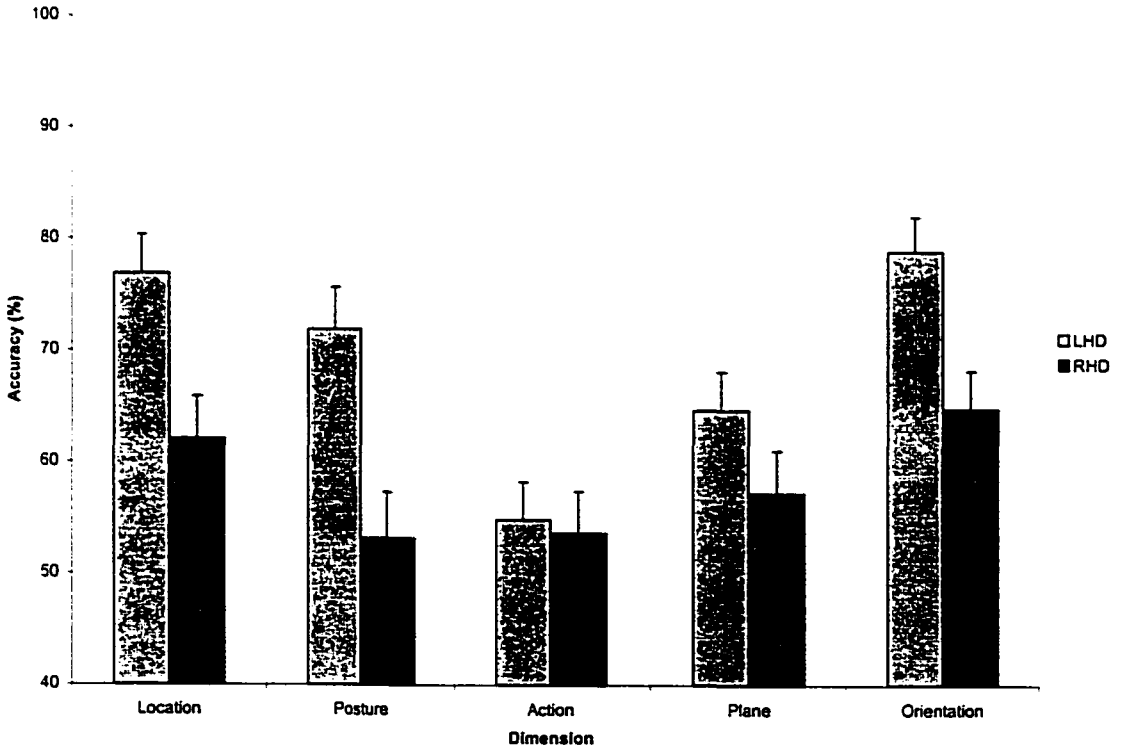

100
95
90
85
80
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65
60
55
50
Accuracy (%)
Location
Posture
Action
Plane
Orientation
Dimension
control
LHD
RHD


105
100
95
90
85
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50
Accuracy (%)
Location
Posture
Action
Plane
Orientation
Dimension
control
LHD
RHD

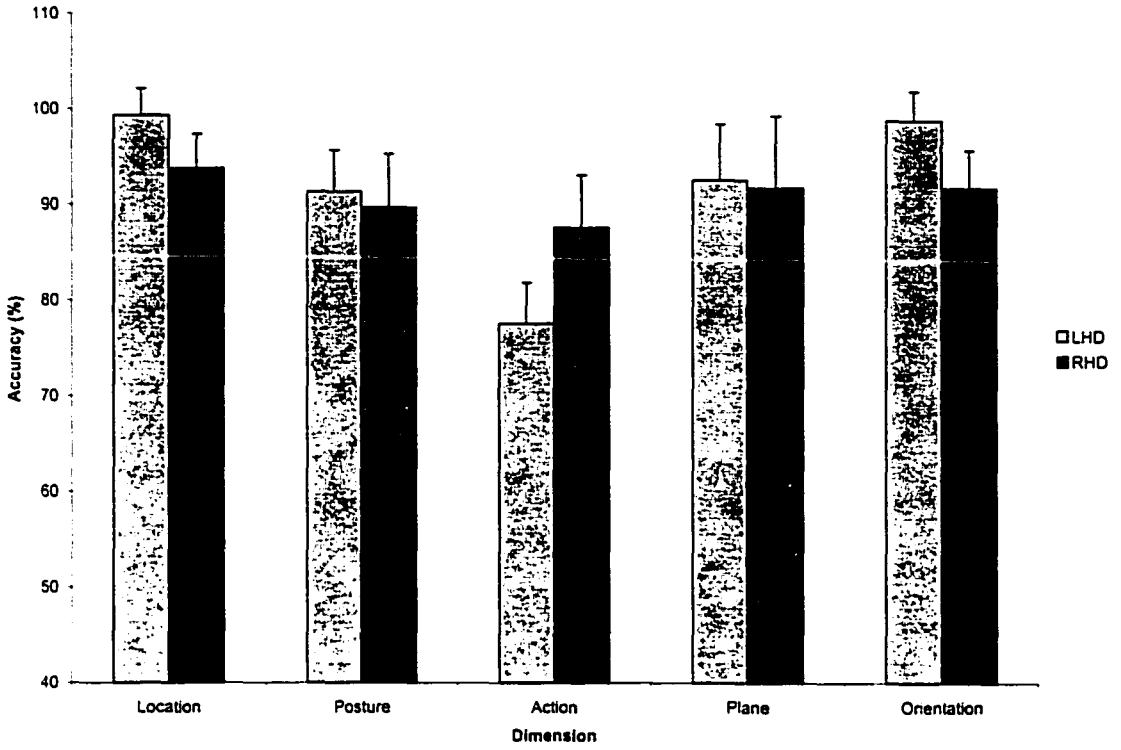
Apraxic to Pantomime Alone



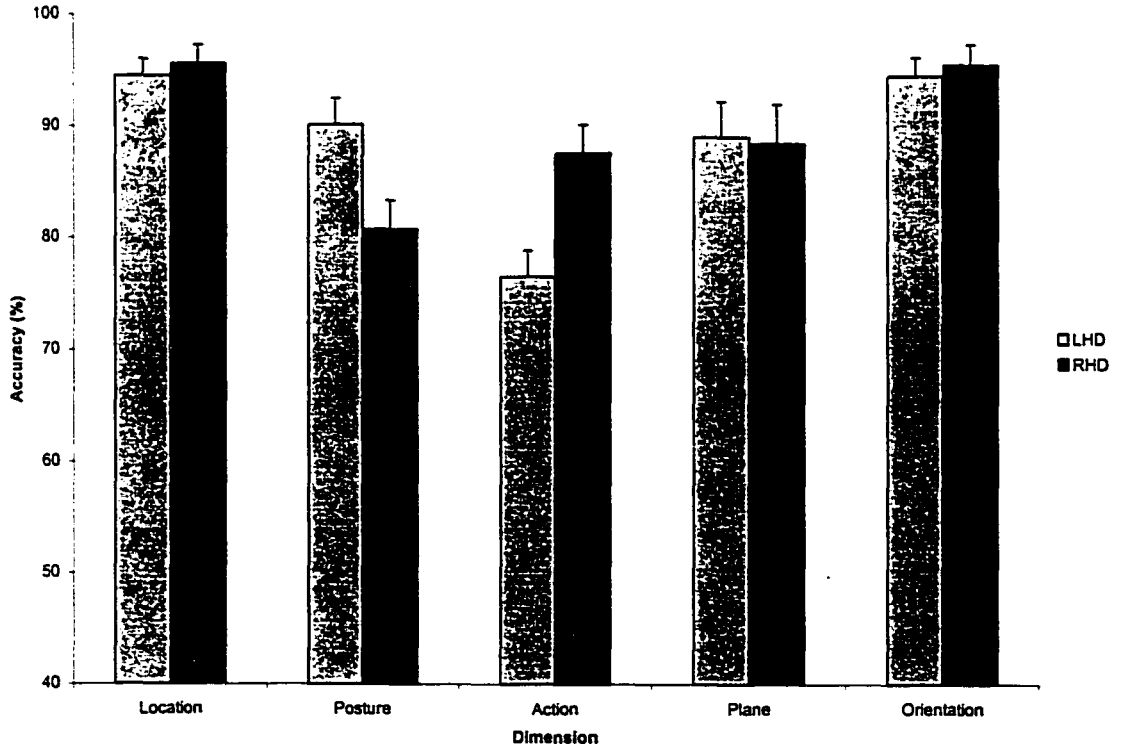
Apraxic to Pantomime and Imitation



Apraxic to Imitation Alone



Apraxic to Pantomime and Imitation



EXPERIMENT FOUR

ABSTRACT

Previous investigations of manual performance asymmetries have utilized relatively simple movements such as goal-directed aiming and rapid finger-tapping. In the present research, three-dimensional kinematic analyses were employed to examine the expression of manual asymmetries during the production of learned, purposeful actions (transitive limb gestures). Transitive limb gestures involve the use of tools and/or objects and represent complex movements used in the evaluation of limb apraxia. Ten healthy participants were instructed to produce two transitive limb gestures in response to verbal command (pantomime) with the tool associated for the gesture in one condition, and in the second, the gesture was performed without the tool present. Three-dimensional kinematic analyses revealed a dominant hand (right) advantage, with the magnitude of this difference marginally influenced by movement context (pantomime vs. tool). This study, provides the first evidence that manual asymmetries are elicited during the production of transitive limb gestures, and mandates that future kinematic analyses of limb apraxia consider the impact of pre-morbid manual asymmetries when contrasting the performance of left or right hemisphere damaged patients.

EXPERIMENT FOUR

The study of manual asymmetries provides an opportunity to examine the contributions of the cerebral hemispheres to the control of goal-directed, learned, or purposeful movement. Moreover, a systematic analysis of manual asymmetries provides critical information for the development of methodological approaches used in quantifying upper-limb movement deficits accompanying unilateral stroke.

Limb apraxia represents an inability to perform learned or purposeful movements such as hammering a nail, which cannot be accounted for by weakness, sensory loss, ataxia, poor language comprehension or inattention to commands. Frequently apraxia has been described as a disorder arising primarily from left hemisphere damage (LHD) (Poizner, Merians, Clark, Rothi, & Heilman, 1997). Indeed, kinematic analyses, which provide a quantitative assessment of the spatial and temporal attributes of movement have bolstered this view. Poizner and colleagues (e.g., Clark, Merians, Kothari, Poizner, Macauley, Rothi, & Heilman, 1994; Poizner, Clark, Merians, Macauley, Rothi, & Heilman, 1998; Poizner, Mack, Verfaellie, Rothi, & Heilman, 1990, see Poizner et al., 1997 for review) have repeatedly shown that LHD apraxic participants demonstrate specific impairments in the spatial-temporal parameters associated with the production of transitive limb gestures (tool-based; e.g., using a saw). However, a paucity of research has similarly identified the kinematic parameters impaired following right hemisphere damage (RHD). Recently, Poizner et al. (1998) examined the production of a 'slicing' gesture by 4 participants with LHD, and 6 participants with RHD, in addition to the performance of 7 age-matched control participants. LHD participants demonstrated impairments in coupling the spatial-temporal aspects of the 'slicing' action. In contrast,

RHD participants did not differ from control participants on these performance dimensions. At the outset these results imply that RHD does not impair movement praxis, however, recent work employing a multi-dimensional error notation system has shown that left or right hemisphere damage can equally impair the praxis system (Heath, Experiment 1 and 3; Roy, Black, Blair, & Dimeck, 1998). How can these results be reconciled? One approach is to address the influence of pre-morbid manual asymmetries, a crucial issue associated with assessing upper-limb performance following unilateral cerebral damage (see Roy, 1996 for review).

Typically LHD participants perform with their ipsilesional, non-dominant left hand due to the severity of contralateral hemiparesis, and this performance is compared to the non-dominant limb of control participants. Conversely, RHD participants perform with their ipsilesional, or dominant right-hand, which is compared to the dominant hand of control participants. This approach minimizes the influence of pre-morbid manual asymmetries. A closer examination of the methodology employed by Poizner et al. (1998) reveals that a direct comparison between the ipsilesional limb of stroke participants and the appropriate limb of age-matched controls was not employed. In their investigation, Poizner et al. did compare the right and left hand of control participants, reporting that "no systematic biases were seen favoring those control participants who used their dominant right arm" (footnote #2, pg. 165). Subsequently, the pooled left/right hand data of control participants was compared to the ipsilesional limb of stroke participants. However, the ability to detect hand differences among control participants in this study may have been limited by factors such as sample size, and statistical design. Specifically, Poizner et al. compared the right (dominant) hand of three control

participants, to the left (non-dominant) hand of four separate control participants. Hence, the small sample of participants performing with their left or right hand, coupled with the between-subject design may have obscured the ability to detect hand differences in this population. If manual asymmetries are expressed during the production of a transitive limb gestures, then the average left/right hand data of control participants, which were later used in comparison to the ipsilesional limb of both stroke groups, may have underestimated performance deficits among participants with RHD, while overestimating deficits in the LHD group.

The goal of the present investigation is to examine whether manual asymmetries are elicited during the production of transitive limb gestures. This question is driven by our interest in understanding the movement parameters that govern the expression of manual asymmetries, and more importantly, to determine whether pre-morbid manual asymmetries are an important methodological consideration when employing kinematic analysis of apraxia following left or right hemisphere stroke.

Method

Participants

Ten male participants ranging in age from 19 to 25 years participated in the present study. Participants were right-handed as assessed by the Waterloo Handedness Questionnaire. All participants were informed of the experimental procedure and signed consent forms approved by the Office of Human Research.

Procedure

Two transitive gestures performed by the left and right hands were selected for motion analysis. The gestures "slicing bread" and "sawing a pipe" were chosen due to

the cyclical nature of their movement which allowed accurate determination of the start and end of an individual movement cycle. The gestures were performed by the left and right hand; half of the participants beginning the experiment with their right hand. Participants performed in a pantomime condition in which the gesture was performed in response to verbal command without the tool or object associated with the gesture present. The second condition involved performing the task with only the object not present, thus providing kinesthetic cues afforded by manipulation of the tool. Instructions were explicit in each condition. For the 'slicing' task participants were asked to "perform a movement consistent with slicing a loaf of bread". Similarly the instruction for the sawing motion was to "perform a movement consistent with cutting a 5 cm plastic pipe". Participants completed 10 trials per gestural condition resulting in a total of 80 trials.

Data Acquisition

An Optotrak^{TM} 3020 motion analysis system was employed to reconstruct arm movements. Five infrared emitting diodes (IRED's) were secured to the acromial process (shoulder), lateral epicondyle of humerus (elbow), styloid process of ulna (wrist), and the first and fourth metacarpal for data acquisition. Sampling of the IRED's was set at 200 Hz and the duration of data acquisition was seven seconds. Data were filtered with a Butterworth filter employing a low-pass cut-off frequency of 7 Hz.

Limb trajectories were examined individually in order to confirm the primary and secondary movement axis. Following this procedure the third, fourth and fifth movement cycles were selected for analysis. Further, individual movement cycles, consisting of one forward and backward trajectory path were divided into half cycles.

Kinematic Analyses

Pilot data revealed that the wrist IRED proved to be the most representative of arm movement due to its combined representation of shoulder and elbow movement. Therefore, the following analyses are based on motion of the wrist. The variables analyzed were developed to ascribe the spatial and temporal features of the movements.

Spatial Accuracy

Several variables were employed in order to describe the spatial path of arm movement. A plane of motion was determined by calculating the best fitting plane for the wrist separately for each movement cycle using a least squares regression to plane the equation. Following this procedure, a three-dimensional plane of motion was constructed, representing anterior-posterior, vertical and lateral movement components. Movement that occurred perpendicular to the plane of motion was identified, and the total area of movement outside the plane of motion was measured to quantify out-of-plane movement.

Planarity was defined as the variability associated with the amplitude of out-of-plane movement. The subsequent values represent the root-mean-squared error of individual coordinate values (out-of-plane) for each movement cycle. Out-of-plane and planarity values were normalized with respected to movement amplitude and inverted, hence, larger values represent movements of greater spatial accuracy.

Trajectory Shape

The shape of the movement trajectory (linearity) was calculated by determining the amplitude of the major and minor movement axis. The major movement axis was defined as the maximum distance between any two points on the movement trajectory,

while the minor axis was identified by the largest perpendicular distance from the major axis. The amplitude of the major movement axis and the perpendicular distance to the minor axis were used to calculate a linearity ratio, with larger numerical values representing a more linear movement. Movement amplitude was the maximum distance between any two points for each cycle of movement.

Temporal Attributes

Temporal attributes of the movement were measured from movement time and peak velocity. Movement time was calculated by determining the time to achieve maximum movement amplitude for each half cycle of movement. Peak tangential velocity of the wrist for each half cycle of movement was evaluated by differentiating displacement data.

Data Analysis

The goal of present investigation was to examine left and right hand performance during pantomime and tool manipulation tasks, hence dependent variables were assessed via 2 hand (left, right) by 2 gesture (pantomime, tool) repeated measures analysis of variance[1]. Interactions were further analyzed using a Fisher-Hayter procedure ($p < .05$).

Results

Spatial Characteristics of the Movement Trajectory

Figure 1 presents trajectories of the left and right hand during the sawing task in both movement conditions. These figures demonstrate that the spatial path of the right hand was more consistent than the left hand during both movement conditions, although the left hand improved somewhat in the tool condition.

Insert Figure 1 about here

Recall that out-of-plane and planarity variables were inverted, hence larger values represent movements of greater spatial accuracy or consistency. Out-of-plane movement for the right hand (240.3) was greater than that of the left (213.3), although this difference was not significant. Movement planarity revealed a main effect for hand, $F(1, 9) = 8.54$, $p < .02$, and a hand by gesture interaction, $F(1, 9) = 11.92$, $p < .01$. The interaction indicated that the extent of a right hand advantage was affected by movement context, with the largest right hand advantage observed in the pantomime condition (Table 1).

Insert Table 1 about here

Trajectory Shape

Movement linearity indicated significant effects for hand, $F(1, 9) = 11.53$, $p < .01$, and gesture, $F(1, 9) = 8.74$, $p < .02$. The effect for hand demonstrated that the right hand was more linear, suggesting that the right hand performed a more effective movement path. Additionally, the effect for gesture demonstrated that the kinesthetic cues afforded by performing the gesture with the tool present enhanced movement efficiency.

Movement Amplitude

The amplitude of right hand movement was greater than left, $F(1, 9) = 6.48$, $p < .03$), in addition movements performed to pantomime were of greater amplitude, $F(1, 9) = 11.97$, $p < .01$).

Temporal Measures

Both temporal measures (movement time and peak velocity) failed to reveal significant differences between the hands ($p > .05$). Movements performed in the pantomime condition achieved higher peak velocity values, $F(1, 9) = 7.26$, $p < .02$).

DISCUSSION

The results reported here provide the first evidence that manual performance asymmetries are elicited during the production of transitive limb gestures. Movements performed by the right hand demonstrated a more effective movement path as indexed by movement linearity. Similarly, movement path variability (planarity) indicated a right hand advantage, although the overall magnitude of this advantage was influenced by movement context, with the largest right hand advantage observed in the pantomime condition.

Interestingly, the amplitude of movements performed by the right hand were significantly greater than the left, despite the fact that our temporal measures (movement time, peak velocity) failed to differentiate between the hands. These results indicate that the right hand was able to execute movements of greater amplitude in the same time frame not because the rate of movement was greater; rather, the right hand formulated and executed a movement trajectory that deviated minimally from an ideal spatial path.

Several investigators have employed kinematic analyses to assess the impact of left or right hemisphere stroke on goal-directed aiming (Haaland, 1989) and reaching and grasping (Hermsdorfer, Ulrich, Marquardt, Goldenberg, & Mai, 1999). These studies have benefited from a wealth of manual asymmetries research demonstrating left/right hand differences in healthy adults (Elliott, Heath, Binsted, Ricker, Roy, & Chua, 1999; Flowers, 1975; Heath & Roy, 2000; Roy & Elliott, 1986). Using a reaching and grasping paradigm, Hermsdorfer, Laimgruber, Kerkhoff, Mai, & Goldenberg (1999) observed that although different in the parameters associated with their movement deficits, both LHD and RHD participants were impaired relative to control participants.

Hermsdorfer et al. compared the ipsilesional (dominant; right) limb of RHD participants to the dominant (right) limb of control participants, and conversely, compared the performance of the ipsilesional (non-dominant; left) limb of LHD participants to the non-dominant (left) limb of controls. These direct hand comparisons allowed the authors to examine how left or right hemisphere damage selectively impairs limb performance independent of pre-existing manual asymmetries.

In contrast to the extensive studies of goal-directed aiming and prehensile movements, the importance of pre-morbid manual asymmetries for assessing apraxia following left or right hemisphere stroke is not documented. Apraxia is manifested by an impaired ability to perform learned, skilled actions such as transitive (tool-based) limb gestures which entail coordinating body parts in a spatial position relative to the rest of the body in a specific order at specific times (Poizner et al., 1998). Given the complexity of these actions, it would seem likely that left/right hand differences would be observed on a magnitude similar to that reported for less complex movements (e.g., a 10% right hand advantage for movement time in goal-directed aiming tasks). Indeed, the present results support this notion, revealing that manual asymmetries are expressed during the production of transitive limb gestures, and are of similar magnitude to other paradigms used in manual asymmetry research (e.g., a 11% right hand advantage for linearity). These results suggest that kinematic analyses of apraxia which employ pooled left/right hand data of control participants, in comparison to the ipsilesional limb of stroke participants (LHD and RHD), may lead to an overestimation of the impact of LHD on gesture production, while underestimating the influence of RHD. Specifically, Poizner et al. may not have observed spatial-temporal deficits in RHD participants due to the fact

the averaged left/right hand data of control participants was compared to the dominant limb of the RHD group, perhaps ameliorating the impact of right hemisphere stroke.

Our future work is aimed at addressing the importance of pre-morbid manual asymmetries in assessing apraxia following left or right hemisphere stroke. In this kinematic investigation of transitive limb gestures, the ipsilesional limb of stroke participants will be compared directly to the appropriate limb of age-matched controls.

Footnotes

[1]Although two gestures (knife and saw) and two movement cycles (forward and backward) were analyzed, significant interactions involving these factors and hand were not revealed. Subsequently the statistical model was reduced to include hand and condition as factors.

Table 1.

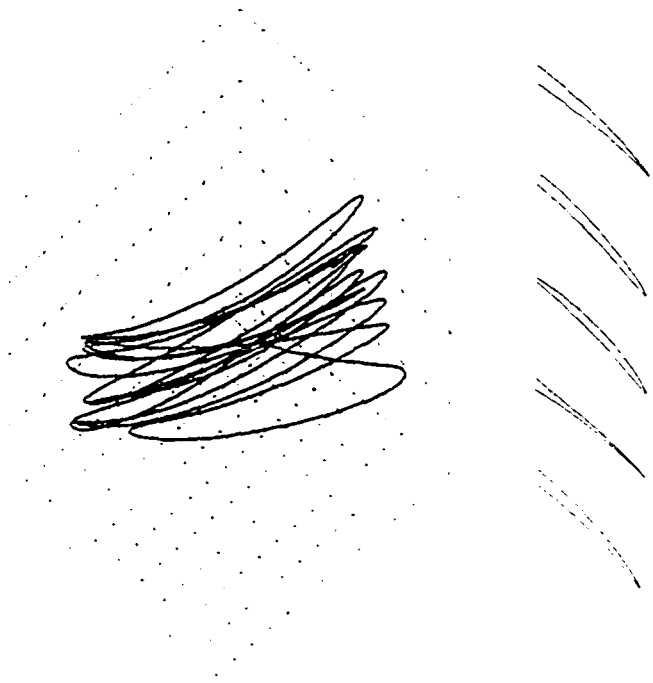
Mean out-of-plane movement, planarity, linearity, amplitude (mm), movement time (ms) and peak velocity (mm/s) as a function of hand and condition.

	Left Hand		Right Hand	
Variable:	Pantomime (sd)	Tool (sd)	Pantomime (sd)	Tool (sd)
Out-of-plane movement	210.39 (190.32)	217.50 (193.02)	244.86 (201.77)	235.92 (193.50)
Planarity	113.72 (77.35)	120.17 (88.35)	151.55 (114.89)	136.15 (96.14)
Linearity	27.41 (17.26)	31.78 (17.56)	30.55 (17.74)	36.68 (18.68)
Amplitude	405.11 (54.10)	362.23 (53.55)	454 (64.49)	389 (51.11)
Movement Time	721 (83.81)	703 (86.22)	751 (73.30)	727 (85.37)
Peak Velocity	939 (284.66)	848 (246.64)	968 (282.20)	874 (217.24)

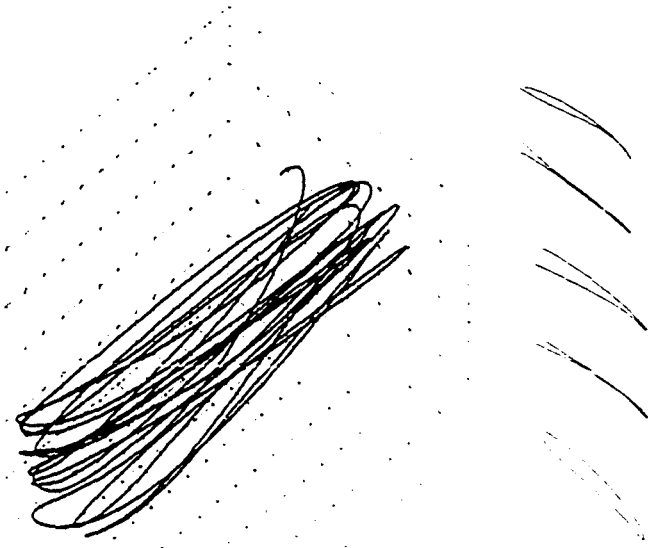
Figure Captions

Figure 1. Three-dimensional view (lateral perspective) of wrist trajectories performed by the right (top) and left (bottom) hand in both pantomime (left) and tool (right) conditions. Grid lines are spaced at 20 mm intervals. The figures presented to the right of each three-dimensional graph represent successive two-dimensional lateral views and provide a qualitative index of movement linearity.

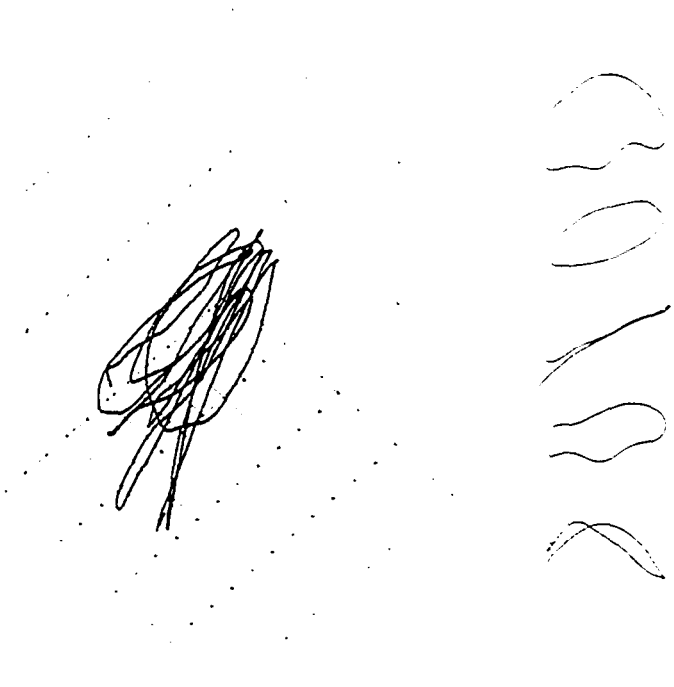
Right Pantomime



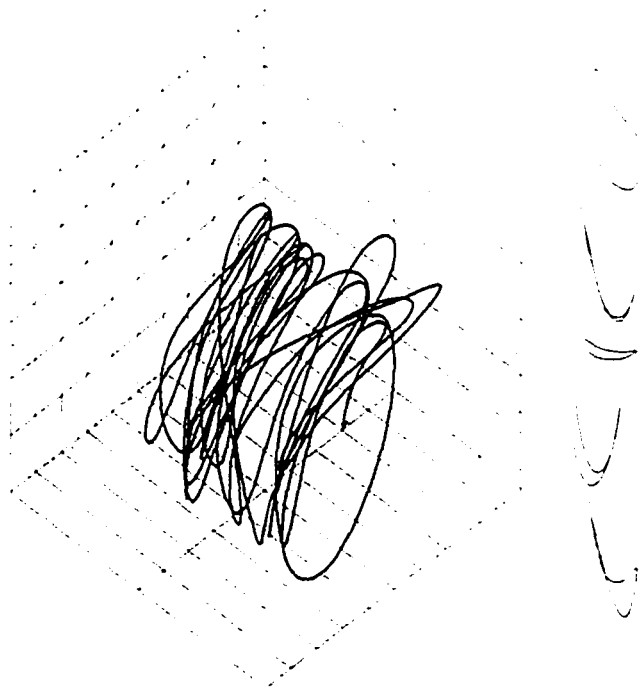
Right Tool



Left Pantomime



Left Tool



EXPERIMENT FIVE

ABSTRACT

Apraxia represents a disorder of skilled, purposeful movement that cannot be attributed to elementary motor or comprehension impairments (Heilman & Rothi, 1985). In the present study, kinematic analyses of a transitive limb gesture (bagel slicing) was employed in a sample of 4 left and 4 right brain-lesioned patients, as well as a group of age-matched control participants. The ipsilesional limb of stroke patients was contrasted to the same limb of control participants to prevent premorbid manual asymmetries from impacting group comparisons. Analyses did not reveal spatial parameterization impairments in either left or right brain-lesioned groups. However, a single left and single right brain-lesioned patient demonstrated joint synchronization, and temporal coordination errors respectively when the slicing action was based upon an internal representation of the gesture. These results suggest that apraxia is not a disorder restricted to left hemisphere damage, as reported by others (e.g., Poizner, Merians, Clark, Macauley, Rothi, & Heilman, 1998), rather, the present findings support recent observational analyses indicating that apraxia can be elicited following left or right hemisphere damage (Heath, Experiment 1 and 3).

EXPERIMENT FIVE

Detailed analyses of apraxia provide a natural framework for investigating the specialized roles of the cerebral hemispheres for the control of learned, purposeful actions. Traditional models of apraxia hold that the disorder arises primarily from unilateral left cerebral damage (e.g., Heilman & Rothi, 1985). Indeed, a plethora of evidence supports this contention (McDonald, Tate, & Rigby, 1994; Schnider, Hanlon, Alexander, & Benson, 1997), however recent work by Heath (see Experiments 1 and 3, see also Roy, Black, Blair & Dimeck, 1998) focussing on the details of gesture production, has questioned the exclusive role of the left hemisphere in movement praxis. Heath (Experiments 1 and 3) employed a multi-dimensional error notation system to assess several elements critical for the accurate production of learned, skilled actions. These analyses revealed that left, or right hemisphere damage can elicit limb apraxia, thus providing novel insight into the genesis of the disorder.

Heath (Experiment 1) observed that left hemisphere damaged (LHD) and right hemisphere damaged (RHD) patients demonstrated apraxic movement deficits during the pantomime or imitation of transitive limb gestures. Component analyses of the error notation system provided information regarding the specific aspects of gesture production impaired following left or right hemisphere stroke. For instance, RHD patients were most impaired in formulating the spatial components of a gesture, whereas LHD patients demonstrated the largest impairment on the action dimension, or formulating a smooth movement trajectory. Haaland and Flaherty (1984) reported similar observations in their examination of gestural imitation following left or right hemisphere damage, thereby

providing convergent evidence supporting collaborative left/right hemisphere mediation of praxis.

The observation that left or right hemisphere damage can result in limb apraxia provides a new avenue of research for understanding the disorder, however, it is impossible to discern the precise patterns of timing and spatial impairments associated with limb apraxia from direct observation, or videotaped recording (e.g., Alexander, Baker, Naeser, Kaplan, & Palumbo, 1992; Barbieri & De Renzi, 1988; De Renzi, Piecquro, & Vignolo, 1968; De Renzi, Faglioni, & Sorgato, 1982; Heath, Experiment 1 and 3; Schnider et al., 1997). Moreover, although multi-dimensional behavioural analysis has identified a specific impairment among LHD patients on the action dimension of gesture production, the precise nature of this trajectory deficit could not be quantified through observational analyses alone. Kinematic analyses provide a methodology for overcoming the limitations of observational analyses, by precisely quantifying the spatial-temporal features of complex movements. Poizner and colleagues (Clark, Merians, Kothari, Poizner, Macauley, Rothi, & Heilman, 1994; Poizner, Mack, Verfaellie, Rothi, & Heilman, 1990; Poizner, Clark, Merians, Macauley, Rothi, & Heilman, 1995) employed kinematic analyses to examine the spatial, temporal and limb coordination impairments associated with the production of transitive (tool based) limb gestures in a sample ($N \leq 3$) of LHD patients with ideomotor apraxia. These studies demonstrated that patients with ideomotor apraxia have difficulty not only in formulating the correct spatial plan for learned actions, but also in translating these plans into the appropriate phase relations among limb components (Poizner et al., 1995). Clarke et al. focussed on the spatial planning deficits associated with ideomotor limb apraxia

following left hemisphere stroke, and noted marked decoupling of the spatial-temporal attributes characteristic of "fluid" limb movements, such that components of the plane-of-motion (x, y, and z axes) of the wrist trajectory did not have the same movement period, resulting in temporal distortion, and an uncharacteristic 'jerky' or non-fluid limb movement. These impairments were particularly evident when actions were performed in response to verbal cue (pantomime), with performance improving somewhat when contextual cues were provided (e.g., knife). Clarke et al. believed that contextual cues (tool and/or object) improved performance by: (1) providing an alternate route to access the time space representations of learned actions contained in the left hemisphere, and/or (2) the physical manipulation of the tool induced mechanical affordances allowing for accurate gesture production.

More recently, Poizner, Merians, Clark, Macauley, Rothi, & Heilman (1998) employed kinematic analyses to examine a slicing gesture in a sample of LHD patients with the clinical diagnosis of ideomotor limb apraxia, and a sample of RHD patients without clinical diagnosis of ideomotor limb apraxia. A third group of age-matched control participants was also included. This study represents the first kinematic analyses to examine transitive limb gestures in a sample of patients with RHD. Participants were required to pantomime and perform the slicing action with its associated tool (knife). LHD patients demonstrated multiple spatial, temporal, and limb co-ordination deficits. In particular, when LHD ideomotor apraxic patients were compared to age-matched controls, their movements were not cyclical or constrained to one plane-of-motion, demonstrating marked decoupling of the velocity-curvature relationship of wrist trajectory, and relative phase relations of upper limb movement. Similar to their previous

results, Poizner et al. noted that LHD patients improved somewhat when the action was performed with its associated contextual cue (knife). In contrast, RHD patients were found to be only 'mildly' impaired in executing their movements within a single plane-of-motion, and their movement was not modified based on the contextual cue afforded the task. Poizner et al. interpreted these results to reflect the fact that LHD, but not RHD, produces multiple impairments in formulating and executing the components of a learned action.

Poizner et al's (1998) findings extend their previous work proposing that LHD alone impairs the spatial-temporal parameterization of learned actions, due to left hemisphere lateralization for the time-space representation for these actions (Heilman & Rothi, 1985). Recall that Poizner et al. (1998) reported mild impairments associated with maintaining a single plane-of-motion in his RHD patients. This finding parallels those of Heath (Experiment 1), who reported spatial impairments of limb trajectory following RHD. Although the two studies differ in terms of their description of the severity of the disorder, with Heath reporting the level of severity to be equal among RHD and LHD patients; together these results provide tentative support for right hemisphere involvement in movement praxis. However, the lack of congruence between the severity of apraxia noted in the two studies requires reconciliation. This discrepancy may be explained by methodological differences. In their investigation, Poizner et al. (1998) utilized a small sample size (N = 4), in addition, LHD patients, but not RHD patients were selected based on their clinical diagnosis of ideomotor limb apraxia. In contrast, Heath (Experiment 1) recruited a consecutive sample of forty-six LHD and fifty-three RHD patients, without selective inclusion of LHD patients based on their clinical

diagnosis of limb apraxia. Thus, Heath (Experiment 1) employed a sample size with sufficient power, and did not bias the elicitation of apraxic deficits in one patient group (e.g., LHD patients), thereby providing a more sensitive index for quantifying apraxia following unilateral stroke.

The fact that Poizner and colleagues (Poizner et al., 1998) detected only 'mild' deficits among RHD patients may also reflect their consideration of premorbid manual performance asymmetries. Specifically, Poizner et al. did not compare the ipsilesional limb of stroke participants to the appropriate limb of age-matched controls. Instead, the pooled left/right hand performance of three control participants using their right hand, and four separate control participants using their left hand was employed to contrast the performance of both stroke groups. Heath (see Experiment 4) has demonstrated that the dominant (right) limb of healthy adults is more effective and spatially constrained relative to the non-dominant (left) limb during the production of transitive limb gestures. Hence, the pooled left/right hand data of control participants used by Poizner et al. may have underestimated performance deficits among RHD patients, while overestimating deficits in the LHD group.

The goal of the present investigation is to employ kinematic analyses to contrast a transitive limb gesture performed by the ipsilesional (left) limb of LHD patients, to the non-dominant (left) limb of control participants. Similarly, the ipsilesional (right) limb of RHD patients is contrasted to the dominant (right) limb of controls. This methodology provides the most sensitive contrast for identifying and understanding apraxic movement deficits in LHD and RHD populations (Heath, Experiment 4). Further, given the results from Heath (Experiments 1 and 3) it is hypothesized that kinematic analyses may provide

relevant information regarding the spatial-temporal elements impaired in LHD apraxics, as well as the precise elements impairing the spatial features of gesture production in RHD patients. Finally, five movement contexts are included in the investigation (pantomime, tool only, object only, tool+object, and imitation). Each movement condition is included to determine whether increasing the contextual cues associated with gesture production (pantomime vs. tool+object) differentially improves performance in brain-lesioned groups. Further, intrinsic (e.g., pantomime, tool only, object only, tool+object) and extrinsic (imitation) movement contexts are examined to assess whether ideational constraints differentially impact left or right brain-lesioned patients.

Method

Participants

Three groups of participants volunteered for this study. The first group consisted of four patients with a single unilateral left hemisphere lesion (mean age = 67.75 years). The second group consisted of four patients with a single right hemisphere lesion (mean age = 62.25 years). Lesion presence was confirmed by CT, MRI or clinically appropriate focal perfusion examination.

All brain-lesioned participants had a single ischemic or hemorrhagic event that had occurred between 5 and 12 months prior to this investigation, thus patients were in the chronic state of their disease (Pantano, Formisano, Ricci, Di Piero, Sabatini, & Barbanti, 1995). Further inclusion criteria for stroke patients included sufficient comprehension and stamina to complete the motion analysis, non-history of other neurological disorders, arthritis or sensory motor deficits that may have secondarily impacted their gesture performance. All participants were right-handed, as assessed by a

modified version of the Waterloo Handedness Questionnaire (Bryden, 1977). Clinical and demographic data of brain-lesioned patients are provided in Table 1.

Inset Table 1 about here

The third group consisted of five right-handed, age- and gender-matched control participants (mean age = 65.00). A modified Christensen Healthy Survey (Christensen, Moye, Armson, & Kern, 1992) questionnaire was administered to control participants to assess their health and physical activity levels. Participants did not report history of neurological impairments, arthritis, psychiatric disorder, or alcoholism.

Procedure

Two transitive limb gestures, "slicing a bagel" and "sawing a pipe" were chosen for motion analysis due to the cyclical nature of their movement which allowed accurate determination of the start and end of an individual movement cycle. Furthermore, the gestures represented complex 'phasic' movements requiring precise spatial and temporal coordination of the agonist and antagonist muscles.

Control participants performed the gestures with their right and left hands, with 2 beginning with their right hand. To eliminate any movement effects due to contralesional hemiparesis, all brain-lesioned participants performed with their ipsilesional limb.

Gestures were performed in five movement contexts: (1) pantomime: participants performed the gesture in response to verbal command ("show me how to cut a bagel with a knife", (2) tool only (partial contextual cue): the action was performed with the tool (e.g., knife) associated with the action, (3) object only (partial contextual cue): the gesture was performed with only the object present (e.g., bagel), (4) tool+object (full contextual cue): the action was performed with tool and object present.

The final context, (5) imitation, involved imitating the action demonstrated by the experimenter. Pantomime trials were performed first to avoid providing cues as to the correct elements of performance. Tool only and object only conditions were performed second or third and were counterbalanced. Tool+object, and imitation trials were performed sequentially following partial contextual cue conditions. To provide an index of response stability, five trials per movement context were collected.

Data Acquisition

An OPTOTRAK™ 3020 motion analysis system was employed to track three-dimensional movement of the limb during gesture production. Four infrared emitting diodes (IRED's) secured to the lateral epicondyle of humerus (elbow), styloid process of wrist, first and fourth metacarpals were used to track movement of the limb. IRED position sampling was set at 200 Hz (1 sample/5 ms) and were off-line filtered using a Butterworth filter employing a low-pass cut-off frequency of 7 Hz.

Limb trajectories were examined individually for each participant in the three cardinal planes in order to confirm the primary and secondary movement axis. Custom interactive software programs were used to analyze two movement cycles per trial. In each case the second, and third movement cycle per trial were selected. Further, individual movement cycles, consisting of one forward and backward component were marked.

In concert with the kinematic data, conceptual knowledge related to the two gestures was assessed. Conceptual tests included Tool Naming, Tool Function Naming, and Tool Action Naming. In the Tool Naming Test, participants were shown a tool and asked to properly name the tool. The Tool Function Test required participants to name

the function of an observed tool (e.g., when shown the knife, participants responded correctly by saying "it is used to cut bread"). The final test, Tool Action Test, required the naming of a tool based on its action. For instance, participants were asked to "name the tool used for cutting a pipe" (e.g., saw).

Kinematic Analyses

Pilot data proved the wrist IRED to be the most representative of arm movement, due to its combined representation of shoulder and elbow movement. Hence, the following analyses are based on the motion of the wrist and are designed to ascribe independently the spatial and temporal features of gesture production, as well as the co-joint spatial-temporal relationship. In addition, velocity-velocity relationships were examined to quantify the degree of synchrony between motion at the elbow and motion at the wrist.

Spatial Accuracy

Out-of-plane motion and movement planarity quantified the degree to which movement was confined to one plane-of-motion, and the consistency of this movement plane. Out-of-plane motion was computed by determining the best fitting plane for the wrist separately for each movement cycle using a least squares regression to plane the equation. Following this, a three-dimensional plane-of-motion was constructed, representing anterior-posterior, vertical and lateral movement components. Subsequent movements perpendicular to the plane-of-motion were identified, and the area of movement (integral) occurring outside the plane-of-motion was used to quantify out-of-plane motion.

Planarity is operationally defined as the variability of the amplitude of out-of-plane motion. Planarity values represent the root-mean-squared error (RMSE) of individual coordinate values (out-of-plane) for each movement cycle. Out-of-plane and planarity values were normalized for movement amplitude and inverted, hence larger values represent movements deviating minimally from the plane-of-motion.

Trajectory Shape

Trajectory shape was calculated to determine the effectiveness of each movement cycle. Movement linearity, representing a ratio between the amplitude of the major and minor movement axis examined the extent to which movement maintained a linear movement path. The major movement axis was defined as the maximum distance between any two points on the movement trajectory, while the minor axis represented the largest perpendicular distance from the major axis. These values were then used to calculate a linearity ratio, with larger numerical values representing a more linear movement.

Trajectory shape was further assessed via comparison of the length of the three-dimensional movement path, and the amplitude of the major movement axis. Values equal to one represented a movement path that exhibited minimal curvature at any point on the trajectory, while larger values are indicative of movement with greater path curvature. For linearity and three-dimensional path distance values, the axes and trajectory paths were calculated individually for each half cycle of movement.

Movement Amplitude

Movement amplitude was the maximum distance between any two points for each cycle of movement.

Temporal Attributes

Movement time, tangential peak velocity, and time after peak velocity were computed. Movement time represents the time required to achieve forward and backward components of each movement cycle, with associated temporal kinematics calculated for each half cycle of movement. Temporal kinematic data were computed by differentiating displacement data. Time after peak velocity was marked to determine whether movements conducted away or towards the body differed.

Spatial-Temporal Attributes

Several authors (e.g., Viviani & Terzuolo, 1982; Morasso, 1983) have described a tightly coupled relationship between movement speed and the shape of the movement trajectory. These investigators have repeatedly noted that for tasks such as handwriting, scribbling and reaching in space, as the speed of the hand decreases, the resultant curvature of the trajectory path increases. Indeed, this spatial-temporal coupling may reflect a control parameter preferentially lateralized to the left hemisphere. In the present investigation a computer algorithm was written to mark tangential velocity minima and radius of curvature minima. The delta time between the two values reflect the degree of spatial-temporal (de)coupling, with a null difference reflecting a tight coupling, and temporal differences reflecting decoupling of the aforementioned parameters.

Relationship Between Wrist and Elbow Velocities

Tangential velocity at the elbow was plotted against tangential velocity of the wrist. Quantitative analysis of this relationship was evaluated for each participant via simple linear regression. Both the degree of the relationship between elbow and wrist

velocity (correlation coefficient), and the magnitude or rate of change (slope) between the wrist relative to the elbow was examined.

Data Analysis

For several of the brain-lesioned patients, fatigue did not permit completion of the full experimental protocol for each gesture type. Thus, only the slicing action was chosen for data analysis, as this gesture represented a complete data set.

To extend the notion that premorbid manual asymmetries are an important consideration in the assessment of unilateral stroke populations, the dominant (right) and non-dominant (left) limb were contrasted in the age-matched control group. A 2 hand (left, right) x 5 movement context (pantomime, tool only, object only, tool+object, imitation) within-subject analysis of variance (ANOVA) was computed to assess a main effect for hand, or a hand by movement context interaction.

Parametric statistical procedures were employed to examine significant group and movement context effects involving brain-lesioned and control participants. The first series of analyses contrasted LHD participants with the left limb of control participants. For out-of-plane motion and movement planarity variables, a 2 group (LHD, controls) x 5 movement context (pantomime, tool only, object only, tool+object, imitation) mixed ANOVA was computed. For the remaining variables (linearity, three-dimensional path distance, amplitude, movement time, peak velocity, time after peak velocity) a third variable, movement half, was entered into the statistical model. Movement half represented forward and backward components of the movement trajectory. Hence, a 2 group (LHD, control) x 5 movement context (pantomime, tool only, object only, tool+object, imitation) x 2 half (forward, backward) mixed design ANOVA was

employed. The second series of analyses employed the same model(s) for each variable, however performance of RHD patients was compared to that of the dominant (right) hand of control participants (e.g., 2 group (RHD, control) x context (pantomime, tool only, object only, tool+object, imitation) ANOVA). The final series of analyses contrasted the performance of brain-lesioned groups (e.g., 2 group (LHD, RHD) x 5 movement context (pantomime, tool only, object only, tool+object, imitation) ANOVA).

Significant effects ($k > 2$), and interactions were further evaluated using the Fisher-Hayter multiple comparison procedure (Seaman, Levin, & Serlin, 1991).

Results

Conceptual Knowledge

Performance of brain-lesioned patients was flawless on the conceptual apraxia tests, achieving 100% accuracy in Tool Identification, Tool Action Naming, and Tool Function Naming tests. Hence, performance errors found in gesture production cannot be attributed to a conceptual deficit related to knife or tool use.

Left versus Right hand of Control Participants

Spatial Characteristics of the Movement Trajectory

The first series of analyses compared the dominant and non-dominant hand of control participants (Figure 1 (left hand), Figure 2 (right hand)). Congruent with previous research (see Heath, Experiment 4) analyses of normalized out-of-plane movement, $F(1, 4) = 6.22$, $p = .06$, and movement planarity, $(1, 4) = 5.98$, $p = .07$) demonstrated a trend favouring a dominant hand advantage. These results indicate that premorbid manual asymmetries are an important consideration when assessing upper-

limb performance in unilateral stroke populations. Further effects involving movement context, or a hand by movement context interaction were not elicited, $p > 0.50$.

Insert Figure 1 and 2 about here

Movement Shape

Three-dimensional path distance, $F(1, 4) = 12.22$, $p < .03$, and movement linearity, $F(1, 4) = 13.31$, $p < .03$, yielded significant effects for hand, demonstrating a more effective and linear path of the dominant (right) hand (see lateral perspective, Figures 1 and 2). Three-dimensional path distance did not reveal a significant effect for movement context, $F(4, 12) = 2.58$, $p = 0.10$, however movement linearity did, $F(4, 12) = 4.35$, $p < .03$, demonstrating that performing gestures in the tool+object and tool only condition resulted in a more linear performance than the imitation or object only conditions.

Movement Amplitude

Movement amplitude did not differentiate between the dominant (209 mm) and non-dominant (204 mm) hand, $F(1, 4) < 1$, indicating that an amplitude artifact did not underlie the nature of left/right differences.

Performance and Kinematic Temporal Measures

Temporal performance and kinematics measures (movement time, peak velocity, time after peak velocity) failed to demonstrated left/right hand differences, $F(1, 4) < 1$. These results, combined with the three dimensional variables demonstrate that although the non-dominant hand is able to complete a movement cycle in the same time frame, movement of this effector is not as linear, or constrained to one plane-of-motion to the

same degree as the dominant hand. Table 2 presents summarized data for control participants.

Insert Table 2 about here

Left Hemisphere Damaged Patients and Control Participants (Left Hand)

Spatial Characteristics of the Movement Trajectory

Figure 3 represents three-dimensional reconstructions of wrist motions for a LHD patient across the five movement contexts (see Figure 1 for comparison of left hand of a control participant). The overlapping movement cycles qualitatively demonstrate that as the contextual cues afforded the task were introduced (e.g., knife), movement became slightly more constrained within one plane-of-motion, and this relationship was similar for LHD patients and control participants. Surprisingly, these representations do not show a remarkable difference between the performance of control participants, and that of LHD patients, suggesting the spatial parameterization of the slicing action was not affected in this sample of brain-lesioned patients. To quantify group differences in spatial accuracy and consistency, data for normalized out-of-plane movement and movement planarity are provided. Mean performance values indicated that out-of-plane movement for control participants (132) was greater than that of LHD patients (89), however this difference was not significant, $F(1, 7) = 2.18$, $p = 0.18$, indicating that the degree to which LHD patients constrained their movement to a single plane-of-motion did not consistently differ from that of control participants (*recall out-of-plane and planarity values are inverted, hence larger values represent movements deviating minimally from one plane-of-motion*). Further effects for movement context, or a group by context interaction were not elicited, $p > 0.30$ (Figure 4 top panel).

Insert Figures 3 and 4 about here

The consistency of the movement trajectory (movement planarity) did not differ between LHD patients and control participants, $F(1, 8) = 0.54$, $p = 0.45$. Further effects involving movement context or a group by movement context interaction were not significant, $p > 0.61$.

Movement Shape

The three-dimensional movement path of LHD patients and control participants did not differ statistically, although a trend favouring greater curvature in the spatial path of LHD patients was evident ($F(1, 7) = 4.28$, $p = 0.08$; LHD = 1.089, controls = 1.022). Further effects for movement context, movement half, or factorial combinations of the above were not elucidated, $p > 0.10$.

Movement linearity did not reveal a significant difference between groups, $F(1, 7) = 0.98$, $p = 0.36$. Surprisingly, linearity ratios for LHD patients (22.7) and control participants (26.2) were remarkable similar. Figure 3 provides lateralized reconstructions, demonstrating movement linearity in a LHD patient and confirming the degree of linearity between the LHD and control participants (see left hand of control Figure 1). Further effects or interactions were not revealed, $p > 0.40$.

Movement Amplitude

Movement amplitude did not differ between LHD and control participants, $F(1, 7) = 2.52$, $p = 0.16$, although the mean value for LHD patients (264 mm) was greater than that of controls (204 mm). A significant effect for movement context was revealed, $F(4, 28) = 6.03$, demonstrating that both participant groups modified their movement program on the basis of the contextual cue afforded with the task. Specifically, the condition in

which tool+object was provided, resulted in a movement amplitude significantly less than pantomime and imitation conditions. Partial contextual cue conditions (tool only, object only) did not differ from the other movement conditions.

Performance and Kinematic Temporal Measures

Movement time for LHD patients (498 ms) and control participants (369 ms), $F(1, 7) = 3.57$, $p = 0.10$, did not differ. Therefore, the overall timing of gestures was similar. Further effects or interactions were not elicited, $p > 0.10$.

Peak velocity failed to differentiate between groups, $F(1, 7) = 1.48$, $p = 0.26$, while a main effect for movement context was revealed, $F(4, 28) = 5.21$, $p < .01$. The effect for movement context demonstrated that performing with full contextual cues resulted in decreased velocity relative to the imitation condition.

Analyses of time after peak velocity yielded an effect for group, $F(1, 7) = 4.67$, $p = .07$, approaching conventional levels of significance, such that LHD patients spent greater time in deceleration (244 ms) relative to control participants (180 ms). Percent time following peak velocity (normalized for movement duration) confirmed this finding, $F(1, 6) = 5.77$, $p < .05$. Hence, although both groups were similar in overall movement timing, LHD patients spent considerably greater time in movement deceleration. (see Table 3 for summary).

Insert Table 3 about here

Within-Subject Variability

In concert with mean performance data, within-subject variability was computed for each movement context to determine if LHD patients and control participants differed in terms of trial to trial variability. Results of these analyses, for each dependent variable

failed to yield significant effects or interactions, $F < 1$. Hence, the degree of variability among brain-lesioned participants and control participants did not differ.

Right Hemisphere Damaged Patients and Control Participants (Right Hand)

Spatial Characteristics of the Movement Trajectory

Three-dimensional wrist trajectory reconstructions for a RHD patient and the right hand of one control participant are depicted in Figure 5 and 2 respectively. Similar to the plots for LHD patients, these depictions qualitatively demonstrate the degree of similarity among RHD patients and control participants. Consistent with these graphical depictions, quantitative analyses of out-of-plane motion failed to demonstrate significant differences between RHD patients and controls, $F(1, 7) = 3.40$, $p = 0.10$, suggesting that both groups were able to maintain their movement in one plane-of-motion. Similarly, movement planarity did not yield a significant effect for group, $F(1, 7) = 1.47$, $p = .26$, however in both cases the average score of control participants (out-of-plane = 166, planarity = 90) was slightly greater than RHD patients (RHD; out-of-plane = 137, planarity = 80). Further effects or interactions were not revealed, $p > .10$ (see Figure 4 bottom panel).

Insert Figure 5 about here

Movement Shape

Three-dimensional path distance did not differentiate between control (1.015) and RHD patients (1.022), $F(1, 7) = 2.39$, $p = .16$. Further effects or interactions were not elucidated, $p > .09$. Similarly, movement linearity did not differ between groups, $F(1, 7) = 1.35$, $p = 0.28$, (control = 35, RHD = 28). The absence of a group effect for movement linearity, $p > .30$, is confirmed in Figure 5 depicting lateral reconstructions of wrist

trajectories for a RHD patient, and one control participant (see Figure 2). Notice the degree to which subjects demonstrated an effective (linear) movement path, with minimal movement directed in the vertical axes.

Movement linearity yielded a significant effect for context, $F(4, 28) = 2.88$, $p = .04$, demonstrating that movements performed with full contextual cues and the tool only condition were more effective that the imitation, object only and pantomime conditions.

Movement Amplitude

Movement amplitude did not vary among RHD patients and control participants, $F(1, 7)$, $p > 0.55$, indicating that both groups performed movements of similar amplitude. A main effect for movement context, $F(4, 28) = 2.88$, $p < .01$, demonstrated that movements with full contextual cues (tool+object) were of less amplitude than movements performed to imitation or pantomime.

Performance and Temporal Kinematic Measures

RHD patients and control participants did not differ in terms of movement time, $F(1, 7) = 2.93$, $p = 0.13$. Further, this measure did not demonstrate a sensitivity to movement context, $F(4, 28) = 0.75$, $p = 0.57$.

Peak velocity yielded an effect for group approaching conventional levels of significance, $F(1, 7) = 4.75$, $p = 0.06$, and a main effect for movement context, $F(4, 28) = 3.95$, $p < .02$. Control participants attained higher velocity values relative to RHD patients (control = 791 mm/s, RHD = 676 mm/s), and velocity in the imitation condition (797 mm/s), was greater than actions performed with partial contextual cues (object only = 629 mm/s, tool only = 620 mm/s), followed by the pantomime (564 mm/s), and full contextual cue condition (tool+object = 479 mm/s).

Time spent following peak velocity, $F(1, 7) = 6.40$, $p < .04$, and percent time following peak velocity, $F(1, 7) = 4.77. = .06$, indicated that control participants spent significantly less time in deceleration relative to RHD (see Table 4 for complete summary).

Insert Table 4 about here

Within-Subject Variability

Within-subject variability did not demonstrate significant group or movement context effects, indicating that RHD patients and control participants did not differ in terms of movement variability.

Left Hemisphere Damaged and Right Hemisphere Damaged Patients

Spatial Characteristics of the Movement Trajectory

Analyses contrasting out-of-plane motion ($F(1, 6) = 0.59$ $p = 0.47$) and movement planarity ($F(1, 6) = 0.48$ $p > 0.51$) did not differentiate between LHD and RHD patients. Further effects of interactions were not revealed, ($p > 0.33$).

Movement Shape

Results for three-dimensional movement path, and movement linearity did not yield significant effects or interactions ($p > .09$).

Movement Amplitude

Analyses of movement amplitude revealed a significant effect of movement context, $F(4, 24) = 6.26$, $p < .01$. Consistent with previous analyses, this result indicated that movements performed in response to imitation or pantomime were of greater amplitude than movements with partial or full contextual cues. Further effects or interactions were not elucidated ($p > 0.12$).

Performance and Temporal Kinematic Measures

Significant effects or interactions involving movement time were not revealed, $p > 0.12$. Analyses of peak velocity indicated a main effect for movement context, $F(4, 24) = 4.33$, $p < .01$. No further effects or interactions were observed ($p > 0.12$). The main effect for movement context indicated that peak velocity in the object only condition was significantly less than the pantomime condition.

Analysis of time after peak velocity was instructive in understanding group differences in the control of movement directed away and toward the body. An interaction involving group and movement half, $F(1, 7) = 9.35$, $p < .03$, indicated that when performing movements toward the body, LHD patients spent a considerably longer portion of the total movement phase in deceleration. This finding was confirmed by percent time after peak velocity, $F(1, 7) = 11.24$, $p < .02$ (Figure 6).

Insert Figure 6 about here

Within-Subject Variability

Consistent with previous analyses, variability between brain-lesioned groups did not differ. Therefore, in the present sample, side of lesion did not influence variability of action response.

Velocity-Curvature Coupling

In normal movement, a close association exists between the spatial path of the moving limb, and the speed at which it travels. This relationship was examined by examining the delta time difference between tangential wrist velocity and radius of curvature for individual participants. A decoupling between these two values results in a temporal difference between the two kinematic parameters. In the present investigation,

for both controls and brain-lesioned patients a tight coupling was found between the two variables (see Figure 7). Indeed, an actual time difference was found in only 2.5% of the total trials, and the magnitude of this difference was reflected by sampling frequency (200 Hz; 5 ms).

Insert Figure 7 about here

Individual Patient Patterning

To provide an indication of individual performance, Figure 8 presents the percent relative amplitudes in horizontal (plane-normal) vertical (plane-normal), and mean out-of-plane motion trajectory planes. An efficient movement strategy is indexed by a greater proportion of overall movement confined to the horizontal (plane-normal), followed by the vertical plane (plane normal) of movement. The top panel of Figure 8 presents the performance of LHD patients and the left hand of control participants, and illustrates the degree to which patient and control participants adopted a spatially effective movement strategy, such that minimal movement was directed outside the primary plane-of-motion. A similar pattern is observed in the lower panel of Figure 8 contrasting RHD patients, and the right hand of controls. Once again, an efficient movement strategy is indicative of both participant groups. In conjunction, Figure 8 indicates that limb trajectories for each brain-lesioned patient, and control participants was consistent with the spatial goals of a slicing action.

Insert Figure 8 about here

Relationship Between Elbow and Wrist Velocity

Figure 9 illustrates the relationship between elbow and wrist velocity for one control participant (top panel) and a RHD patient (bottom panel). Notice that as elbow

velocity increases, wrist velocity increases proportionally, hence wrist and elbow velocity share an overall synchrony in patterning and magnitude. Graphical analyses confirmed that one brain lesioned patient, SR a LHD individual, demonstrated a lack of synchronization among joint velocities (Figure 9 middle panel). In contrast to the linear increase and decrease in velocity, SR demonstrated marked variations between elbow and wrist velocities, such that drifts and variations in the patterning of wrist and elbow velocity occurred across successive cycles of movement. This decoupling was prevalent during intrinsic (pantomime, tool only, object only, tool+object) but not extrinsic (imitation) movement contexts.

Insert Figure 9 about here

Quantitative assessment examined joint and elbow velocities for each trial per participant across the five movement contexts. Linear regression analyses were performed across each movement context, with correlations and slopes used to examine the degree and magnitude of the velocity-velocity relationship at the elbow and wrist. The distributions of the correlation coefficients and the distribution of the slopes of wrist velocity against elbow velocity are presented in Figures 10 and 11. Figure 10 represents the frequency of correlation coefficients among all participants. The left bar represents control participants and seven of the brain lesioned patients who did not demonstrate instability in joint synchronization. The right bars represent SR's unstable performance across the five movement contexts. For most subjects, correlations between wrist and elbow velocity clustered between 0.96 and 1.00 in each movement context indicating tight intersegmentation of joint velocities. In contrast, SR's coefficients ranged between 0.45 and 0.92, indicating a decreased relationship between wrist and elbow velocity.

Although SR's performance improved somewhat in the imitation context this performance did not achieve normative levels.

The slope of the regression equation was employed to determine if elbow and wrist velocity increased and decreased at the same magnitude. Plots depicting the distributions of the slopes for the regression of wrist against elbow velocity in each movement context are presented in Figure 11. Slopes for control subjects ranged from 0.93 to 1.12, (bottom bars) and from .98 to 1.30 for seven of the brain-lesioned patients (centre bars). For SR, regression slopes ranged from 0.22 to 0.89 (top bars). Similar to the correlation coefficient, the magnitude of elbow and wrist velocity coupling improved somewhat in the imitation condition. These results demonstrate that SR was markedly impaired in the synchronizing the temporal components of a multi-joint segment, particularly during intrinsic movement contexts.

Insert Figures 10 and 11 about here

Temporal Errors

Two brain lesioned patients (SR, EV) show impairments in the fluidity of their movements. Figure 12 (top panel) demonstrates tangential wrist velocity profiles of a control participant in gestural pantomime and imitation. The velocity profiles are smooth reflecting sinusodial movement repetitions. In contrast, the wrist velocity profiles of SR (middle panel) and EV (bottom panel) are nonsinusodial and have many irregularities reflecting a lack of fluidity for intrinsically generated movements. During gestural imitation the velocity profiles of SR and EV improved.

Insert Figure 12 about here

DISCUSSION

The primary goal of this investigation was to determine whether the movement deficits observed in earlier observational analyses of apraxia (Heath, Experiments 1 and 3), could be quantified using more detailed kinematic analysis. Indeed, previous kinematic studies (Clarke et al., 1994; Poizner et al., 1990, 1995) have reported spatial-temporal errors among LHD patients with ideomotor apraxia, however, a paucity of research has similarly examined apraxic movement errors following RHD. To this end, three-dimensional analyses of a transitive limb gesture ('slicing a bagel') was investigated in a sample of four left and four right brain-lesioned patients, and a control group consisting of five age-matched participants.

In addition to the primary research goal, a secondary research question addressed the importance of contextual cues in gesture production. Specifically, does increasing the ecological validity of a transitive limb gesture result in a more efficient and stable level of performance? Further, the inclusion of an imitation condition, in which participants replicated the action demonstrated by the experimenter, permitted analyses of the degree to which intrinsic and extrinsic control parameters influenced gesture production following left or right hemisphere damage.

Performance of Control Participants

Analyses of control participants comparing the dominant (right) and non-dominant (left) limb, reproduced those of an earlier study by Heath (Experiment 4). Three-dimensional motion analyses indicated that the trajectory of the right limb was constrained within a single plane-of-motion to a greater degree than the left limb. Further, the right limb demonstrated a linear movement with minimal trajectory

curvature. In contrast, the left limb was more circular and tended to deviate from a single plane-of-motion. These results extend Heath's assertion that learned, skilled actions, such as the transitive slicing gesture used in this study, are performed more effectively by the dominant limb.

A right hand dominance for learned, skilled actions represents an intriguing question not readily accounted for by motor control theories of manual asymmetries. Previous manual asymmetries research has focussed on simple unimanual tasks such as rapid finger-tapping and goal-directed aiming movements (Binsted, Cullen, & Elliott, 1999; Elliott, Heath, Binsted, Ricker, Chua, & Roy, 1999; Flowers, 1975; Heath, Hodges, Chua, & Elliott, 1998; Heath & Roy, 2000; Peters, 1976; Todor & Kyprie, 1980; Roy & Elliott, 1986/1989; Woodworth, 1899). These studies have generated two theories accounting for a right hand dominance: output and input theories. Output theories posit that motor centres within the left hemisphere are lateralized for programming the neuromuscular synergies associated with purposeful actions (Roy & Elliott, 1986/1989), whereas the input theory states that the right hand/left hemisphere advantage stems from the ability of this system to incorporate response-produced feedback into an ongoing movement. While both theories have been instructive for relatively simple unimanual movements, they are unable to account for more complex learned actions (e.g., slicing a bagel), where programming a ballistic movement phase, or utilizing response-produced visual feedback are minimized. Alternatively, several authors (Peters, 1976; Peters, 1980; Todor & Kyprie, 1980; Todor, Kyprie & Price, 1982) have suggested that a right hand superiority for unimanual tasks may arise due to a left hemisphere specialization for programming movement sequences (e.g., repetitive

flexion/extension movements). In the present investigation, temporal kinematic measures (e.g., total movement time, peak velocity, time after peak velocity) did not differentiate between left and right hand performance. Instead, the right hand demonstrated superior spatial parameterization, suggesting that the movement sequence used in the present task was not an overriding factor in contributing to a right hand advantage, as temporal measures did not denote hand differences. Hence, the present results necessitate an alternative explanation for the right hand advantage.

Provins (1997) argues that a right hand dominance for complex skills develops as a result of social and environmental influences that favour right hand use, and ultimately impact skill performance. Thus, as individuals become more skilled with their dominant limb, neural noise unrelated to the activity is reduced, while the activity related to the movement is increased (Basmajian, 1973). Provins cumulative practice hypothesis may best explain the dominant hand advantage associated with transitive limb gestures, as the heightened effectiveness and spatial accuracy of the dominant limb may reflect a simple practice effect. In this interpretation, the accumulated experience of the dominant limb results in decreased neural noise leading to greater effectiveness for learned, skilled actions.

Although the nature of a dominant hand advantage is not entirely clear, the fact that manual asymmetries are expressed during the production of transitive limb gestures has clear implications for apraxia research. Indeed, the results mandate that kinematic analyses of apraxia contrast the ipsilesional limb (e.g., right hand in RHD patients) of brain-lesioned patients to the same limb of control participants (e.g., right-hand). This methodology prevents premorbid manual asymmetries from impacting group contrasts,

and provides the most sensitive comparison for quantifying apraxic impairments in unilateral stroke populations.

Effects of Left Hemisphere Damage

Clinical evaluation of apraxia follows that performance is evaluated in response to verbal command, followed by imitation of movement modelled by the clinician. In the final step, gestures are performed with partial or full contextual cues (Heilman & Rothi, 1985). Previous kinematic evaluations of apraxia have compared only a partial subset of these elicitation techniques. Poizner et al. (1998) compared pantomime and tool+object (full contextual cue) conditions, while in a subsequent study, pantomime and tool only (partial contextual cue) conditions were examined (Poizner et al., 1995). In contrast to Poizner and colleagues approach, the current research examined each elicitation technique relevant to the clinical diagnosis of apraxia, enabling quantitative examination of how contextual cues, and intrinsic (e.g., pantomime) and extrinsic (e.g., imitation) response modalities impact gesture production following unilateral stroke.

The LHD patients in this study did not demonstrate clear and marked deficits in the spatial parameterization of wrist movement across each elicitation context. As indicated by control participants, a successful and efficient slicing action required that the shape of the wrist trajectory be linear and maintained in one plane-of-motion. LHD patients demonstrated similar cyclic, linear forward and backward movement within one-plane of motion.

Elicitation modalities impacted amplitude and peak velocity measures equally among LHD patients and control participants, as movement amplitude and peak velocity decreased as contextual cues were included in the movement. However, spatial accuracy

and effectiveness was found to improve only slightly when contextual cues (tool and/or objects) were added to the movement context. Moreover, the intrinsic contexts (pantomime, tool only, object only, tool+object) which required an internal representation of the action were found not to differ significantly from the extrinsic context (imitation) in which the appropriate representation of the action was modelled. In conjunction, these results indicate that LHD and the manipulation of movement context for this sample of participants did not impair, or influence the spatial parameters associated with the production of a learned, skilled action.

Clarke et al. (1994) and Poizner et al. (1990, 1998) reported significant spatial-temporal implementation deficits in their sample of LHD patients during gestural pantomime, with slight improvements during tool (Clarke et al., 1994) and tool+object (Poizner et al. 1998) contexts. The LHD patients in these studies generated circular movements oriented in the incorrect plane-of-motion, with marked instability in maintaining movement planarity within individual movement cycles. Examination of spatial-temporal coupling, defined by a robust temporal synchrony between tangential velocity minima and radius of curvature of the wrist (Morasso, 1983) revealed marked temporal decoupling, resulting in a non-fluid or 'jerky' wrist trajectory. Poizner and colleagues (e.g., Poizner et al., 1995) believed these findings reflect a model of apraxia in which the disorder results from a destruction of the space-time engrams of learned movements located in the left hemisphere, and/or a disconnection between these representations and more frontal executive systems (Rothi, Ochipa, & Rothi, 1991/1997).

The discrepancy between the present findings which failed to observe spatial parameter deficits in the wrist trajectory among LHD patients, and those of Poizner and

colleagues (Clarke et al., 1994) may relate to patient selection. Poizner and colleagues (Clarke et al., 1994; Poizner et al., 1990; Poizner et al., 1995; Poizner et al., 1998) selected LHD patients based on their clinical diagnosis of limb apraxia (FAST, Heilman & Rothi, 1985), whereas in the current study, brain-lesioned patients (LHD and RHD) were selected upon confirmation of a single unilateral stroke (see Participants section). Thus, Poizner and colleagues (e.g., Poizner et al., 1998) provide detail related to the spatial, temporal, and cojoint spatial-temporal deficits associated with *ideomotor apraxia*, and do not describe specific deficits associated with LHD in general. The present findings highlight this notion, as the absence of spatial or temporal impairments in this sample of LHD indicates that a left hemisphere stroke alone, is not a sufficient condition for the elicitation of limb apraxia. This interpretation is parsimonious with Haaland, Harrington, & Knight (1999), who argue that the spatial errors associated with limb apraxia are not exclusive to LHD, but rather, ideomotor apraxia in general.

Temporal kinematic data indicated that LHD patients spent considerably greater time in the deceleration phase (time after peak velocity), particularly for movements directed toward the body. An increased deceleration phase for body-directed movements may indicate that these gestures require greater spatial precision than movements directed away from the body (Roy & Square, 1994), or reflect a cognizant control strategy which LHD patients adopt to overcome a known performance deficit (Heath, Roy, & Weir, 1999). Kinematic examination of reaching and grasping, and pointing movements have shown that RHD impairs the processing of response-produced visual feedback, while LHD impairs the ballistic phase of movement programming (Haaland, 1989; Haaland & Harrington, 1989; Hermsdorfer, Ulrich, Marquardt, Goldenberg, & Mai, 1999; Pohl,

Winstein, & Onla-or, 1997; Winstein & Pohl, 1995). In the present investigation, LHD patients spent greater time in deceleration during forward and backward movements relative to control participants, and spent greater time in deceleration relative to RHD patients during movements directed toward the body. In both cases, these results are incongruent with Haaland and Harrington's (1989) assertion that RHD, not LHD results in greater movement deceleration. Moreover, the fact an increased deceleration phase was not restricted to body-centred movements (LHD vs. controls) does not support Roy and Square's (1994) notion that body-directed movements may be particularly impaired following stroke.

As mentioned previously, visual processing constraints and the programming of a ballistic movement phase are minimized in the present task, thus Haaland and Harrington's (1989) model may not best explain the increased deceleration phase associated with LHD. Wyke (1967, 1971) demonstrated that left hemisphere stroke impaired coordination of the muscle synergies necessary for the smooth transition between primary muscle agonists during a cyclical elbow flexion and extension task. Thus, the prolonged deceleration phase associated with LHD patients in the present investigation may indicate an impaired temporal synergy between muscle agonists, or an increased preparatory phase associated with this postural transition (Kimura, 1977; 1982; Mateer & Kimura, 1977). In this interpretation, LHD patients may adopt a control strategy by which movement deceleration is prolonged to allow greater time to co-ordinate the muscular synergies necessary for a movement transition (e.g., flexion to extension or extension to flexion).

There was one aspect of movement that markedly impaired a left brain-lesioned patient (SR). SR improperly synchronized elbow and wrist velocity, such that wrist velocity was greater in magnitude than elbow velocity. This decoupling was particular evident during intrinsic control conditions (pantomime, tool only, object only, tool+object), and improved during the extrinsic movement context (imitation). In most individuals, velocity of the elbow is produced by shoulder motion, whereas speed at the wrist is produced by combined motion of shoulder and elbow joints, resulting in a linear relationship between the two (Lacquaniti, 1989). This control property reflects an invariant relationship between shoulder and elbow joint motion, providing a sensorimotor map between upper and lower limb phase relations, which may serve as a mechanism to simplify the neuromuscular control of movements with multiple degrees of freedom (Soechting & Terzuolo, 1987a; 1987b; Soechting & Flanders, 1992). For patient SR, the lack of joint synchronization, in terms of degree and magnitude, suggests a breakdown in the ordered patterning of joint motions, indicating a destruction of the sensorimotor map that coordinates individual movement segments. To accommodate this breakdown, SR generated movement at more distal joints. Interestingly, inspite of this control strategy, SR's movements were linear and constrained to one plane-of-motion, similar to control and other brain-lesioned participants. Although somewhat surprising, that synchronization of limb segments can be impaired independent of spatial parameterization impairments, this finding is consistent with Lacquaniti, Soechting, & Terzuolo (1986) who postulated that wrist (plane-of-) motion can be planned independent of a decoupling of the temporal relations at more proximal joints.

The trajectory characteristics of SR present a unique pattern of apraxia not reported in previous kinematic analyses (Poizner et al., 1995; Poizner et al., 1998). Recall that Poizner and colleagues reported multiple kinematic impairments in the limb movements of LHD patients, while the present study demonstrates an apraxic impairment restricted to the sensorimotor map for the ordered patterning of joint motions, without concomitant deficits in the spatial parameterization of the task. These results suggest that kinematic deficits in apraxia are dissociable, and can be restricted to a single element of the movement trajectory. Moreover, SR's improved performance during gestural imitation, during which movement was guided by an external frame of reference, provides further evidence that SR's deficits during intrinsically guided movements (pantomime, tool only, object only, tool+object) was restricted to a loss of the sensorimotor map for the patterning of joint motions. Indeed, the presence of a model, which provided SR with the appropriate representation of the action and synchronization of elbow and wrist motion, resulted in improved phase relations among the joints.

Effects of Right Hemisphere Damage

The findings comparing RHD patients to control participants generally reproduce those of Poizner et al. (1998), although the mild deviations in plane-of-motion described in Poizner et al's sample of RHD patients was not observed in the present study. In both studies, spatial (e.g., linearity), temporal (movement time) and spatial-temporal (velocity-curvature coupling) movement parameters were generally not impaired following RHD. As discussed previously, the pooled left/right hand data of control participants was compared to the ipsilesional (right) limb of RHD patients in Poizner et al's work. A priori it was hypothesized that since control participants express a dominant hand

advantage for transitive limb gestures (Heath, Experiment 4), the pooled left/right hand comparison employed by Poizner et al. may not have provided a sensitive index to examine apraxic movement deficits following RHD. However, this hypothesis was not borne out. The spatial parameters associated with RHD patients indicated movement in one plane-of-motion, with minimal path curvature and an effective and linear movement trajectory consistent with the constraints of a slicing action. Additionally, contrasts of intrinsic and extrinsic movement cues did not reveal significant performance differences.

Temporal kinematic data revealed that the magnitude and timing of trajectories differed among RHD and control participants. The overall magnitude of peak velocity was diminished in the RHD group, accompanied with a prolonged deceleration phase. Recall that LHD patients also demonstrated an increase in movement deceleration, but without associated reductions in peak velocity. The pattern revealed by LHD patients was attributed to a disorder in the muscle synergies associated with postural transitions (Wyke, 1968, 1970, Kimura, 1977; 1982; Mateer & Kimura, 1977). However, the temporal kinematic pattern of RHD patients, revealing a reduction in peak velocity and a prolonged deceleration phase suggests an alternative control deficit. Haaland's (1989) proposal that that RHD impairs response-produced feedback, encompassing visual and proprioceptive modalities (see also Adamovich, Berkinblit, Fookson, & Poizner, 1998; Pohl et al, 1997) may provide a framework explaining the temporal kinematic profile of RHD patients. Specifically, the impaired ability to monitor proprioceptive and visual information may lead to a control strategy by which the magnitude of the initial movement impulse (peak velocity) is minimized in conjunction with an increased deceleration phase to accommodate temporal feedback limitations in coordinating

postural transitions. This explanation could be extended using a reciprocal task, such as Fitts' tapping task (Fitts, 1954) which requires greater sensorimotor regulation. For this task, kinematic and electromyography measures could determine whether increased deceleration following LHD is related to impairments in the temporal synergies of primary muscle agonists, and conversely determine whether the temporal pattern exhibited by RHD (decreased peak velocity and increased movement deceleration) is associated with temporal limitations of feedback regulation.

Cyclical movements such as the slicing gesture used in this study are characterized by fluid, sinusoidal velocity profiles, reflecting a basic organizational principle of the motor system (Hogan, 1984; Ostry, Cooke, & Munhall, 1987). Poizner et al. (1990) identified irregular and non sinusoidal velocity profiles in two LHD ideomotor apraxics, which was attributed to a destruction of the spatio-temporal representations of learned movement within the left hemisphere. In the present investigation, one LHD patient (SR) demonstrated irregular velocity profiles, which have been attributed to a joint synchronization disorder. A RHD patient, EV, also demonstrated irregularities in wrist velocity. EV's velocity profiles were irregular, exhibiting multiple velocity peaks, indicative of an initial hesitancy and slow build-up of movement velocity. These irregularities could not be attributed to an elementary motor deficit, as performance improved during gestural imitation. Thus, similar to SR's improved joint synchronization during imitation, the temporal synchrony of EV's trajectory improved when the action was modelled.

EV's irregular velocity profiles represent a novel finding, that is, a movement deficit for a learned action to be kinematically identified in a RHD patient. Indeed, EV's

performance demonstrates an impaired internal representation of a slicing action. Specifically, the temporal structure of this internal representation was impaired independent of the spatial parameterization of the action, as evidenced by improved performance during imitation. Kinematic features such as irregular velocity profiles have been interpreted as an indication of a deficient motor plan, and direct indication of insufficient programming of the details of movement execution. While these deficits have been reported infrequently following RHD, a limited number of studies have noted velocity anomalies following RHD (Hermsdorfer et al., 1996; Platz & Mauritz, 1995; Poizner et al., 1998), although in each case, the frequency and severity of the anomaly was more evident in LHD patients. The paucity of kinematic studies reporting movement deficits in RHD patients may reflect the tendency for these studies to employ small sample sizes. Heath's (Experiment 1 and 3) observational analyses of transitive and intransitive gestures reported that twenty-three and twenty-two percent of RHD patients respectively in Experiments 1 and 3, were classified as ideomotor apraxic, while the frequency of ideomotor apraxia was significantly greater following LHD (transitive = 43%, intransitive = 30%). In conjunction observational and kinematic analyses illustrate that apraxia can arise following right hemisphere stroke; however, more work is needed to fully understand the nature of apraxia following RHD.

CONCLUSIONS

The sample of unilateral stroke patients in this investigation did not exhibit impaired spatial parameterization of a slicing motion. These results contradict those of Poizner and colleagues (Clarke et al., 1994; Poizner et al., 1995; Poizner et al., 1990) who reported spatial and temporal impairments following LHD. In contrast, the present findings suggest that LHD alone is not a sufficient condition to elicit apraxic movement deficits, rather, the deficits described in Poizner et al's work may reflect a disorder specifically associated with ideomotor apraxia. The recent work of Haaland et al. (1999) and Heath (Experiments 1 and 3) extend this notion, finding that spatial impairments in a pointing task are not characteristic of left or right hemisphere lesions, but more accurately, are associated with ideomotor apraxia, regardless of lesion location.

Sample size may have been a limiting factor in quantifying apraxic errors in this investigation (see Heath, Experiment 1). However, one left and one right hemisphere damaged patient did demonstrate apraxic deficits, a proportion roughly equivalent to that reported in earlier observational analyses (Heath, Experiment 1). Both EV and SR demonstrated a specific impairment in translating the temporal elements of tool-use into overt action, as evidenced by their improved response during imitation. Moreover these two cases indicate that left or right hemisphere stroke can impair the formulation of a learned action. Future work is designed to determine whether the spatial errors described by Poizner et al. (1998) are related to LHD, or ideomotor apraxia in general. To this end, left and right hemisphere damaged individuals with ideomotor apraxia, evaluated via the multi-dimensional error notation system and pattern analysis technique described in

Heath (Experiments 1 and 3), will be investigated using the kinematic techniques reported in this study.

Table 1.

Age, gender, aphasia type, post-stroke onset testing date, and lesion localization.

Case	Age (years)	Sex	Aphasia	Months Since Onset	Lesion Site
LHD Patients					
1. WE	78	M		9	Left MCA territory infarct (BG, TL, PL, OL)
2. BJ	61	F		12	Left PCA territory (including OL)
3. HG	72	M	-	5	Left parietal lobe
4. SR	60	F		10	Left MCA territory (TL, frontal region)
RHD Patients					
1. MG	60	M	-	10	Right MCA territory
2. NJ	54	M	-	9	Right MCA territory (FL, PL)
3. TL	56	M	-	6	Right MCA territory
4. EV	79	F	-	5	Right MCA territory
Control Participants					
1. BD	65	M	-	-	
2. WH	61	M	-	-	
3. HD	57	M	-	-	
4. RH	79	F	-	-	
5. GJ	63	F	-	-	

BG = basal ganglia, TL = temporal lobe, FL = frontal lobe, PL = parietal lobe, OL = occipital lobe, MCA = middle cerebral artery, PCA = posterior cerebral artery

Table 2

Mean out-of-plane movement, movement planarity, three-dimensional distance, linearity, amplitude (mm), movement time (ms), peak velocity (mm/s), and time after peak velocity (ms) for the left and right hand of control participants as a function of movement context.

Hand/ Variable	Pantomime (sd)	Tool Only (sd)	Object Only (sd)	Tool+Object (sd)	Imitation (sd)	Row Mean (sd)
Left Hand						
Out-of-plane movement	113.72 (79.65)	133.85 (84.42)	127.42 (75.31)	159.81 (123.60)	131.33 (97.10)	132.40 (94.68)
Planarity	69.91 (41.15)	75.12 (42.99)	62.90 (34.52)	83.02 (52.46)	73.78 (52.97)	72.54 (45.45)
3D distance	1.026 (0.018)	1.019 (0.015)	1.028 (0.017)	1.025 (0.018)	1.020 (0.016)	1.022 (0.017)
Linearity	24.16 (13.58)	27.70 (14.97)	23.41 (14.91)	27.62 (17.01)	28.66 (19.82)	26.21 (16.06)
Amplitude	245.53 (116.78)	219.17 (104.93)	212.71 (110.81)	156.11 (70.10)	185.16 (71.02)	204.29 (102.19)
Movement Time	411.43 (130.36)	372.30 (89.83)	344.92 (93.78)	362.93 (92.40)	353.50 (60.14)	369.76 (100.00)
Peak Velocity	748.28 (213.74)	700.07 (178.42)	726.10 (235.02)	576.99 (194.85)	921.19 (252.54)	722.37 (237.40)
Time After Peak Velocity	199.76 (64.46)	181.82 (48.60)	169.52 (49.87)	180.30 (51.83)	170.14 (30.35)	180.84 (52.15)
Right Hand						
Out-of-plane movement	138.97 (96.70)	166.01 (111.94)	178.29 (126.02)	188.20 (128.18)	157.05 (114.65)	166.16 (117.09)
Planarity	87.24 (55.39)	95.19 (63.00)	91.48 (64.19)	90.47 (57.87)	85.96 (57.57)	90.27 (59.70)
3D distance	1.015 (0.016)	1.016 (0.016)	1.016 (0.017)	1.010 (0.012)	1.016 (0.011)	1.015 (0.015)
Linearity	35.27 (18.90)	37.25 (17.50)	32.27 (21.00)	41.13 (19.20)	31.07 (19.27)	35.27 (19.42)
Amplitude	259.61 (111.68)	227.12 (100.54)	220.85 (106.24)	153.85 (66.89)	178.65 (68.05)	209.38 (100.71)
Movement Time	436.53 (142.83)	365.85 (88.21)	315.92 (68.40)	301.80 (54.74)	347.94 (65.82)	353.80 (102.91)
Peak Velocity	771.66 (265.53)	776.84 (232.74)	838.40 (269.50)	646.87 (192.98)	986.62 (294.02)	791.49 (270.22)
Time After Peak Velocity	209.69 (70.02)	180.50 (47.30)	155.28 (70.00)	151.10 (28.94)	168.19 (39.38)	173.20 (50.77)

Table 3

Mean out-of-plane movement, movement planarity, three-dimensional distance, linearity, amplitude (mm), movement time (ms), peak velocity (mm/s), and time after peak velocity (ms) for LHD patients in each movement context.

Variable	**Pantomime (sd)**	**Tool Only (sd)**	**Object Only (sd)**	**Tool+Object (sd)**	**Imitation (sd)**	**Row Mean (sd)**
Out-of-plane movement	69.23 (53.81)	84.64 (55.41)	104.66 (57.51)	112.91 (74.76)	77.80 (62.56)	89.78 (63.02)
Planarity	61.75 (45.34)	73.49 (51.88)	71.61 (35.63)	78.98 (40.20)	63.32 (43.43)	69.80 (43.82)
3D distance	1.162 (0.204)	1.174 (0.442)	1.038 (0.0458)	1.047 (0.155)	1.021 (0.023)	1.089 (0.100)
Linearity	15.61 (12.12)	23.40 (20.22)	20.78 (13.38)	27.07 (20.78)	26.93 (10.34)	22.73 (16.40)
Amplitude	297.00 (87.30)	282.81 (95.09)	240.80 (82.52)	182.37 (78.95)	317.53 (62.11)	264.36 (94.47)
Movement Time	565.27 (99.64)	512.14 (153.21)	425.99 (127.98)	480.44 (180.00)	510.43 (118.00)	498.92 (145.40)
Peak Velocity	869.90 (268.18)	891.87 (272.12)	901.29 (135.44)	637.35 (202.43)	998.12 (214.97)	876.18 (260.03)
Time After Peak Velocity	273.29 (102.75)	263.33 (79.46)	212.61 (72.22)	237.34 (94.19)	245.12 (69.42)	243.45 (87.42)

Table 4

Mean out-of-plane movement, movement planarity, three-dimensional distance, linearity, amplitude (mm), movement time (ms), peak velocity (mm/s), and time after peak velocity (ms) for RHD patients in each movement context.

Variable	**Pantomime (sd)**	**Tool Only (sd)**	**Object Only (sd)**	**Tool+Object (sd)**	**Imitation (sd)**	**Row Mean (sd)**
Out-of-plane movement	136.77 (100.44)	143.51 (120.84)	138.49 (107.67)	133.53 (134.41)	133.26 (104.34)	137.10 (114.80)
Planarity	72.75 (60.76)	86.67 (54.40)	74.35 (50.18)	79.29 (57.26)	89.85 (60.68)	80.68 (56.88)
3D distance	1.028 (0.028)	1.013 (0.034)	1.028 (0.050)	1.026 (0.041)	1.016 (0.012)	1.022 (1.022)
Linearity	22.56 (12.87)	39.63 (27.29)	25.26 (12.33)	28.08 (14.61)	28.34 (12.65)	28.91 (17.94)
Amplitude	136.61 (52.19)	152.09 (41.40)	135.51 (57.62)	129.29 (47.14)	252.50 (71.30)	161.58 (71.73)
Movement Time	349.09 (147.92)	462.09 (265.73)	395.23 (214.98)	557.72 (174.28)	446.54 (187.98)	442.13 (273.48)
Peak Velocity	665.18 (246.71)	623.99 (240.51)	609.94 (286.37)	494.82 (205.04)	984.86 (302.54)	676.41 (306.64)
Time After Peak Velocity	177.84 (75.66)	224.92 (93.34)	198.20 (150.48)	293.56 (102.73)	215.15 (102.24)	221.43 (110.44)

Figure Captions

Figure 1. Three-dimensional view (lateral perspective) of limb trajectories performed by the left hand of a control participant in the five experimental contexts. The figures presented to the right of each three-dimensional graph represent successive two-dimensional lateral views, and provide a qualitative index of movement linearity.

Figure 2. Three-dimensional view (lateral perspective) of limb trajectories performed by the right hand of a control participant in the five experimental contexts. The figures presented to the right of each three-dimensional graph represent successive two-dimensional lateral views and provide a qualitative index of movement linearity.

Figure 3. Three-dimensional view (lateral perspective) of limb trajectories performed by a LHD patient (SR) in each of the five experimental contexts. The figures presented to the right of each three-dimensional graph represent successive two-dimensional lateral views and provide a qualitative index of movement linearity.

Figure 4. Movement planarity and standard error of the mean for LHD patients, the left hand of control participants (top panel), RHD patients and the right hand of control participants (bottom panel), as a function of movement context.

Figure 5. Three-dimensional view (lateral perspective) of limb trajectories performed by a RHD patient (EV) in each of the five experimental contexts. The figures presented to the right of each three-dimensional graph represent successive two-dimensional lateral views and provide a qualitative index of movement linearity.

Figure 6. Time after peak velocity (ms) and standard error of the mean for control participants, LHD and RHD patients as a function of movements directed away (Half 1) and towards (Half 2) the body. The left hand of control participants is represented by the

vertical gray bar; the right hand of control participants is represented by the solid gray bar.

Figure 7. Velocity-curvature coupling for a RHD patient in the pantomime condition. Tangential wrist velocity (grey line) and radius of curvature (black line) are plotted. The graph demonstrates a strong temporal relationship between peak velocity minima and radius of curvature.

Figure 8. Percent relative movement amplitude of horizontal (plane-normal) and vertical (plane-normal) movement axes, and out-of-plane movement for LHD patients, and the left hand of control participants (top panel). RHD patients and the right hand of control participants are depicted in the bottom panel.

Figure 9. Tangential velocity of the wrist (Y) and elbow (X) in pantomime and imitation contexts are depicted for a control participant (top panel), LHD patient (SR, middle panel), and a RHD patient (MW, bottom panel). Notice that the magnitude of peak elbow and wrist velocity is quite similar for the control participant and the RHD patient, while the LHD patient demonstrates a striking disparity between the two velocities, which improved during the imitation condition.

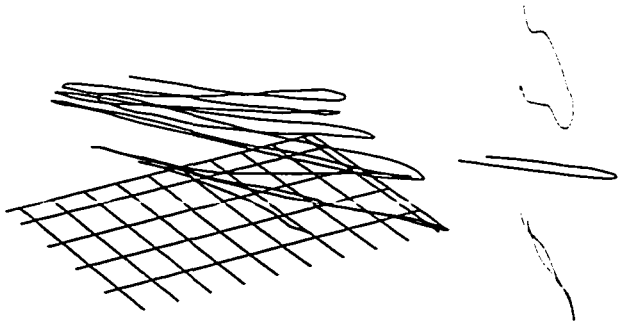
Figure 10. Correlation coefficient frequencies for each movement context. For each participant, one trial per movement context is included in the frequency plot. SR's performance (right bars) is contrasted to the performance of control participants, and the seven brain-lesioned patients (left bar) who did not demonstrate a lack of synchronization between wrist and elbow tangential velocity.

Figure 11. Frequency of regression slopes for each movement context. For each participant, one trial per movement context is included in the frequency plot. SR's

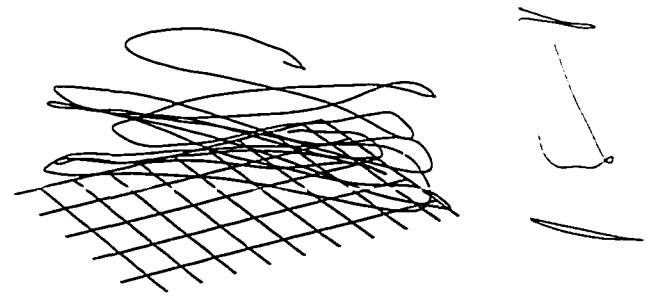
performance (right bars), the control participants (left bars) and the seven brain lesioned participants (centre bars) who did not demonstrate an impaired synchronization between the magnitude of wrist and elbow velocity are depicted in three distinct groups.

Figure 12. Tangential wrist velocity profiles for a control participant (top panel), a LHD patient (SR, middle panel), and a RHD patient (EV, bottom panel). For the control participant, velocity profiles are sinusoidal in both pantomime and imitation contexts, while for patients SR and EV many irregularities are present in the pantomime condition, with an improvement in performance during gestural imitation.

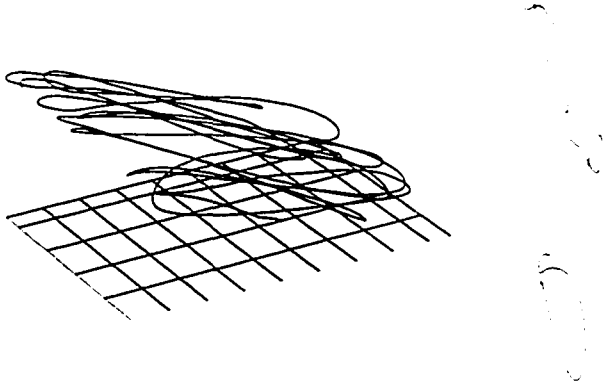
Control Left: Pantomime



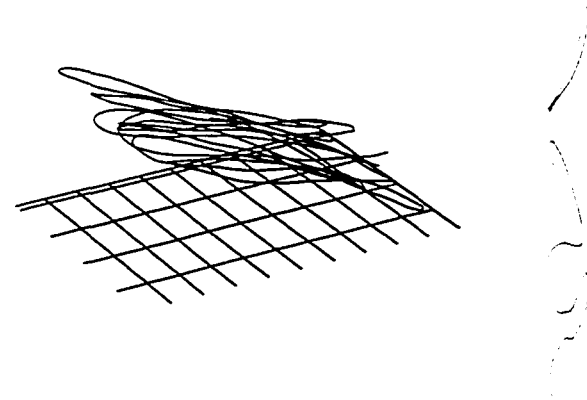
Control Left: Tool Only



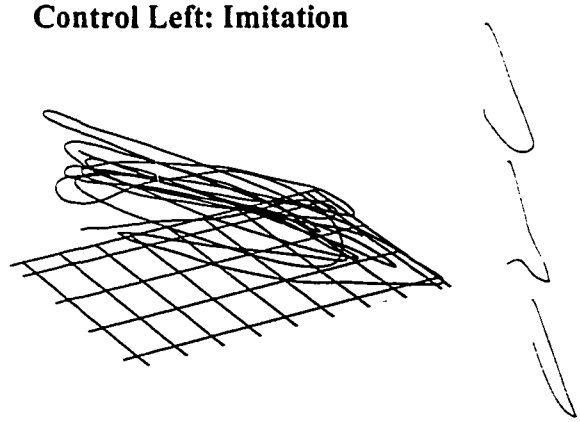
Control Left: Object Only



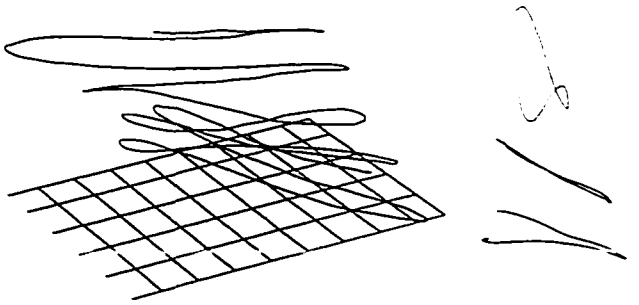
Control Left: Tool+Object



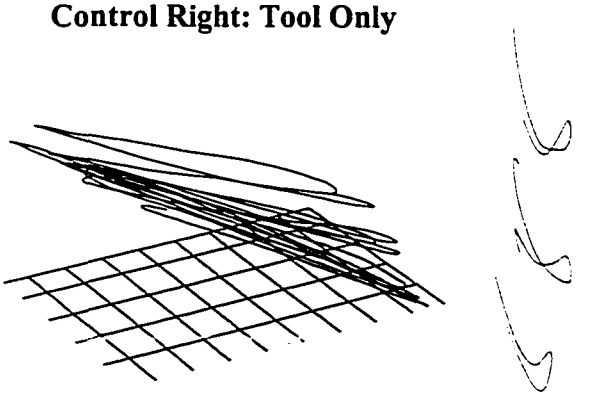
Control Left: Imitation



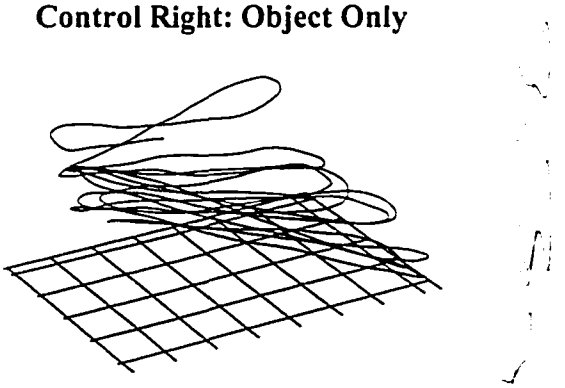
Control Right: Pantomime



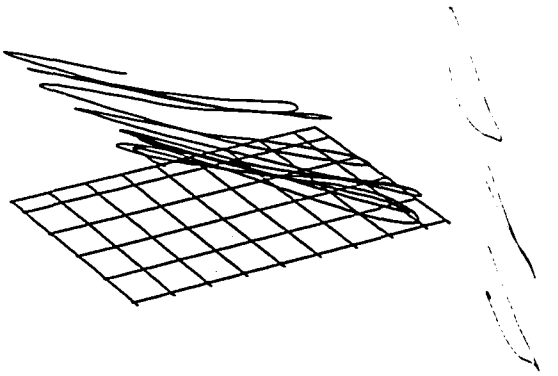
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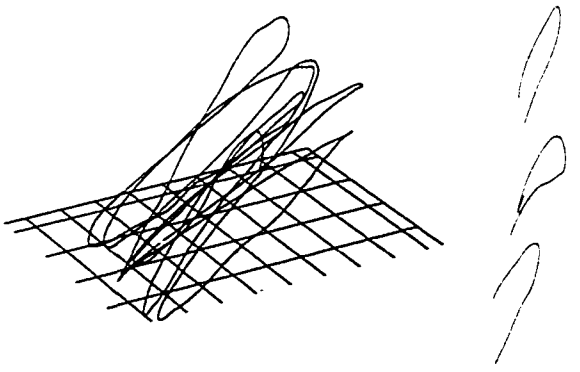
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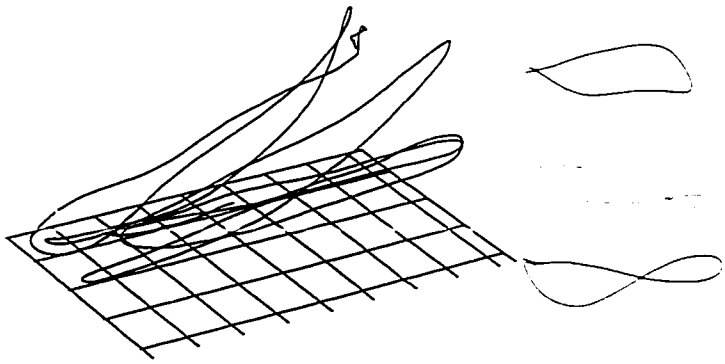
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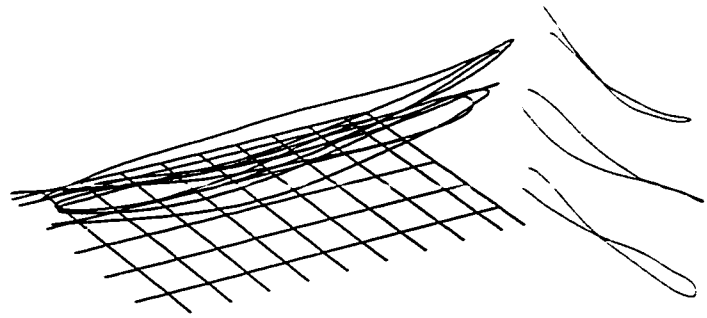
Control Right: Imitation



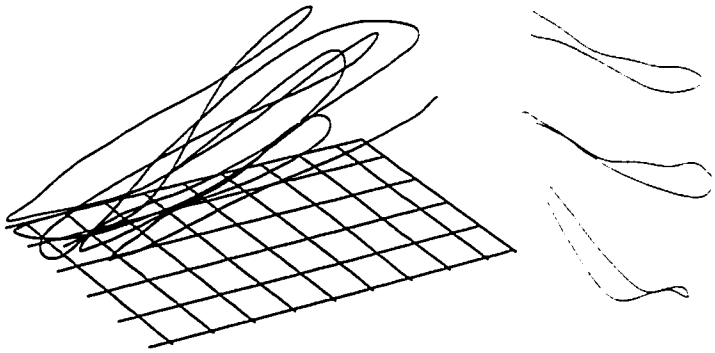
LHD: Pantomime



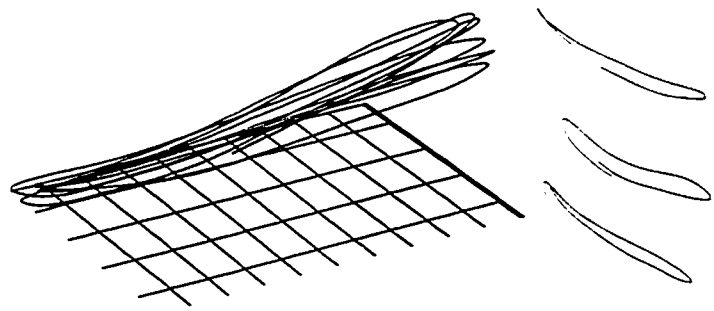
LHD: Tool Only



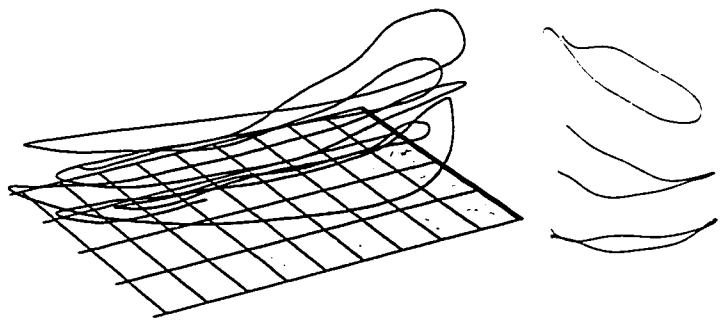
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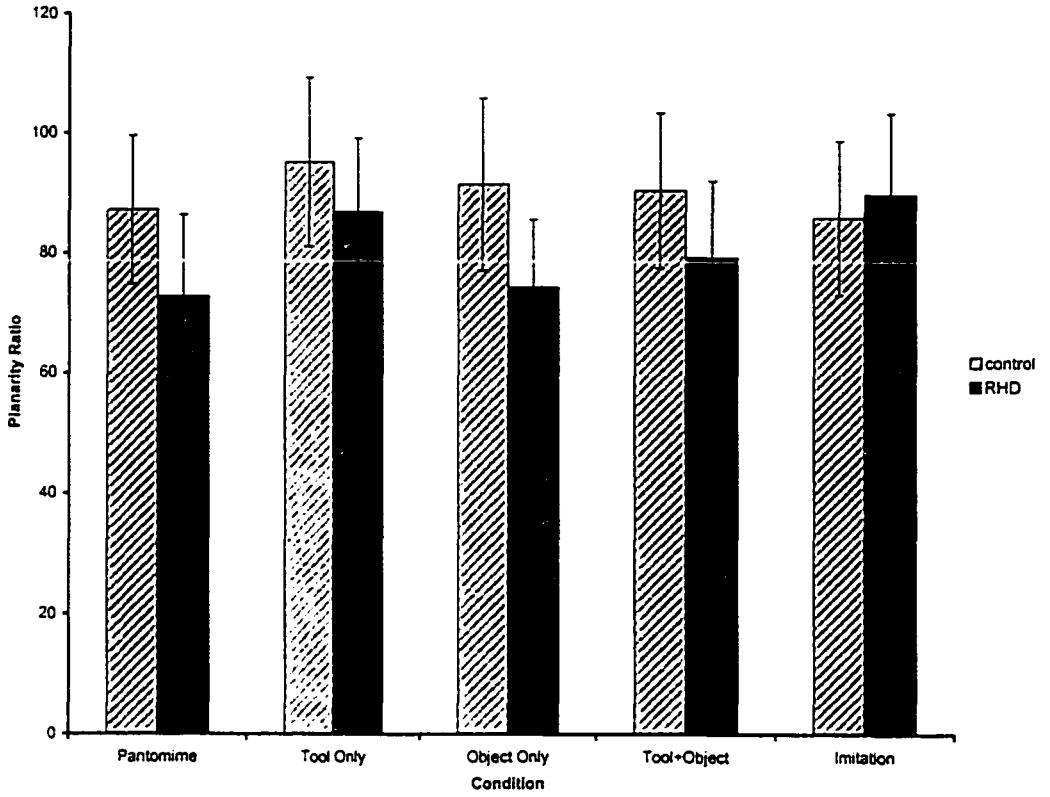


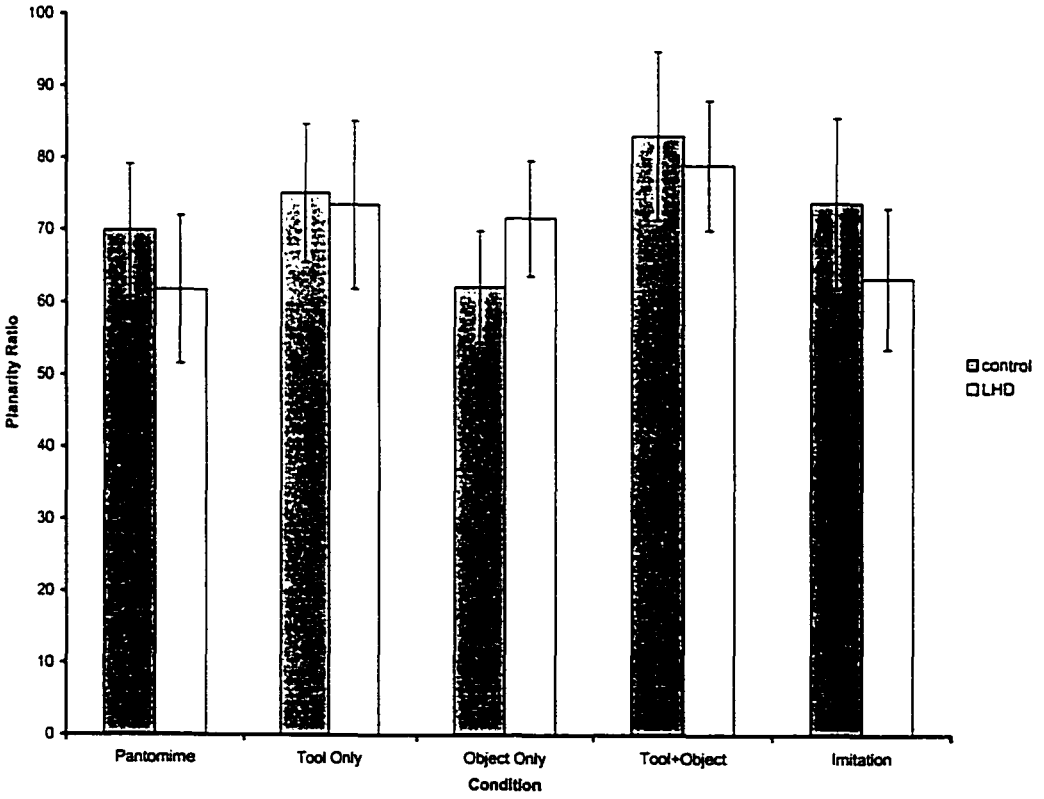
LHD: Tool+Object



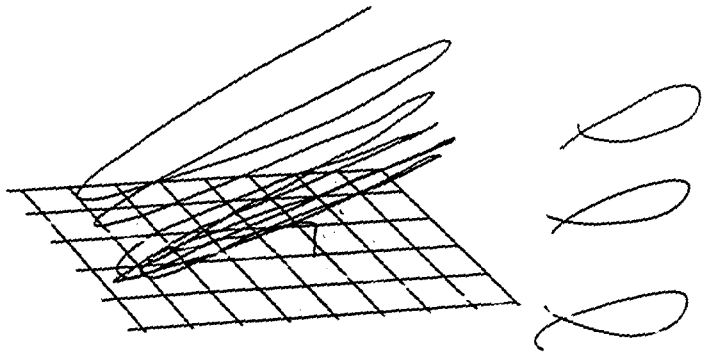
LHD: Imitation



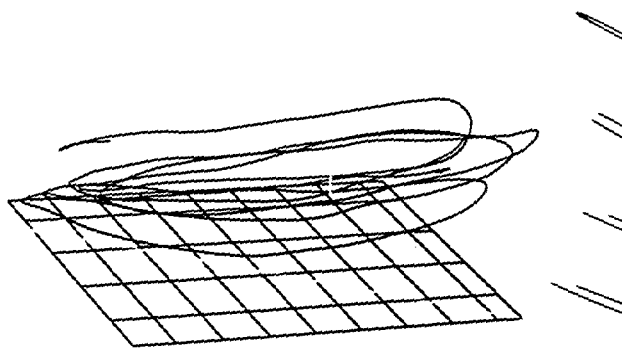

120
100
80
60
40
20
0
Planarity Ratio
Pantomime
Tool Only
Object Only
Tool+Object
Imitation
Condition
control
RHD


100
90
80
70
60
50
40
30
20
10
0
Planarity Ratio
Pantomime
Tool Only
Object Only
Tool+Object
Imitation
Condition
control
LHD

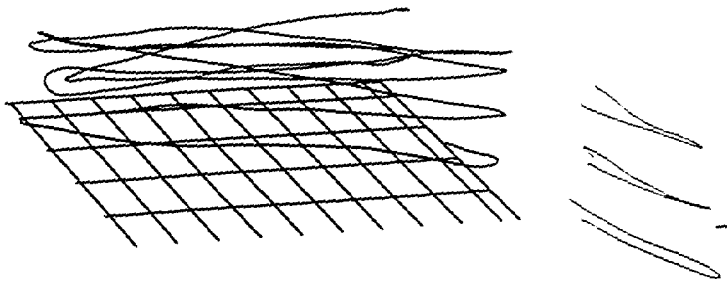
RHD: Pantomime



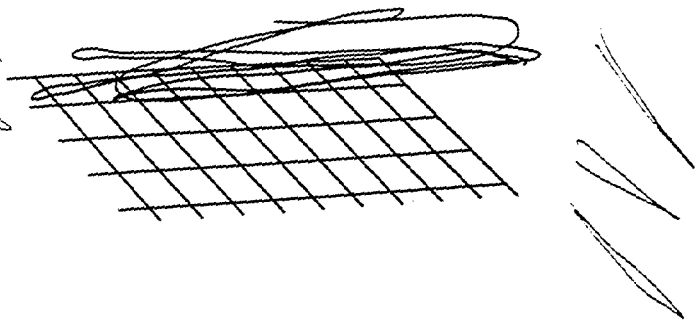
RHD: Tool Only



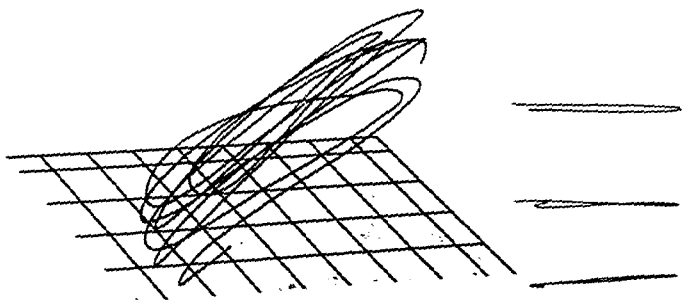
RHD: Object Only

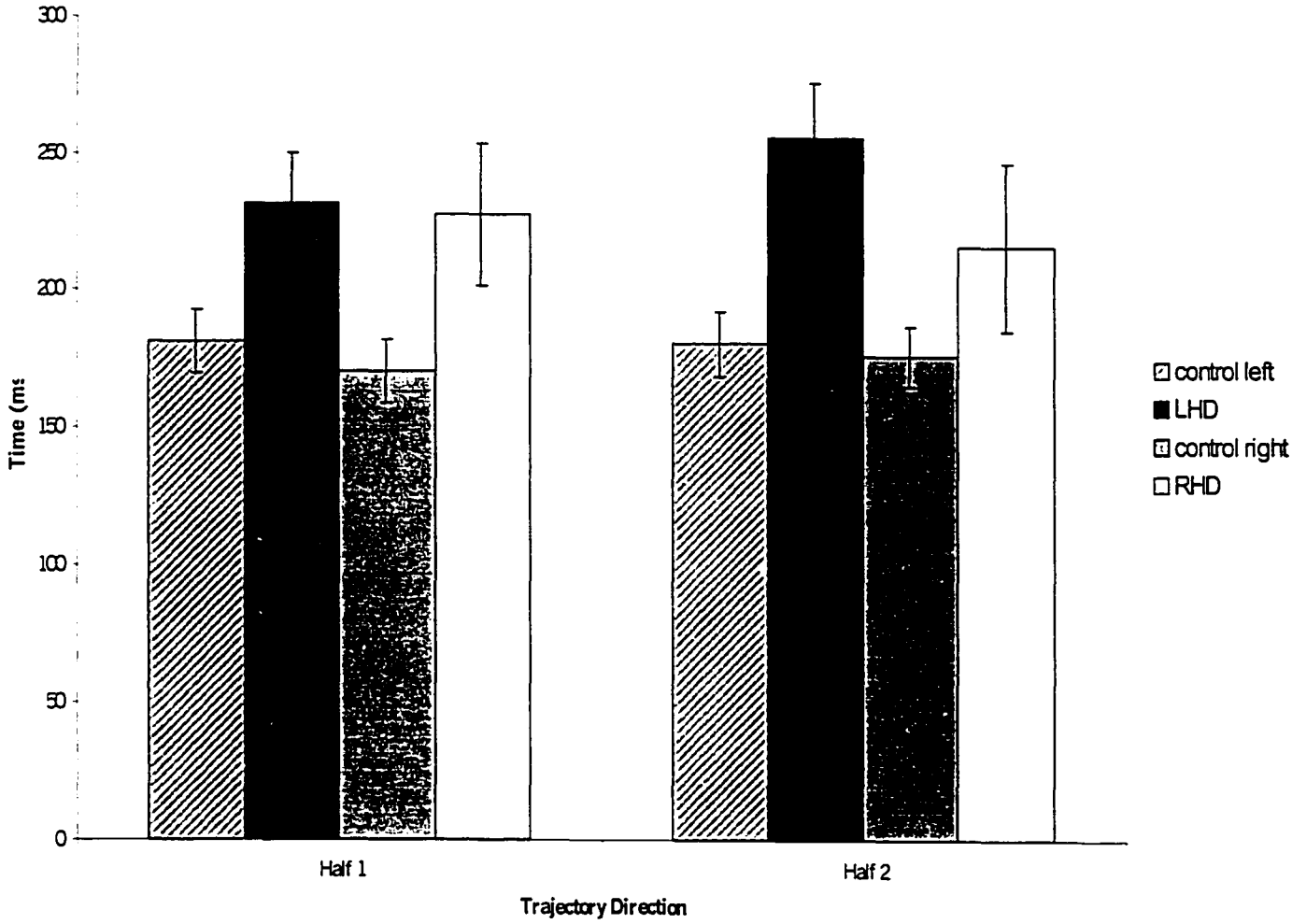


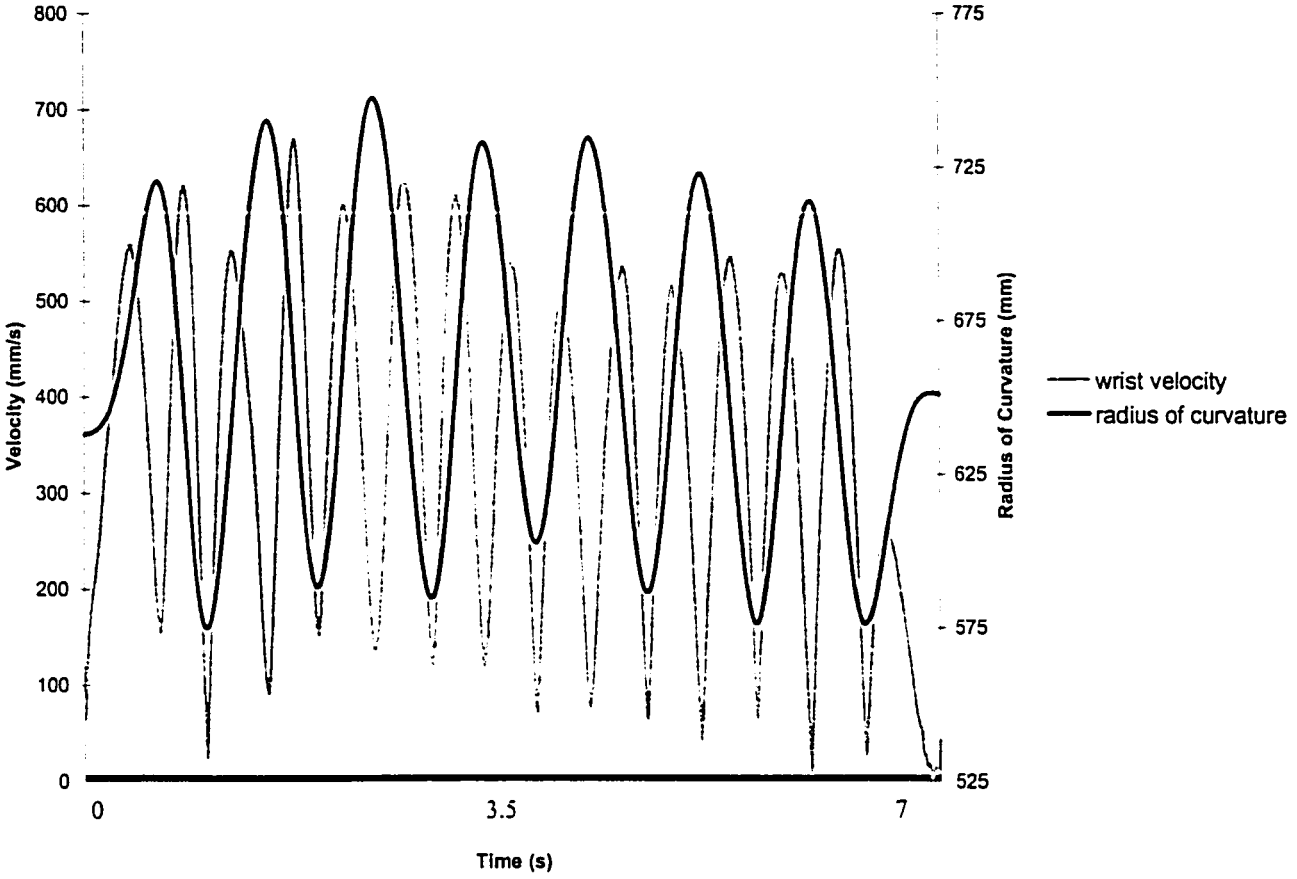
RHD: Tool+Object

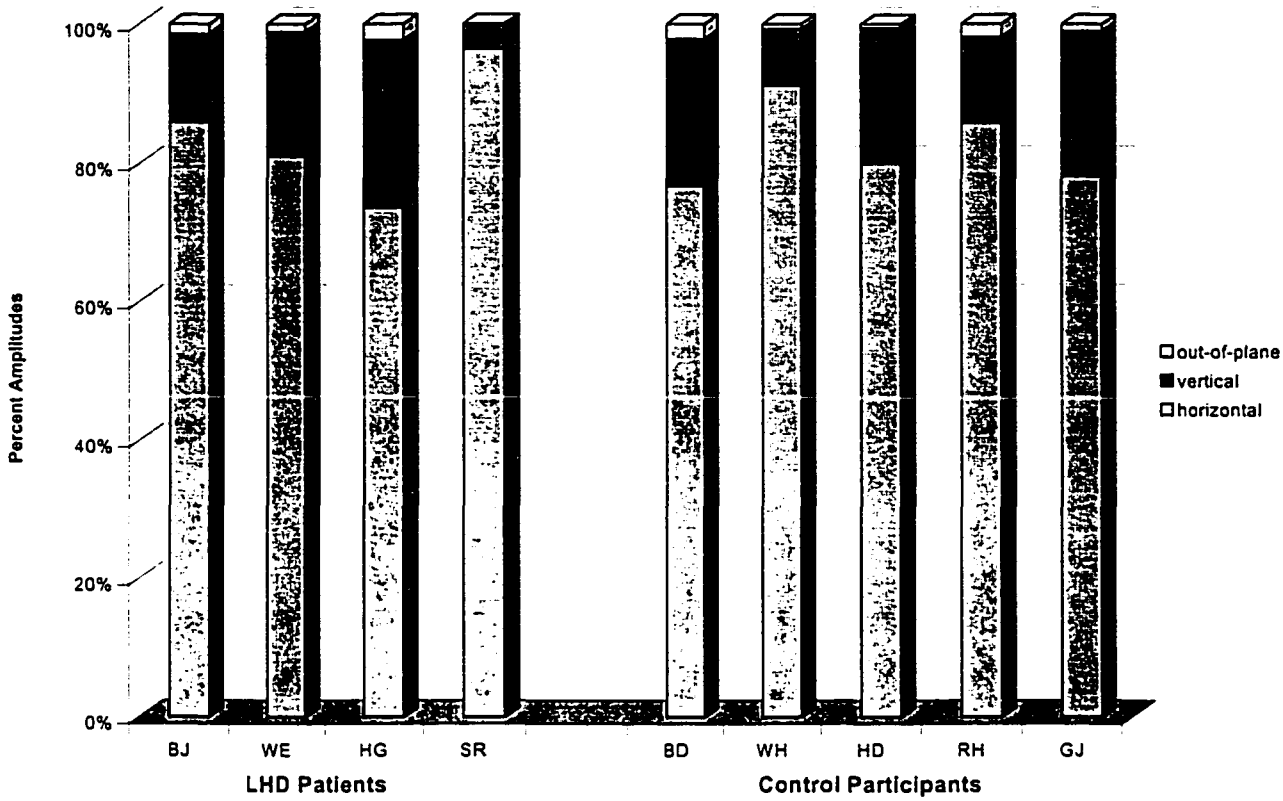


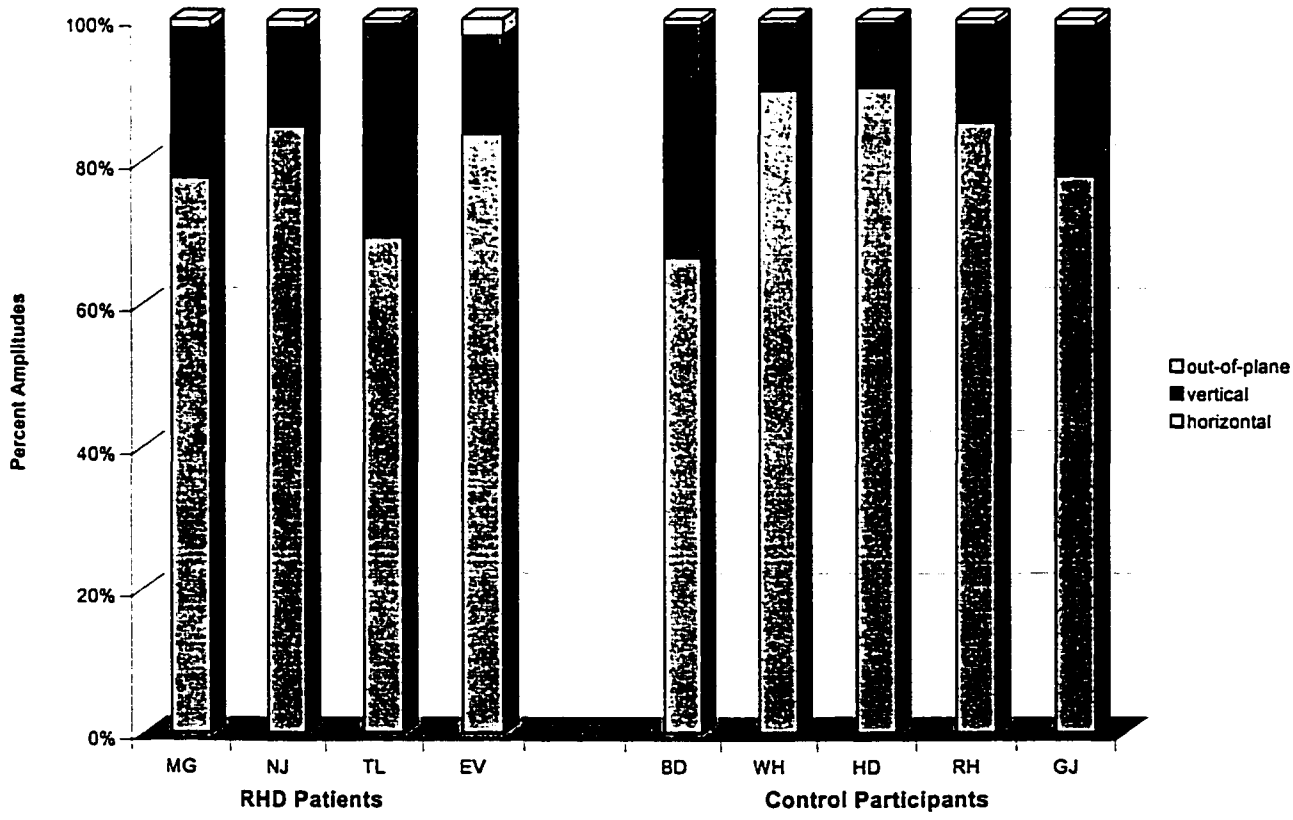
RHD: Imitation




300
250
200
150
100
50
0
Time (ms
Half 1
Half 2
Trajectory Direction
control left
LHD
control right
RHD

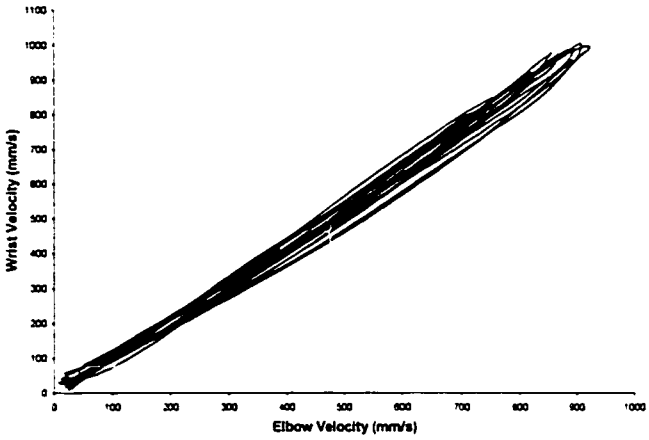

800
700
600
500
400
300
200
100
0
Velocity (mm/s)
775
725
675
625
575
525
Radius of Curvature (mm)
0
3.5
7
Time (s)
wrist velocity
radius of curvature


100%
80%
60%
40%
20%
0%
Percent Amplitudes
BJ
WE
HG
SR
BD
WH
HD
RH
GJ
LHD Patients
Control Participants
out-of-plane
vertical
horizontal

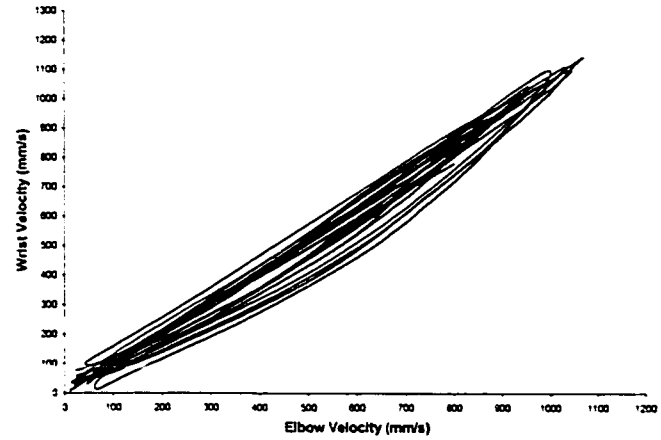

100%
80%
60%
40%
20%
0%
Percent Amplitudes
MG
NJ
TL
EV
BD
WH
HD
RH
GJ
RHD Patients
Control Participants
out-of-plane
vertical
horizontal

Control

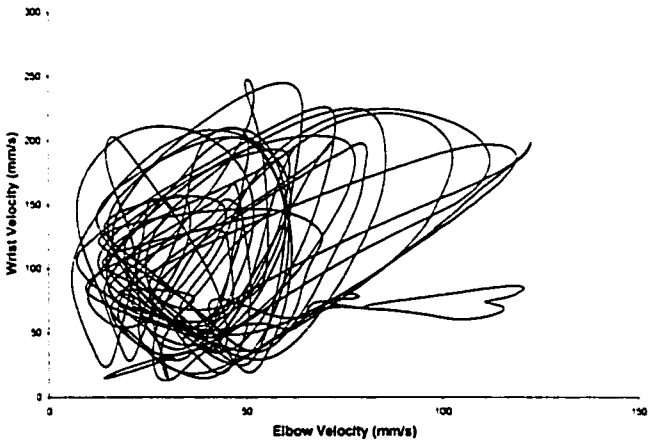
Pantomime

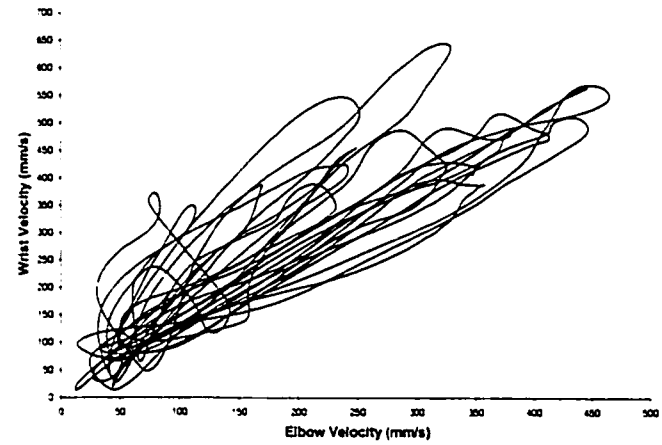


Imitation

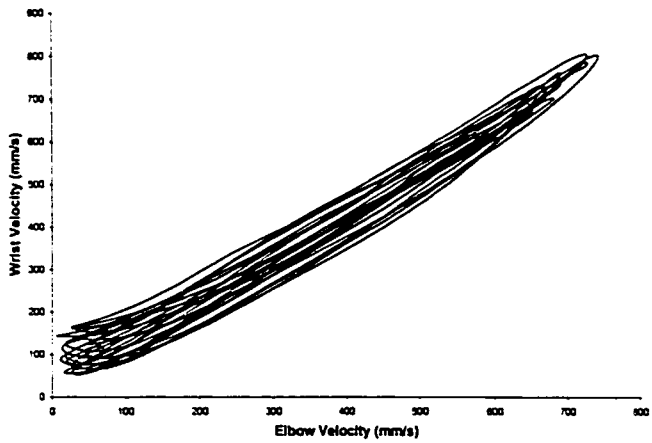


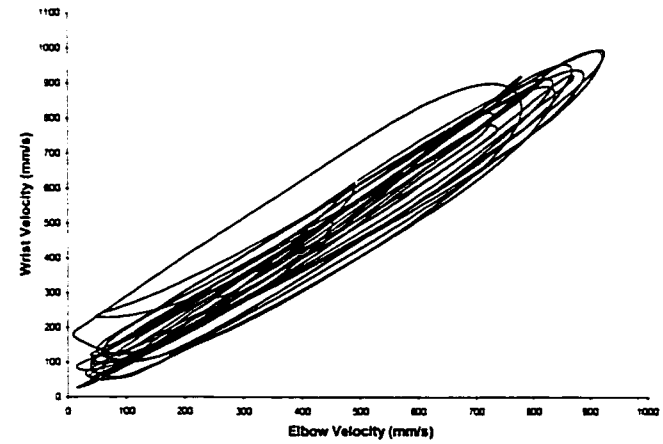
LHD: SE

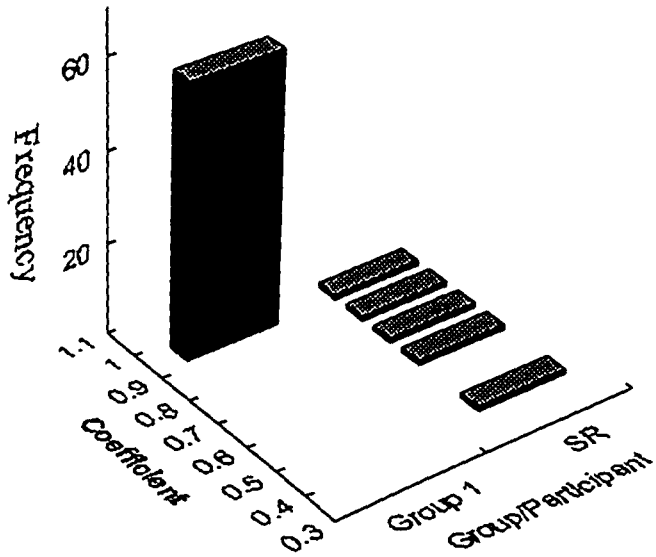


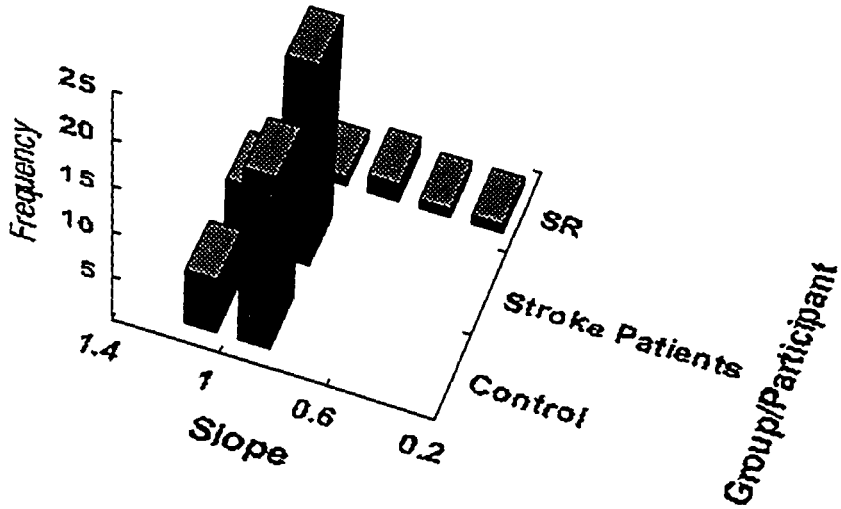


RHD: MW



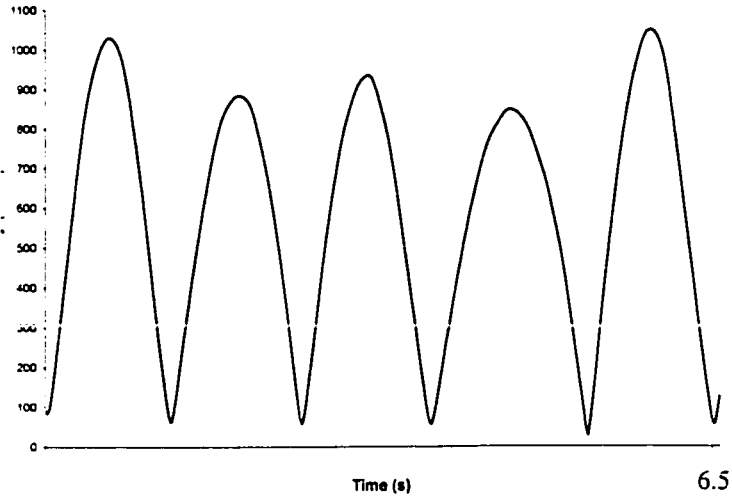



Frequency
60
40
20
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
Coefficient
Group 1
SR
Group/Participant

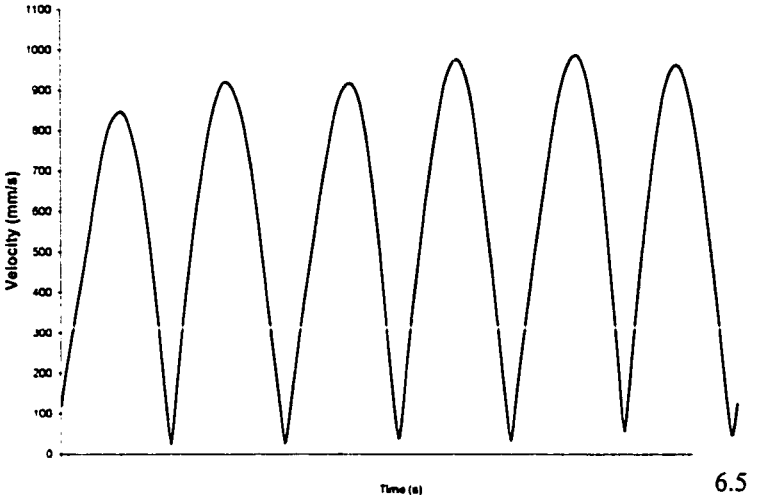

Frequency
25
20
15
10
5
1.4
1
0.6
0.2
Slope
SR
Stroke Patients
Control
Group/Participant

Control: WH

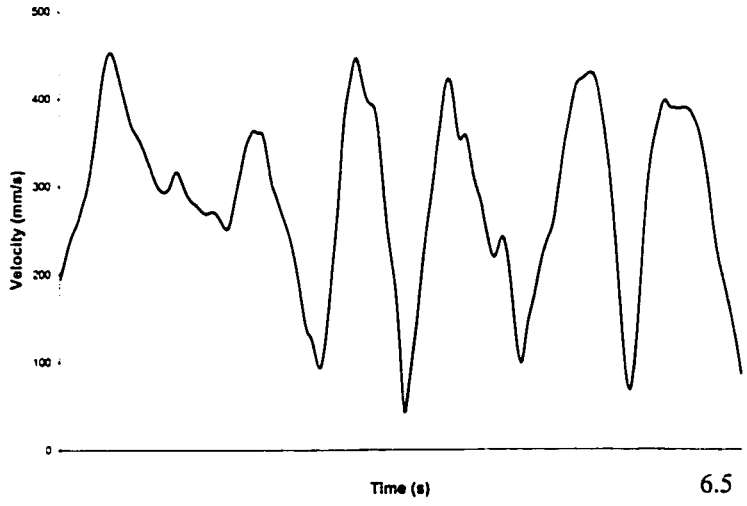
Pantomime

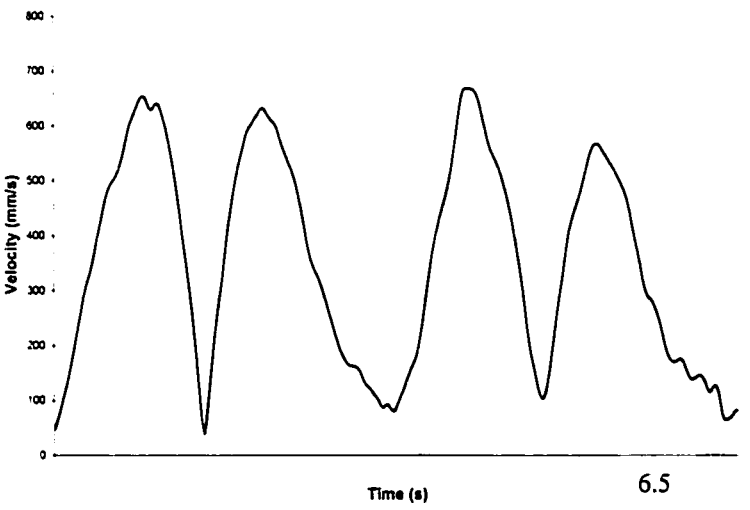


Imitation

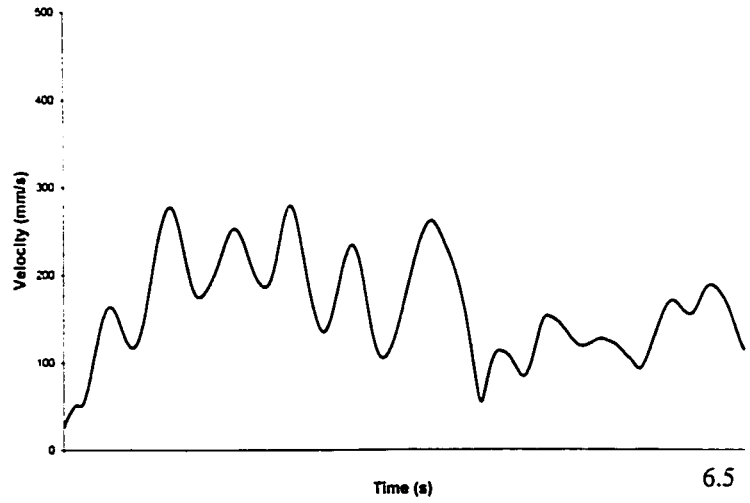


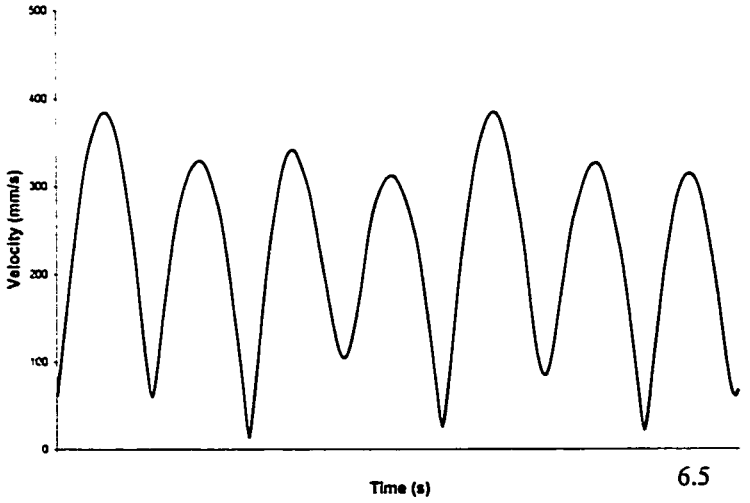
LHD: SR





RHD: EV





GENERAL DISCUSSION

Limb apraxia comprises a wide spectrum of higher-order motor disorders arising from acquired brain disease affecting the performance of learned, skilled, purposeful actions. Central to apraxia doctrine, is the pervasive adherence to Liepmann's (1908) notion that apraxia is a disorder associated with left hemisphere lesions. The present research which examined limb praxis and praxic disorders has demonstrated that limb apraxia is not limited to left hemisphere lesions, but can also be observed following right hemisphere lesions. Central to this understanding was the application of quantitative measurement techniques, in combination with an appreciation of how elicitation modality and gesture forms contribute to the expression of the disorder.

Transitive limb gestures involve the use of tools and/or objects and are reportedly more sensitive to brain damage (Leiguarda & Marsden, 2000) than intransitive (expressive/communication: e.g., saluting an army officer), or nonrepresentational (novel hand posture) limb gestures. This notion served as justification for the first experiment in this research project (Experiment 1), as the frequency and severity of apraxia associated with the pantomime and imitation of transitive limb gestures was examined in a sample of individuals with left or right hemisphere stroke. Previous analyses have consistently reported that left hemisphere stroke more frequently impairs the ability to produce a transitive limb gesture in response to verbal command (Alexander, et al., 1992; Barbieri & De Renzi, 1988; Belanger et al., 1996; De Renzi & Luchelli, 1988; Heilman et al., 1982), whereas imitation deficits are associated with left or right hemisphere stroke (De Renzi et al., 1980; Haaland & Flaherty, 1984). Using the approach of examining pantomime and imitation performance in isolation, the results of Experiment 1 present

findings congruent with previous research, revealing a more frequent occurrence of apraxia in the pantomime condition among LHD patients (LHD = 22 or 48%; RHD = 15 or 28%), and an equal proportion of left and right brain-lesioned patients apraxic in the imitation conditions (LHD = 28 or 61%; RHD = 27 or 51%). Given this type of approach it appears that limb apraxia impairs gestural pantomime more frequently following left hemisphere lesions. Indeed, De Renzi and colleagues (De Renzi & Lucchelli, 1988) and Heilman and colleagues (Heilman et al., 1982) argue that this finding indicates left hemisphere dominance for the representation of learned, skilled actions. However, as proposed by Roy (1996), examining pantomime and imitation performance independently does not provide an opportunity to examine *patterns of apraxia*, or more specifically, identify the mechanisms associated with the failure to pantomime and/or imitate actions.

Examination of the patterns of apraxia described by Roy (1996) suggested that left hemisphere damage alone does not lead to a specific impairment in the response selection/evocation stage of gesture production. LHD patients were not selectively impaired in the pantomime condition, contrary to that hypothesized by De Renzi and colleagues (Barbieri & De Renzi, 1988; De Renzi & Luchelli, 1988; De Renzi et al., 1968). Rather, a significant percentage of LHD patients were impaired concurrently in pantomime and imitation contexts. The considerable number LHD patients demonstrating impaired performance in pantomime and imitation contexts suggests that executive structures are susceptible to impairments following left hemisphere lesions, perhaps indicating left hemisphere dominance for the executive components of gesture production.

Another salient feature from Experiment 1, was the significant number of RHD patients classified as apraxic. Moreover, composite score measures which provided an index of apraxia severity indicated that LHD and RHD patients did not differ in terms of the severity of the disorder. The frequency and severity data fly in the face of traditional apraxia literature citing left hemisphere dominance for the disorder (see Leiguarda & Marsden, 2000 for review). The present findings may reflect the sensitivity of the error notation system used in the present research, and the ability of this system to detect production deficits following RHD. Indeed, the present work, in combination with that of Haaland and colleagues (Haaland & Flaherty, 1984) and Roy and colleagues (Roy et al., 1998) which also employed multi-dimensional error analyses, suggests that this type of measurement technique provides the requisite sensitivity for quantifying gesture production deficits not readily quantified in more qualitative approaches (e.g., De Renzi et al., 1968). Hence, the development of more sensitive clinical tests for the bedside evaluation of apraxia may provide clinicians with the requisite tool for quantifying apraxic movement deficits in RHD patients.

As expressed above, the impetus for examining transitive (tool based) and intransitive (expressive/communicative) gestures separately was based on the assertion that intransitive limb gestures are less sensitive to production errors following stroke. In comparison, transitive limb gestures are purportedly more sensitive to brain damage due to the complexity associated with interacting with external tools and/or object (Leiguarda & Marsden, 2000; Poizner et al., 1998). The second experiment in this research project proposed a new rationale for differentiating between transitive and intransitive gesture forms. Indeed, the case study of KF demonstrated a selective deficit in the

selection/evocation of intransitive limb gestures, without concomitant deficits for transitive limb gestures. Moreover, KF's apraxic deficit could not be attributed to elementary motor or executive-motor deficits, as he was wholly able to imitate transitive, intransitive, and meaningless limb gestures. This case is similar to that of Dumont et al. (1999) who reported an individual selectively impaired when producing transitive limb gestures. Based on these case studies, Experiment 2 proposed a model of gesture production, in which parallel and independent systems support the production of separate gesture forms (transitive vs. intransitive). In this formulation, the selection/evocation and executive stages supporting the production of intransitive limb gestures are functionally independent from similar processes that underlie the production of transitive limb gestures.

The results from Experiment 2 demonstrate the importance of differentiating between different gestures in the evaluation of limb apraxia. However, discriminating between gesture forms has typically not been considered an essential feature of apraxia research, as several investigators have failed to distinguish between gesture forms in their praxis assessment (e.g., Alexander et al., 1992; Barbieri & De Renzi, 1988; De Renzi et al, 1968). Experiment 3 of this research project adopted the notion that a failure to differentiate gesture forms (transitive vs. intransitive) may preclude a firm understanding of apraxia, and whether transitive and intransitive limb gestures differentially impact the expression of the disorder following left or right hemisphere stroke. Hence, Experiment 3 examined the frequency and severity of apraxia associated with the pantomime and imitation of intransitive limb gestures in a sample of patients with left or right hemisphere damage. Moreover, the patterns of apraxia described by Roy (1996) were again

examined to determine the underlying mechanisms associated with the failure to accurately produce intransitive limb gestures.

The results from Experiment 3 indicated that the frequency and severity of apraxic movement deficits among LHD and RHD patients was markedly similar when pantomime performance was examined in isolation (LHD = 39 or 68%; RHD = 40 or 64%). Moreover, an equal number of patients from each group were similarly classified in the imitation condition (LHD = 22 or 38%; RHD = 17 or 37%). Composite score data revealed that the severity of apraxia did not differ among brain-lesioned groups in either pantomime or imitation contexts. The relative equality among LHD and RHD patients in terms of the frequency and severity of apraxia in the pantomime context is a novel finding. Previous research has not reported similar findings however this may reflect: (1) the qualitative nature of praxis evaluation (e.g., De Renzi et al., 1968; De Renzi & Luchelli, 1988; Heilman et al., 1982) and/or (2) the failure of previous investigations to systematically differentiate between gestures forms (e.g., Alexander et al., 1992).

Another issue requiring reconciliation regarding apraxia and intransitive limb gestures is the absence of research concurrently reporting the frequency and severity of the disorder. Previous investigations have typically focussed on describing the observed frequency of apraxia following left or right hemisphere stroke (e.g., Heilman et al., 1982), proposing that LHD should more frequently impair gestural pantomime. Instead of focussing on the frequency of apraxia following left or right brain-lesions, Schnider et al. (1997) examined the severity of gesture production impairments. Schnider et al's findings are congruent with those of Experiment 3, demonstrating that the severity of apraxia is equally marked following left or right hemisphere lesions (pantomiming

intransitive gestures). Although Schnider et al. did not concurrently report frequency data, their results in combination with the frequency and severity data of Experiment 3 provide emergent evidence that LHD or RHD does not differentially contribute to the frequency or degree of praxic disorders.

Recall that in Experiment 1 each patient was ascribed a pattern of apraxia based on their pantomime and imitation performance. This technique was again used, revealing that LHD patients were more frequently classified as apraxic in pantomime and imitation contexts, a finding consistent with an executive impairment, or an ideomotor form of apraxia (Roy, 1996). Indeed, in Experiment 1, twenty (43%) LHD patients and twelve (23%) RHD patients demonstrated this pattern, while Experiment 3 revealed that 17 (30%) LHD patients and 14 (22%) RHD patients were similarly classified. Indeed, the relatively equal number of LHD and RHD patients demonstrating this pattern across Experiments 1 and 3 suggests a disruption to a unitary executive system underlying transitive and intransitive gestures. However, based on the case study of KF (Experiment 2), and more specifically the work of Dumont et al. (1999), demonstrating that transitive and intransitive limb gestures are subserved by independent processing stages (selection/evocation; executive), the relatively stable number of patients concurrently impaired in pantomime and imitation conditions across Experiments 1 and 2 may reflect the neuroanatomical proximity of the processing systems underlying transitive and intransitive limb gestures. Hence, KF and Dumont et al's case study may represent individuals with specific and rare lesions which selectively impaired a specific stage (selection/evocation; executive) and type of gesture (transitive versus intransitive). Although these case studies represent rare instances, they do provide critical theoretical

information regarding the organization and distribution of praxis networks, and further our understanding of how different gestures forms can differentially impact the expression of apraxia.

One finding that differed between Experiments 1 and 3 was the frequency of patients classified in the apraxic to pantomime alone pattern. The number of patients demonstrating this pattern was infrequent in Experiment 1, with a total of five patients demonstrating this pattern (LHD = 2 or 5%, RHD = 3 or 6%). In contrast, forty-eight patients demonstrated this pattern in Experiment 3 (LHD = 22 or 38%; RHD = 26 or 42%). The nature of this difference may relate to the manner in which the pantomime condition was elicited across experiments. In Experiment 1 a verbal command prompted gesture performance (e.g., "show me how to drive a nail"), in addition, participants were provided an opportunity to view the tool (hammer) prior to performance. In contrast, only a verbal command prompted performance in the third experiment (e.g., "show me how to salute an army officer"). The infrequent occurrence of patients exhibiting impaired performance in the pantomime condition alone during Experiment 1 may relate to the fact that pantomiming the action was not strictly reliant upon selecting/evoking the representation of the action from memory. Instead, participants may have performed the gesture correctly based on mechanical knowledge of the tool afforded through visual observation, thereby bypassing the need to select/evoke the representation from memory. Goldenberg (1996; Goldenberg & Hagmann, 1997) demonstrated that affordances provided by visual observation of a tool provide sufficient information for the accurate formation of a transitive limb gesture. As a result, the infrequent occurrence of the pattern reflecting impaired performance to pantomime alone (Experiment 1) may reflect

the presence of two forms of gestural knowledge (mechanical and selection/evocation) which could have been used alone or together to accurately guide the action. Thus, participants may have been selectively impaired in selecting/evoking a gesture from memory, however, vision of the tool precluded the need to access the selection/evocation stage. In contrast to the infrequent number of participants noted in Experiment 1, a considerable number of patients demonstrated this pattern in Experiment 3, perhaps reflecting the strict reliance placed upon the accurate selection/evocation of the representation from memory. Hence, the elicitation of the pantomime condition in Experiment 3 served as a more sensitive index for quantifying the integrity of the selection/evocation stage of gesture production, as a second form of gestural knowledge was unavailable.

Future studies examining gestural pantomime may wish to carefully examine how gestural pantomime is elicited. Indeed, a plethora of research has confounded conceptual (mechanical affordances) and ideational knowledge (Barbieri & De Renzi, 1988; Belanger et al., 1996; De Renzi & Luchelli, 1988; De Renzi et al., 1968; Roy et al., 1998), as verbal instructions and the visual presentation of the tool associated with the action are typically provided when examining the frequency of selection/evocation deficits in this modality. A recommendation from this research project is that future studies examining pantomime performance utilize a condition in which a verbal command serves as the sole element guiding performance (see Experiment 2). This response condition provides the most sensitive modality for indexing selection/evocation deficits, as mechanical knowledge regarding the action is not concurrently provided.

A limitation of the first three studies in this research project was that the spatial and temporal errors associated with apraxia could not be precisely identified through the observational techniques used in this research. To overcome this limitation a three-dimensional kinematic analysis technique was developed to evaluate the spatial parameterization of transitive limb gestures. Poizner and colleagues (Clark et al., 1994; Poizner et al., 1990; 1995) have previously employed kinematic analyses to investigate the spatial temporal errors associated with the production of transitive limb gestures following left hemisphere lesions, and the clinical diagnosis of ideomotor apraxia. Indeed, these studies have detailed spatial, temporal and joint coordination deficits in this population. Lacking in kinematic research, is similar research evaluating kinematic deficits in learned, purposeful actions following right hemisphere lesions. The one published study by Poizner et al. (1998) examining this issue failed to reveal spatial-temporal or joint synchronization errors, thereby supporting the classical interpretation that apraxic deficits are specific to LHD (Rothi et al., 1997). In his investigation, Poizner et al. contrasted the pooled left/right hand performance of control participants to the ipsilesional (right) limb of RHD patients. However, results from Experiment 4 in this research project demonstrate that contrasting the pooled left/right hand performance of control participants to the ipsilesional limb of RHD patients is an inappropriate methodology for quantifying apraxic movement deficits. Experiment 4 revealed a dominant (right) limb advantage for the production of transitive limb gestures in a sample of healthy adults. In particular, the spatial path of the dominant limb was more effective with regard to task goals than the non-dominant limb. The observed right hand superiority noted among healthy adults in Experiment 4 served as the foundation for the

fifth experiment in this research project, which examined the spatial parameterization of a transitive limb gesture in a sample of patients with unilateral left and right hemisphere damage.

A priori it was hypothesized that because healthy controls are more effective when producing transitive limb gestures with their dominant hand, the pooled left/right hand comparison used in Poizner et al's study may have underestimated performance deficits following RHD damage, while overestimating similar impairments among LHD patients. To accommodate this limitation, Experiment 5 contrasted the dominant (right) limb of control participants to the ipsilesional (right) limb of RHD patients. Similarly, the non-dominant (left) limb of control participants was contrasted to the ipsilesional (left) limb of LHD patients.

The results of Experiment 5 failed to denote spatial parameterization errors in either left or right brain-lesioned groups, as the spatial dimensions associated with gesture production were congruent with task demands. Inspite of the fact that group contrasts did not indicate spatial parameterization deficits, one notable feature of this experiment was the observation that one LHD and one RHD patient demonstrated joint synchronization, and temporal regulation errors respectively. The performance of both patients was impaired when gestures were produced on the basis of an internal representation of the action (e.g., pantomime modality), with improved performance noted when an external reference (imitation) guided action. In both cases, the impaired ability to accurately produce a transitive gesture when guided by an intrinsic representation of the action suggests the inappropriate selection/evocation of the action from memory.

The findings from Experiment 5 demonstrate two key elements. Firstly, the observation of a kinematic deficit in a RHD patient supports similar evidence from observational analyses of apraxia (Experiment 1-3). Secondly, the fact that as a group, LHD patients were not significantly impaired on the spatial parameterization of the action demonstrates that LHD alone is not a sufficient condition for the elicitation of apraxia. Instead, these results support those of Haaland et al. (1999) who proposed that the spatial-temporal errors reported by Poizner and colleagues (Poizner et al., 1990) may not be linked to LHD, but ideomotor apraxia in general regardless of lesion location.

The overriding goal of this research project was to provide an understanding of the role(s) of the left and right cerebral hemispheres in praxis. To this end, both hemispheres were found to contribute to praxis, as evidenced by the number of LHD and RHD patients classified as apraxic. Although this assertion is inconsistent with traditional views of apraxia, positing that the disorder arises primarily from left hemisphere damage, the current findings demonstrate that this viewpoint may be subsumed by methodological limitations. Indeed, the present research has shown that focussing on the details of gesture production (multi-dimensional and kinematic analyses), as well as differentiating between gesture forms and elicitation modalities, provides the requisite knowledge for furthering our understanding of the genesis of limb apraxia, and more importantly, left and right hemisphere contributions in praxis. Future research in this area should endeavour to combine multi-dimensional observational and kinematic approaches to extend our knowledge of the mechanisms involved in limb praxis, and the deficits underlying praxic disorders.

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APPENDIX

Appendix A

Schematic representation of a theoretical movement trajectory for an apraxic patient (solid black line [A]). A plane-of-motion for each movement trajectory (grey box [B]) was computed to determine out-of-plane motion and movement planarity. Out-of-plane motion represents the total area of the movement trajectory occurring outside the constructed plane-of-motion, whereas movement planarity represents the amplitude of out-of-plane motion. Subsequent planarity values indicate the root-mean-squared error for individual coordinate values extrinsic to the constructed plane of motion. Three-dimensional path distance represents the 3D amplitude (mm) of each movement trajectory.

