

CROSSED APRAXIA: IMPLICATIONS FOR HANDEDNESS*

A.M. Raymer¹, A.S. Merians², J.C. Adair³, R.L. Schwartz⁴, D.J.G. Williamson⁵,
L.J.G. Rothi^{6,7}, H. Poizner⁸ and K.M. Heilman^{6,7}

(¹Old Dominion University, Norfolk, VA; ²University of Medicine and Dentistry of New Jersey, Newark, NJ; ³University of New Mexico, Albuquerque, NM; ⁴St. Barnabas Institute of Neurology and Neurosurgery, West Orange, NJ; ⁵Auburn University, Auburn, AL; ⁶University of Florida, Gainesville, FL; ⁷VA Medical Center, Gainesville, FL; ⁸Rutgers University, Newark, NJ)

ABSTRACT

Liepmann posited that right hand preference relates to left hemisphere dominance for learned skilled movements. Limb apraxia, impairment of skilled movement, typically occurs in individuals with left hemisphere (LH) lesions. The occurrence of apraxia in right-handed individuals following *right*-hemisphere lesions appears to refute Liepmann's hypothesis. We studied the apraxia of a right-handed man, RF, following a right frontal lesion to determine whether his apraxia paralleled the apraxia seen following LH lesions. Results of behavioral testing indicated that, like individuals with apraxia following left frontal lesions, RF was better at gesture recognition than gesture production which was significantly impaired across tasks. Kinematic motion analyses of movement linearity, planarity, and the coupling of temporospatial aspects of movements substantiated the parallel impairments in RF and patients with LH apraxia. The impairment seen in our patient with crossed apraxia provides evidence for the fractionation of systems underlying hand preference and skilled movement.

Key words: limb apraxia, handedness, kinematics

INTRODUCTION

Ideomotor apraxia is an impairment in the production of skilled limb movements that is not caused by elemental motor, sensory, or cognitive abnormalities and is typically associated with lesions of the left cerebral hemisphere (Geschwind, 1975). Heilman and his colleagues (Heilman, Rothi and Valenstein, 1982; Rothi, Heilman and Watson, 1985) observed an association between limb apraxia and disturbances in gesture recognition in individuals with posterior lesions of the left hemisphere, and proposed that memories for skilled movements are stored in the left parietal region. In contrast, patients with anterior lesions of the left hemisphere had limb apraxia, but they did not have problems with gesture recognition.

More recently, Rothi, Ochipa and Heilman (1991) proposed a distributed model of praxis processing incorporating modules for movement representation (action input and output praxicons) and for implementation of skilled movements

*Portions of this paper were presented at meetings of the Society for Neuroscience, Washington, D.C., November, 1996, and the International Neuropsychological Society, Orlando, FL, February, 1997.

(innervatory patterns). Impairments of praxis processing among subjects with acquired brain damage suggest that the left hemisphere plays the primary role in mediating this complex array of mechanisms. More specifically, Rothi and her coworkers suggested that anterior left hemisphere regions play a critical role in the implementation stages for the production of skilled movements, and posterior regions are important for representational stages of praxis processing.

Liepmann (1905) noted that in right-handed individuals, ideomotor apraxia is associated with left cerebral hemisphere lesions. This observation led Liepmann and Maas (1907) to propose that the left hemisphere maintains the space-time memories for skilled movements and, further, that it is the asymmetric representation of movement memories that may account for hand preference (Geschwind and Galaburda, 1985; Heilman, 1997). When acquiring a new manual skill, the right hand, unlike the left, has direct access to the portions of the brain that store the time-space movement representations. When performing a skilled movement, the movement representations stored in the left hemisphere have most direct access to the left motor cortex which controls the right hand by way of the crossed corticospinal pathway. Thereby the right hand is dominant for performing skilled manual actions. However, there have been reports of right-handed individuals who, following a *right* hemisphere lesion, had impaired gesture production or “crossed apraxia”. Some individuals had crossed apraxia in the presence of normal language processing (Alexander and Annett, 1996, case 9; Marchetti and Della Sala, 1997; Mozaz, Marti, Carrera et al., 1990). More often researchers have described crossed apraxia occurring in conjunction with crossed aphasia (Assal, Perentes and Deruaz, 1981; Basso, Capitani, Laiacona et al., 1985; Berthier, Starkstein and Leiguarda, 1987; Cappa, Perani, Bressi et al., 1983; Perani, Papagno, Cappa et al., 1988; Rapcsak, Rothi and Heilman, 1987; Starkstein, Berthier and Leiguarda, 1988). Individuals with limb apraxia which develops following a right hemisphere lesion appear to violate Liepmann’s (1907) hypothesis and suggest that hand preference may not be entirely related to the laterality of skilled movement representations.

Although the right hemisphere may have an important role in the production of skilled movements in individuals with crossed apraxia, the left hemisphere still may play the major or dominant role. If the right hemisphere of patients with crossed apraxia plays the dominant role in movement programming, the pattern of impairment with right hemisphere lesions should parallel the apraxia typically associated with left hemisphere (LH) lesions. However, if the right hemisphere has a different role in the production of skilled movement, the error pattern associated with crossed apraxia should diverge from that typically associated with LH lesions.

The errors in gesture production and comprehension produced by individuals with crossed apraxia have not been well-characterized and contrasted with the error pattern typically observed in the LH presentation of limb apraxia (Alexander and Annett, 1996; Assal et al., 1981; Basso et al., 1985; Mozaz et al., 1990; Marchetti and Della Sala, 1997). One study described the error pattern of an individual with crossed apraxia in greater detail (Rapcsak et al., 1987). In gesturing to viewed objects and gesture imitation, their patient’s apraxia errors evolved over the course of eight weeks from primarily perseverative gestures at

onset, to a pattern of numerous spatial and body-part-as-object errors, in keeping with the types of errors typically seen in individuals with apraxia following LH lesions (Maher, Rothi and Heilman, 1997). Performance in tasks of gesture recognition was not evaluated.

In recent years researchers have developed advanced methods for studying limb apraxia. Rothi and colleagues (Rothi et al., 1988; Rothi, Raymer and Heilman, 1997) have constructed an extensive battery of cross modal gesture tasks and have described an elaborate gesture error coding systems that is sensitive to the content of the gesture as well as temporal and spatial aspects of gesture production. Poizner and his colleagues (Poizner, Wooten and Salot, 1986; Poizner et al., 1990; Clark, Merians, Kothari et al., 1994; Poizner, Clark, Merians et al., 1995) have developed a system for three-dimensional motion analysis of gesture production and have applied this technology to the study of limb apraxia in left hemisphere lesions. In this paper we describe an individual with severe crossed apraxia whose gesture processing we recently studied using these sensitive techniques for analysis of limb apraxia.

CASE DESCRIPTION

Our patient, RF, a 50 year old right-handed salesman with 15 years of education, sustained a right hemisphere cerebral infarction leading to left hemiparesis, emotional aprosodia, aphasia, and limb apraxia. When queried about a variety of skilled manual activities based on versions of handedness questionnaires, RF reported that he had always used his preferred right hand for all activities since childhood. Both elderly parents who also were alive reported that they too were fully right-handed and never were forced to change handedness in childhood. RF's two siblings also were right-handed. RF's parents confirmed that he always was right-handed and never incurred an injury during childhood that caused him to change handedness.

RF completed standardized aphasia testing one month post stroke onset. On the *Western Aphasia Battery* (Kertesz, 1982), his aphasia quotient was 79.8/100 and he demonstrated a pattern consistent with transcortical motor aphasia. He was severely nonfluent and aprosodic in his spontaneous utterances, but demonstrated retained repetition abilities with intact phonologic production. He evidenced moderate anomia, scoring 33/60 on the *Boston Naming Test* (Kaplan, Goodglass and Weintraub, 1983) which is significantly poorer than expected for his age and education. On a test of controlled oral word association (F, A, S) (Borkowski, Benton and Spreen, 1967), RF produced a total of 7 words in three minutes, which is far below expected levels. In the Florida Apraxia Screening Test-Revised (Rothi, Raymer, Ochipa et al., 1990) in which subjects produce 20 transitive and 10 intransitive gestures to verbal command, RF correctly produced only 9/30 gestures with his right arm/hand, indicating a significant crossed apraxia compared to normal levels of performance (cutoff score = 15/30) (Rothi et al., 1997).

RF's right hemisphere lesion viewed on an MRI completed two months post-stroke was mapped onto computerized images (Damasio, 1995). The lesion shown in Figure 1 involved a large portion of right dorsolateral frontal cortex (Brodmann's areas 4, 44, 45, 47) extending posteriorly to the postcentral gyrus (Brodmann's area 3, 1, 2), as well as patchy involvement of subcortical white matter.

We completed measurements of brain asymmetry using methods described by Pieniadz and colleagues (Pieniadz, Naeser, Koff et al., 1983; Pieniadz and Naeser, 1984). The angle of slices in RF's MRI varied from the slices described in the Pieniadz methods, therefore we measured slices representing full views at two frontal and four occipital planes. Frontal width and length was greater on the left than on the right, and occipital width and length was greater on the right than on the left. Therefore RF demonstrated a pattern of brain asymmetry opposite that seen in the majority of right-handed individuals.

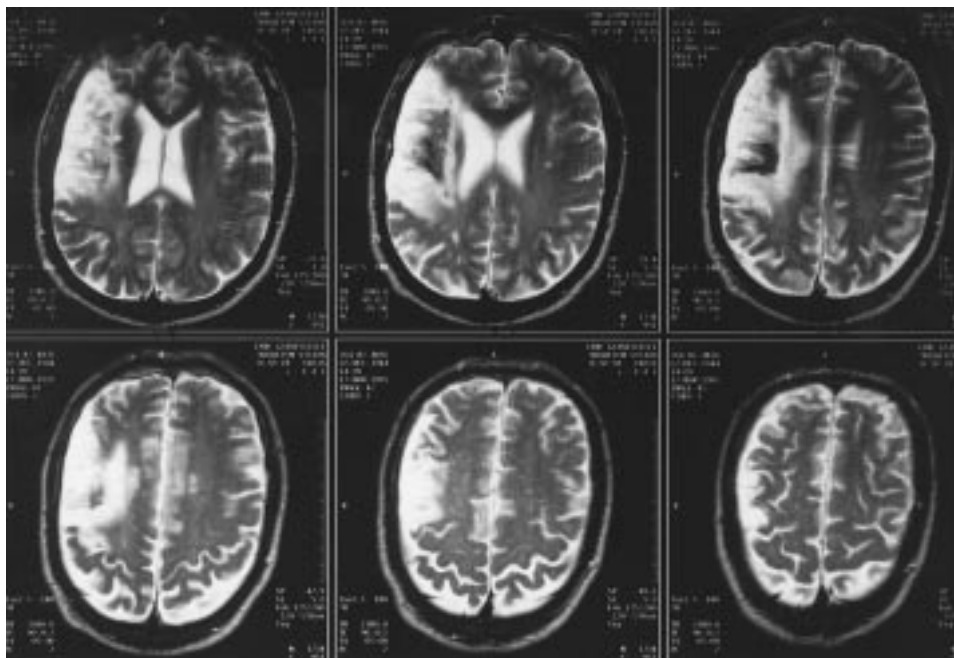


Fig. 1 – Magnetic resonance images of RF's right hemisphere lesion taken two months after his stroke.

EXPERIMENT 1: BEHAVIORAL TESTING FOR APRAXIA

The Florida Apraxia Battery

Four months following his stroke, RF completed the Florida Apraxia Battery (Rothi et al., 1990, 1997), a series of tasks designed to evaluate gesture processing with respect to a cognitive neuropsychological model of the praxis system (Rothi et al., 1991). The tasks incorporated the same basic set of stimuli: 20 transitive gestures for tool pantomimes (e.g. hammer, pencil), 10 intransitive gestures representing common emblems (e.g. salute, good-bye), and 20 meaningless gestures developed by modifying familiar gestures by one dimension to create unrecognizable gestures. The gesture processing tasks included:

(1) Gesture Recognition (transitive and intransitive gestures): RF matched a spoken word to one of three viewed gesture choices which included the target gesture (e.g. hammering) and two gesture foils consisting of either a different but well-performed semantically-related gesture (e.g. turning a screwdriver) or poorly-performed versions of the target gesture that had a temporal or spatial aberration (e.g. hammering at varying locations in space).

(2) Gesture to Word Matching (transitive and intransitive gestures): RF viewed a gesture (e.g. hammering) and then selected the corresponding word from among three choices including the target gesture word (e.g. hammer), semantically-related word (e.g. screwdriver), and a word corresponding to a visually-similar gesture (e.g. ice pick).

(3) Gesture to Verbal Command (transitive and intransitive gestures): RF produced gestures corresponding to commands spoken by the examiner.

(4) Gesture to Viewed Tool (transitive gestures): RF viewed a tool (and did not touch it) and then provided the appropriate gesture.

(5) Gesture Imitation (transitive, intransitive, and meaningless gestures): RF viewed gestures on a video monitor and then imitated each gesture.

In the three gesture production tasks, examiners videotaped RF as he produced gestures with his preferred right hand. He was unable to use his weakened left hand to produce gestures. Three trained scorers independently coded RF's videotaped gestures as to accuracy and error type using a system of gesture error coding developed by Rothi et al. (1988). Errors included temporal/spatial errors (e.g. aberrations in the external spatial placement of the gesture, inappropriate coupling of limb joints and directions of movements during actions, wrong internal hand configuration including the use of body-part-as-tool errors), content errors (the production of completely different recognizable gestures), and unrecognizable gestures. A correct response was a gesture that was accurate in content and temporal/spatial aspects of the movement. The three scorers reached consensus for items in which there were disagreements in coding.

Results

Table I displays percent correct performance for each of the experimental tasks. RF recognized gestures well, although in gesture recognition and matching tasks, he made occasional errors for transitive stimuli. In contrast, performance was uniformly poor across the three gesture production tasks. RF performed transitive gestures more poorly than intransitive gestures, although this difference was significant only in the gesture to command task (Fisher Exact Test, $p < 0.00$). He was equally poor at imitating real and meaningless gestures.

Table II displays the pattern of errors across the three gesture production tasks. The majority of gesture responses across tasks (45-70%) incorporated recognizable but significantly degraded gestures produced with temporal/spatial aberrations related to combinations of errors (incorrect joint movement, incorrect internal hand configuration including some use of body-part-as-tool, and

TABLE I
Percent Correct Performance across Gesture Comprehension and Production Tasks Overall and for Transitive, Intransitive and Meaningless Gestures

	(1) Recog. (n = 30)	(2) Matching (n = 30)	(3) Command (n = 30)	(4) Viewed (n = 20)	(5) Imitate (n = 50)
Overall	83.3%	83.3%	30%	20%	26%
Transitive (n = 20)	75%	75%	5%	20%	20%
Intransitive (n = 10)	100%	100%	80%	—	50%
Meaningless (n = 20)	—	—	—	—	20%

TABLE II
Response Patterns in Three Gesture Production Tasks

	Correct responses	Temporal/spatial errors	Unrecognizable responses	Content errors
Gesture to command				
Transitives	5%	70%	20%	5%
Intransitives	80%	0	0	20%
Gesture to viewed tool				
Transitives	20%	45%	35%	0
Gesture imitation				
Transitives	20%	60%	20%	0
Intransitives	50%	50%	0	0
Nonmeaningful	20%	60%	20%	0

inappropriate external spatial location of intended gestures). In 20-35% of gestures, the movement and spatial characteristics of the responses were so severely degraded as to render the gesture unrecognizable. Content errors were infrequent, with more occurring in intransitive gesture to command than in any other condition.

We monitored RF's performance in gesture to command for the 20 transitive gestures as part of a study of his language recovery over the course of six months. We observed no improvement in gesture production as performance ranged only 0-15% correct. No change was evident in his gesture error pattern as RF continued to produce gestures with marked aberrations related to spatial location, joint movement, and hand configuration including some unrecognizable gestures.

EXPERIMENT 2: THREE-DIMENSIONAL MOTION ANALYSES

In addition to the behavioral analysis of gestures, RF participated in experiments in which his gestures were assessed using three-dimensional motion analyses. To our knowledge this represents the first evaluation of an individual with crossed apraxia using kinematic techniques which allow quantitative comparison of RF's gesture performance to individuals with limb apraxia after left hemisphere injury.

Subjects

We compared RF's gesture performance to that of a group of subjects with apraxia consequent to left hemisphere damage (LH) who were reported elsewhere (See Clark et al., 1994, for detailed case histories and MRI lesion analyses for the LH subjects). The LH group consisted of three subjects, two males (RS and CS) and one female (MR), whose ages ranged from 66 to 72 years. Each subject had sustained a cerebral infarct and neuroimaging indicated lesions in the left posterior regions. Each LH subject demonstrated ideomotor apraxia during clinical examination with the Florida Apraxia Screening Test (FAST) (Rothi and Heilman, 1984). The LH subjects were right-hand dominant as determined by pre-stroke writing preference. An additional neurologically-normal comparison group consisted of four male subjects, aged 51-65 years. All subjects provided informed consent to participate in the research.

Procedures

Three-dimensional movement analyses were done as the subjects performed the gesture of "slicing bread". This transitive movement which requires the use of a tool is commonly impaired in patients with ideomotor apraxia (Clark et al., 1994; Poizner et al., 1995; Raymer et al., 1997). In the first condition, the subjects produced the slicing gesture to verbal command, whereas in the second condition they used a knife to actually slice bread. The skilled learned movement of slicing bread is a cyclical forward and backward motion characterized by sharp reversals and overlapping planes of movement across cycles. In addition, the trajectory shape of successful motion should be both linear and planar.

In order to eliminate the effects of primary motor or sensory damage in the brain lesioned subjects, the LH apraxia subjects used their left upper extremity and the crossed apraxia subject used his right upper extremity to perform the gesture. To control for hand dominance, we tested the normal subjects using their right hand and then using their left hand to slice. The position of four light emitting diodes secured to the shoulder, elbow,

wrist and hand were sampled at 100 Hz from neighboring views by two optoelectric cameras (Northern Digital, Inc., Waterloo, Canada), then low pass filtered with a modified Butterworth filter using a cut-off frequency of 8 Hz. The three-dimensional trajectories were reconstructed and analyzed graphically and numerically as described elsewhere (Kothari, Poizner and Figel, 1992; Jennings and Poizner, 1988; Poizner et al., 1986).

Kinematic Analyses

Kinematic analyses were performed on movement linearity, movement planarity (degree of restriction of movement to a single plane), and velocity-curvature coupling (temporal correspondence between path curvature and movement speed) for all wrist paths as described in earlier publications (Clark et al., 1994; Poizner et al., 1990).

The slicing gesture, when appropriately performed, requires precise coordination between motion at the shoulder and the elbow. Analysis of interjoint coordination involved computing the relative arm angle amplitudes for motion of the upper arm and forearm in the horizontal and vertical planes (for detailed descriptions of this arm coordinate system and arm angle computations, see Soechting and Ross, 1984; Soechting and Terzuolo, 1986; Poizner and Soechting, 1992; Poizner et al., 1995).

Statistical Analyses

The Kruskal-Wallis non-parametric statistic (H) for more than two groups was used to compare distributions of normal controls, subjects with LH apraxia and our subject with crossed apraxia, RF, as this statistic avoids the assumption of normal distribution and the need for relatively equal variance across data sets. In addition, non-parametric statistics are relatively unaffected by single outlier values. A stringent alpha level ($p < 0.01$) was selected due to the number of comparisons computed. Post-hoc tests of differences between pairs of groups using two-tailed z values were performed on those parameters having significant Kruskal-Wallis values.

Results

Linearity

The upper and lower panels of Figure 2 present the mean ratios and standard errors for movement linearity for the control subjects (hatched lines), the crossed apraxia subject RF (gray), and the LH apraxia subjects (black) for the two movement conditions. Figure 2 shows that the control subjects produced linear trajectory paths both when performing the slicing gesture to command and when using the knife to cut the bread. In contrast, the trajectory paths of both the LH subjects and RF, the crossed apraxia subject, were less linear and more curved. This pattern was evident when these subjects produced the movement to verbal command and when they used the tool to actually slice the bread (see Table III for results of the statistical analysis) and reflect the fact that the apraxia subjects lack appropriate coordination between joint movements to maintain a linear course throughout the slicing activity.

Planarity

The upper and lower panels of Figure 3 present the mean ratios and standard errors for movement planarity for the same subjects and the same cue conditions. Results show that the control subjects were able to maintain the high

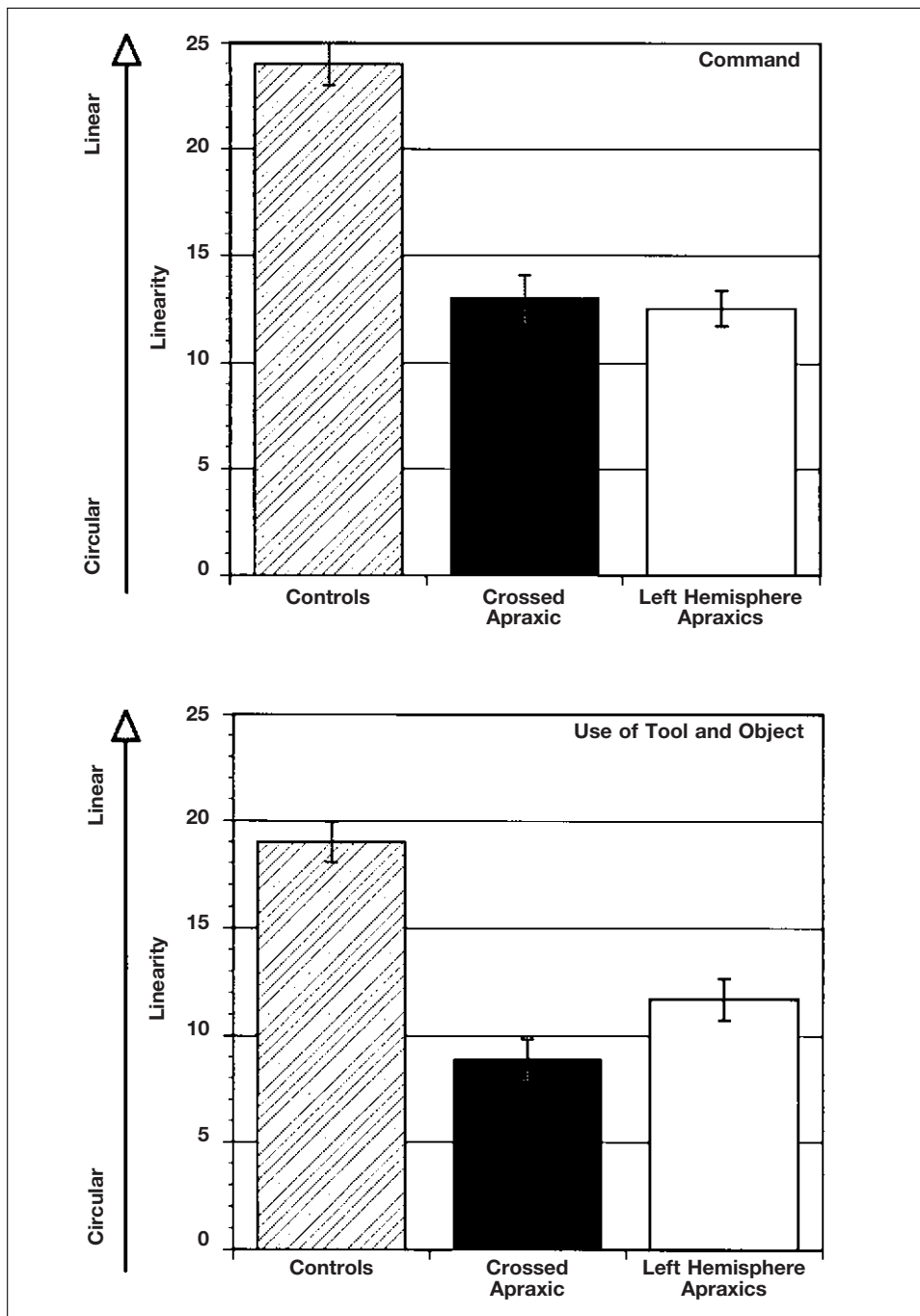


Fig. 2 – Movement linearity ratios for the control subjects, the left hemisphere lesion apraxia patients, and the patient with crossed apraxia for the verbal command condition (top) and the use of tool and object condition (bottom). The height of each bar represents the mean linearity ratio and error bars represent one standard error of the mean.

TABLE III
Results of Statistical Comparisons among Subjects with Crossed Apraxia (Cros), Apraxia Following Left Hemisphere Damage (Lhd) and Normal Controls (Cont) in Three-Dimensional Movement Analyses

	Command						Both						
	Cont		LH		LH		Cont		Cont		LH		Kruskal Wallis
	vs	sig	vs	sig	vs	sig	vs	sig	vs	sig	vs	sig	
Linearity	sig	sig	n.s.	n.s.	sig	sig	sig	sig	n.s.	n.s.	n.s.	Cros = 6.91 Lhd = 9.50 Cont = 17.00	H = 113.48 d.f. = 354, 138, 72 p < 0.001
Planarity	sig	sig	n.s.	n.s.	sig	sig	sig	sig	n.s.	n.s.	n.s.	Cros = 31.46 Lhd = 34.15 Cont = 57.88	H = 44.79 d.f. = 153, 77, 36 p < 0.001
Velocity curvature	sig	sig	n.s.	n.s.	sig	sig	sig	sig	n.s.	n.s.	n.s.	Cros = 10.00 Lhd = 10.00 Cont = 0.00	H = 105.23 d.f. = 307, 260, 120 p < 0.001
Theta/Beta	sig	sig	n.s.	n.s.	sig	sig	sig	sig	n.s.	n.s.	n.s.	Cros = 0.42 Lhd = 0.27 Cont = 1.21	H = 134.52 d.f. = 299, 117, 81 p < 0.01
Alpha/Eta	sig	sig	n.s.	n.s.	sig	sig	sig	sig	n.s.	n.s.	n.s.	Cros = 1.42 Lhd = 0.94 Cont = 0.32	H = 208.75 d.f. = 299, 117, 81 p < 0.001
Alpha/Phi	sig	sig	sig	sig	sig	sig	sig	sig	sig	sig	sig	Cros = 0.39 Lhd = 0.75 Cont = 0.28	H = 146.81 d.f. = 299, 117, 81 p < 0.001
Phi/Beta	sig	sig	n.s.	n.s.	sig	sig	sig	sig	sig	sig	sig	Cros = 0.54 Lhd = 0.66 Cont = 3.70	H = 322.88 d.f. = 299, 117, 81 p < 0.001

* p < 0.05

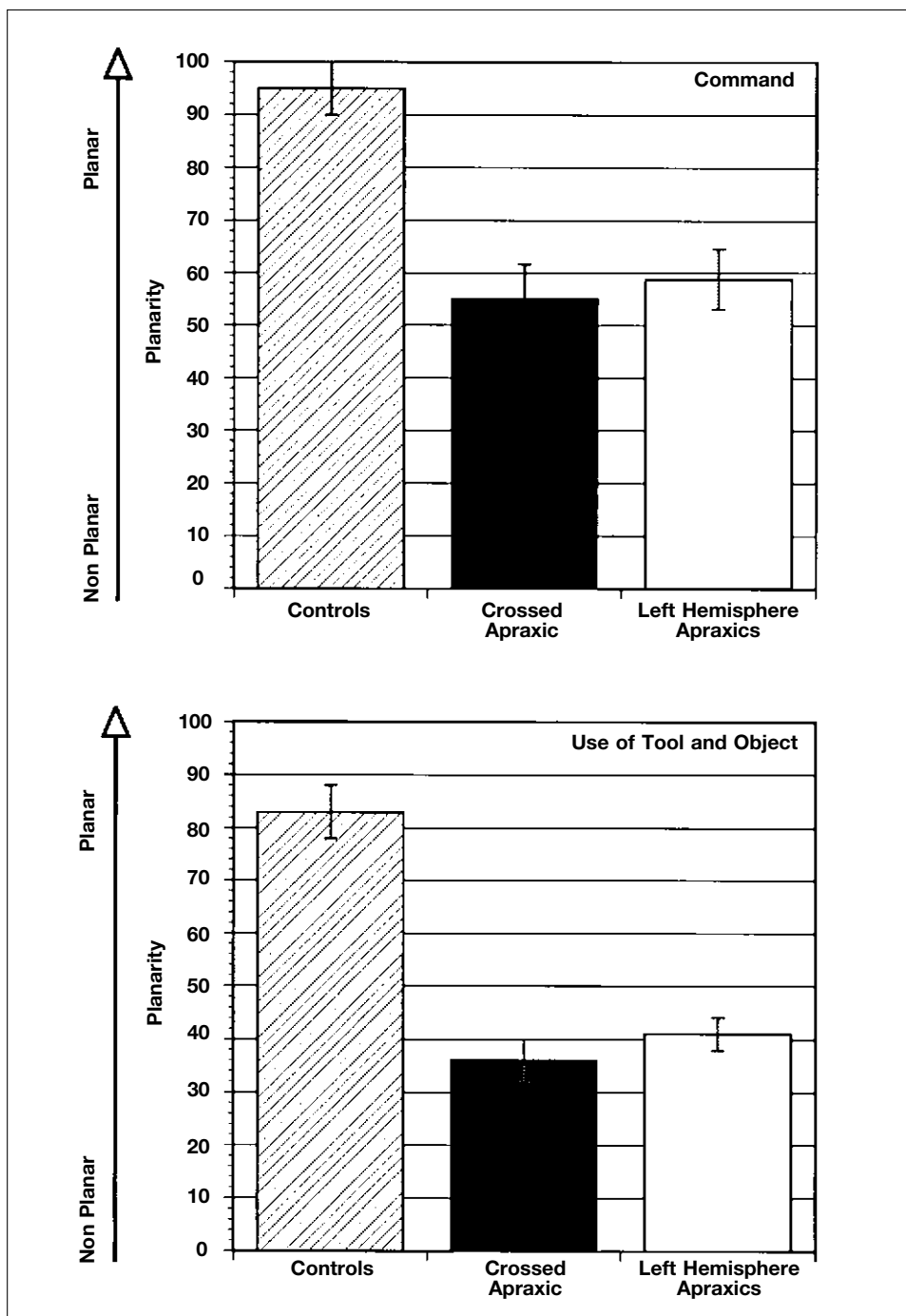


Fig. 3 – Movement planarity ratios for the control subjects, the left hemisphere lesion apraxia subjects, and the subject with crossed apraxia for the verbal command condition (top) and the use of tool and object condition (bottom).

degree of planarity in the wrist trajectory both when performing to verbal command and with the knife in hand by making proper adjustments among joints to remain within an established slicing plane through the course of the movement. In contrast, the movement planarity ratios show that RF and the LH apraxia subjects were significantly less planar than the control subjects for both the command condition and when using the knife as seen in Figure 3 and Table III. The trajectory paths of the crossed apraxia subject and the LH apraxia subjects were significantly different from that of the controls, but similar to each other in the aberrant shape of the movement.

Velocity-Curvature Coupling

In normal movement patterns, a strong relationship exists between the spatial path of the wrist trajectory and the time sequence of this path. The upper panel of Figure 4 shows a representative profile of tangential wrist velocity (black lines) and radius of curvature (gray lines) for one control subject (JM), the crossed apraxia subject (RF), and one LH apraxia subject (CS) for the verbal command condition. The time correspondence for velocity minima and radius of curvature minima are plotted in the lower panels. Figure 4 shows that the time correspondences between the minima in the velocity profile and the peaks in the curvature profile are matched for the control subject, indicating a strong linkage between velocity and curvature; as the radius of curvature of the wrist trajectory increased for this subject, the velocity increased. Points of peak curvature occurred at points of minimal velocity. In comparison, the center and right panels show that both the LH apraxia subject and the crossed apraxia subject had a marked decoupling of velocity and curvature leading to aberrant spatiotemporal relationships in their wrist trajectories. In both the command condition and when they used the knife, each of these groups differed significantly from the control subjects, but not from each other (Table III).

Interjoint Relationships

Figure 5 presents histograms of the relative amplitudes of four pairs of arm angles for the control subjects (hatched), the LH apraxia patients (white), and the patient with crossed apraxia (black) for the slicing gesture performed to verbal command. The arrows in the figure indicate median ratios. Figure 5 presents the ways in which subjects apportioned the relative amplitudes of horizontal motion of the forearm (α) to horizontal motion of the upper arm (η) (upper left panel), of vertical motion of the upper arm (θ) to that of the forearm (β) (lower left panel), of horizontal motion of the forearm (α) to elbow flexion-extension (ϕ), and of elbow flexion-extension (ϕ) to motion of the forearm in the vertical plane (β). Figure 5 and Table III show that, in general, the crossed apraxia patient apportioned the relative motions of his limb segments in a manner similar to that of the patients with LH apraxia and different from that of the control subjects. Thus, RF showed deficits in interjoint coordination, and did so in a manner similar to that of the LH apraxia patients.

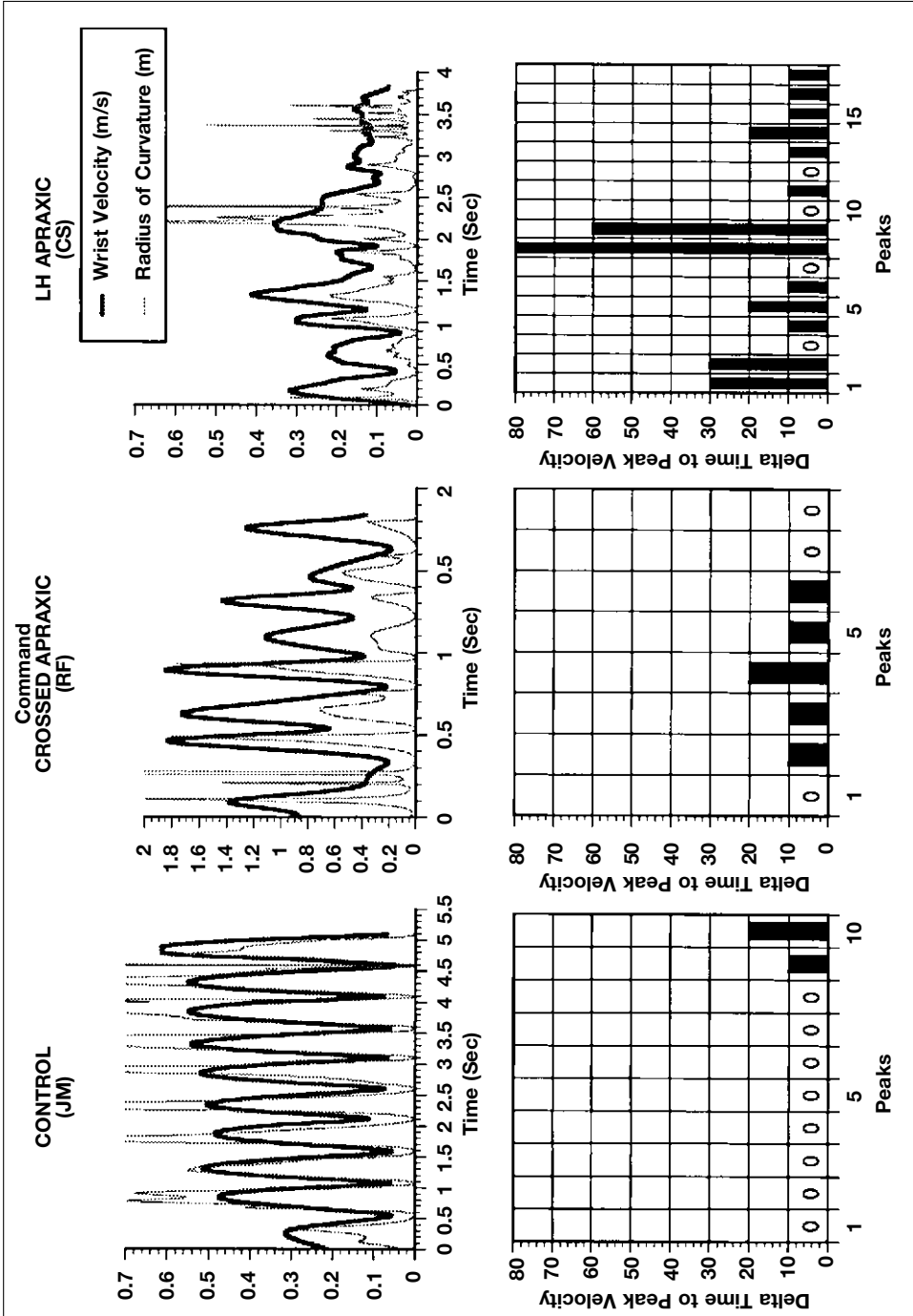


Fig. 4 – Velocity-curvature coupling for the cue conditions of verbal command and manipulation of tool and object in one control subject, one subject with a left hemisphere lesion, and the subject with crossed apraxia.

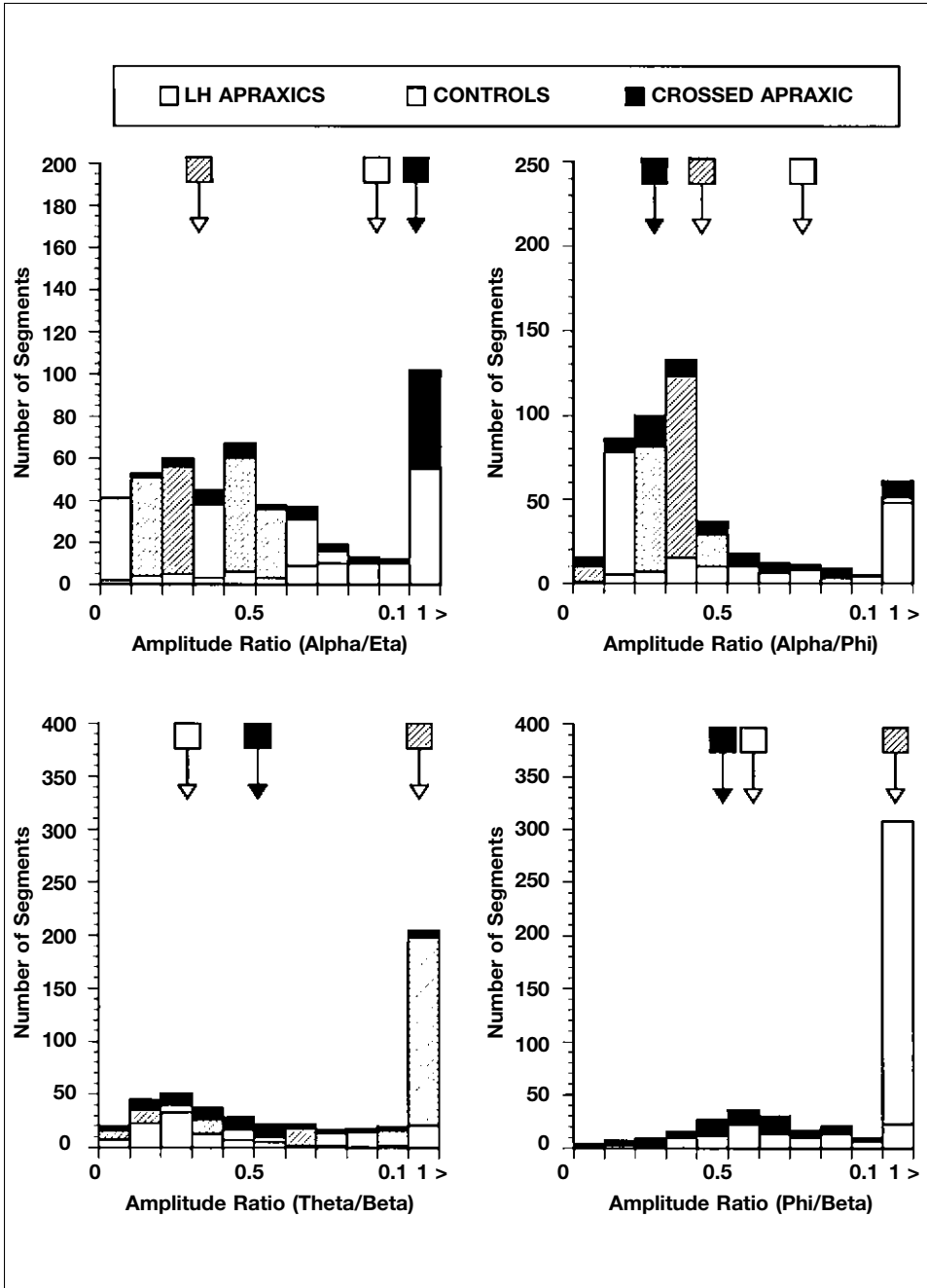


Fig. 5 – Relative amplitudes of selected arm angles for control subjects (hatched), the left hemisphere apraxia subjects (white), and the subject with crossed apraxia (black) for all segments and replications of the slicing gesture performed to verbal command. Arrows represent median amplitude ratios. Ratios between 0 and 1.0 are plotted at intervals of 0.1; all ratios above 1.0 plotted together.

DISCUSSION

Crossed apraxia offers the unique opportunity to study the relationship between skilled movement (limb praxis) and hand preference (handedness). We have described a right-handed subject who following a large right frontal lesion demonstrated severe limb apraxia. Therefore, hand preference (left hemisphere dominance) and dominance for programming skilled limb movements (right hemisphere) appear to be dissociated in this patient. However, to make this claim it is important to determine whether his crossed apraxia parallels that of individuals with the typical presentation of limb apraxia following a left hemisphere (LH) lesion, or whether his gesture disorder relates to impairment of different aspects of movement contributed by the right hemisphere.

As in patients with LH apraxia whose lesions spare parietal cortex, RF demonstrated better performance in gesture comprehension than gesture production (Rothi et al., 1985). We could not determine whether RF's gesture comprehension was mediated by intact portions of his right posterior cortex or his left cerebral hemisphere. Also like patients with LH apraxia, RF demonstrated better production of intransitive than transitive and meaningless gestures. Better performance with intransitive gestures is consistent with the proposal that this type of gesture may have bilateral hemispheric representation (Rapsack, Ochipa, Beeson et al., 1993). Alternatively, intransitive gestures may also be more complex to perform (Raymer, Maher, Foundas et al., 1997).

Some patients with right hemisphere lesions may produce minor aberrations in gesture production (Haaland and Flaherty, 1984). However, recent evidence indicates that although RH subjects may show abnormalities in movement amplitude, in general they perform like normal control subjects (Maher et al., 1997). RF's gesture production errors included abnormalities of joint movements, spatial location, and hand configurations. These errors were at times so severe that the intent of the gesture was unrecognizable. Thus RF's error pattern conformed to that of patients with LH apraxia who have substantial impairments in the production of gestures across conditions (Haaland and Flaherty, 1984; Maher et al., 1997; Rothi et al., 1988).

Using three dimensional movement analyses of slicing gestures, we found that RF's apraxia conformed to the pattern observed in the comparison subjects with LH presentation of apraxia. Like LH subjects, RF was unable to maintain the normal linear trajectory within an established plane during individual or successive slicing cycles. He had difficulty coupling changes in hand speed with changes in the slicing trajectory as normals do. He also had deficits in coordinating joint movements during the slicing gesture.

Thus, on both behavioral and three dimensional movement analyses, our patient with crossed apraxia performed similarly to subjects with LH lesions. Although admittedly the comparison LH patients had lesions primarily confined to posterior regions and RF's right hemisphere lesion involved frontal regions, the patterns of movement impairment across production tasks were remarkably similar. This is not surprising as prior research contrasting gesture performance in individuals with left anterior versus left posterior lesions has indicated that they differ in gesture recognition abilities, but are similar in gesture production

impairments (Heilman, Rothi and Valenstein, 1982). Although some research has suggested that apraxia is less severe following anterior lesions than posterior lesions (Faglioni and Scarpa, 1989), we have observed a patient with a left frontal lesion who had a profound impairment of gesture production (Barrett, Schwartz, Raymer et al., 1998). RF had a limb apraxia pattern that was just as severe as the apraxia seen in the left hemisphere lesioned patients.

Whereas some researchers have proposed a role of the right hemisphere in the production of skilled movements (Haaland and Flaherty, 1984; Kertesz and Ferro, 1984), this role is typically considered as an adjunct or corollary to the role of the left hemisphere. It is less common to document the right hemisphere as the dominant hemisphere for skilled movement production as appears to be the case for our subject with crossed apraxia/crossed aphasia. To complement our findings of atypical brain asymmetry for the representation of skilled movement and language, we noted that RF also has atypical asymmetry for brain morphometric measures. RF showed a reverse pattern compared to the typical left occipital/right frontal asymmetry seen in right-handed individuals. Although Faglioni and Scarpa (1989) found no consistent relationship between brain asymmetries and the presence of apraxia in individuals with left hemisphere, it is of interest that RF presented with a reverse asymmetry and concurrent reversed asymmetry of praxis and language functions to the right hemisphere.

It is unclear what RF's left hemisphere contributed to his cognitive abilities. With a right hemisphere lesion, he demonstrated impairments of spatial attention and emotional prosody typical of right hemisphere dysfunction as well as aphasia and apraxia which are typically associated with left hemisphere dysfunction. However, he did not evidence impairments in phonological planning and sequencing for speech production which are commonly observed in individuals with left inferior frontal lesions (Alexander, 1997). Therefore, all aspects to left hemisphere functioning do not appear to be lateralized to RF's right hemisphere.

Marchetti and Della Sala (1997) described a patient, GP, with crossed apraxia (without aphasia) and proposed that the dissociation between dominance for handedness and dominance for skilled movements was not a counter argument to the role of skilled movement representation in determining handedness. They proposed that the right mesial frontal cortex lesion responsible for limb apraxia in their patient is less lateralized than other brain regions and therefore may represent individual variability in how movement is represented in the brain. However, we have found a similar dissociation of handedness and skilled movement in our patient, RF, with a large right dorsolateral frontal lesion, a region that has greater asymmetric function. We propose that RF's crossed apraxia provides evidence for dissociation of handedness and skilled movement representation.

Alexander and Annett (1996) postulated a genetic right shift (RS) account for anomalous findings such as those observed in our patient, RF. They suggested that a small proportion of right-handed individuals are missing a gene (RS-) that typically determines the left hemisphere lateralization of functions such as language, praxis, and handedness. Half of the individuals who are RS- are just as likely to lateralize cognitive functions anomalously to the right hemisphere as to the left hemisphere. All left hemisphere functions will not necessarily be

linked and shift anomalously. This may be the case for RF for whom language and praxis functions have lateralized to the right hemisphere and handedness to the left hemisphere.

Heilman (1997) reviewed a number of factors that may lead to the determination of hand preference such as language, attentional, motor, and praxis asymmetries as well as cultural learning influences. Our results have documented that the characteristics of RF's severe limb apraxia paralleled the pattern of apraxia seen in many LH patients. Apparently, the neural and functional instantiation of hand preference and the production of skilled movement are independent for RF. We propose that these findings provide compelling evidence that dominance for skilled movement cannot be the sole determinant of hand preference (Liepmann and Maas, 1907). Right-handed individuals with crossed apraxia and crossed aphasia help us to disentangle the factors underlying hand preference and lead us to suggest that motor, attentional and learning influences also are important contributing factors for determining hand preference.

Acknowledgments. We thank Maryann Clark and Gregory Feldman for their assistance in data processing. We also thank RF for this patience and willingness to participate in these studies. This research was supported in part by grants provided by the National Institutes of Health (grant number 2 R01 NS 28665-07, NS 25675, and NS 20665).

REFERENCES

- ALEXANDER, M.P. Aphasia: Clinical and anatomic aspects. In T.E. Feinberg and M.J. Farah (Eds.), *Behavioral Neurology and Neuropsychology*. New York: McGraw-Hill, 1997, pp. 133-149.
- ALEXANDER, M.P., and ANNETT, M. Crossed aphasia and related anomalies of cerebral organization: Case reports and a genetic hypothesis. *Brain and Language*, 55: 213-239, 1996.
- ASSAL, G., PERENTES, E., and DERUAZ, J.P. Crossed aphasia in a right-handed patient. *Archives of Neurology*, 38: 455-458, 1981.
- BARRETT, A.M., SCHWARTZ, R.L., RAYMER, A.M., CRUCIAN, G.P., ROTH, L.J.G., and HEILMAN, K.M. Dyssynchronous apraxia: Failure to combine simultaneous preprogrammed movements. *Cognitive Neuropsychology*, 15: 685-704, 1998.
- BASSO, A., CAPITANI, E., LAIACONA, M., and ZANOBIO, M.E. Crossed aphasia: One or more syndromes? *Cortex*, 21: 25-45, 1985.
- BERTHIER, M., STARKSTEIN, S., and LEIGUARDA, R. Behavioral effects of damage to the right insula and surrounding regions. *Cortex*, 23: 673-678, 1987.
- BORKOWSKI, J.G., BENTON, A.L., and SPREEN, O. Word fluency and brain damage. *Neuropsychologia*, 5: 135-140, 1967.
- CAPPA, S.F., PERANI, D., BRESSI, S., PAULESU, E., FRANCESCHI, M., and FAZIO, F. Crossed aphasia: A PET follow-up study of two cases. *Journal of Neurology, Neurosurgery, and Psychiatry*, 56: 665-671, 1993.
- CLARK, M.A., MERIANS, A.S., KOTHARI, A., POIZNER, H., MACAULEY, B., ROTH, L.J.G., and HEILMAN, K.M. Spatial planning deficits in limb apraxia. *Brain*, 117: 1093-1106, 1994.
- DAMASIO, H. *Human Brain Anatomy in Computerized Images*. New York: Oxford University Press, 1995.
- GESCHWIND, N. Disconnexion syndromes in animal and man. II. *Brain*, 88: 585-644, 1965.
- GESCHWIND, N. The apraxias: Neural mechanisms of disorders of learned movement. *American Scientist*, 63: 188-195, 1975.
- GESCHWIND, N., and GALABURDA, A. Cerebral lateralization. Biological mechanisms, associations, and pathology: I. A hypothesis and a program for research. *Archives of Neurology*, 42: 428-459, 1985.
- HAALAND, K.Y., and FLAHERTY, D. The different types of limb apraxia errors made by patients with left vs right hemisphere damage. *Brain and Cognition*, 3: 370-384, 1984.
- HEILMAN, K.M. Handedness. In L.J.G. Roth and K.M. Heilman (Eds.), *Apraxia: The Neuropsychology of Action*. East Sussex, UK: Psychology Press, 1997, pp. 19-28.
- HEILMAN, K.M., and ROTH, L.J.G. Apraxia. In K.M. Heilman and E. Valenstein (Eds.), *Clinical Neuropsychology (3rd ed.)*. New York: Oxford University Press, 1993, pp. 141-163.
- HEILMAN, K.M., ROTH, L.J.G., and VALENSTEIN, E. Two forms of ideomotor apraxia. *Neurology*, 32: 342-346, 1982.
- JENNINGS, P.J., and POIZNER, H. Computergraphic modeling and analysis II: Three-dimensional

- reconstruction and interactive analysis. *Journal of Neuroscience Methods*, 24: 45-55, 1988.
- KAPLAN, E., GOODGLASS, H., and WEINTRAUB, S. *The Revised Boston Naming Test*. Philadelphia, P.A.: Lea and Febiger, 1983.
- KERTESZ, A. *The Western Aphasia Battery*. Orlando: Grune and Stratton, 1982.
- KERTESZ, A., and FERRO, J.M. Lesion size and location in ideomotor apraxia. *Brain*, 107: 921-933, 1984.
- KOTHARI, A., POIZNER, H., and FIGEL, T. Three-dimensional graphic analysis for studies of neural disorders of movements. *SPIE Visual Data Interpretation*, 1668: 82-82, 1992.
- LIEPMANN, H. Die linke Hemisphere und das Handeln. *Muenchner Medizinische Wochenschrift*, 49: 2322-2326, 2375-2378, 1905.
- LIEPMANN, H., and MAAS, O. Fall von linksseitiger Agraphie und Apraxie bei rechtsseitiger Lahmung. *Zeitschrift für Psychologie und Neurologie*, 10: 214-227, 1907.
- MAHER, L.M., ROTH, L.J.G., and HEILMAN, K.M. Praxis performance with left versus right hemisphere lesions. *NeuroRehabilitation*, 9: 45-55, 1997.
- MARCHETTI, C., and DELLA SALA, S. On crossed apraxia. Description of a right-handed apraxic patient with right supplementary motor area damage. *Cortex*, 33: 341-354, 1997.
- MOZAZ, M., MARTI, J.F., CARRERA, E., and DE LA PUENTE, E. Apraxia in a patient with lesion located in right sub-cortical area. Analysis of errors. *Cortex*, 26: 651-655, 1990.
- PERANI, D., PAPAGNO, C., CAPP, S., GERUNDINI, P., and FAZIO, F. Crossed aphasia: Functional studies with single photon emission computerized tomography. *Cortex*, 24: 171-178, 1988.
- PIENIADZ, J.M., and NAESER, M.A. Computed tomographic scan cerebral asymmetries and morphologic brain asymmetries. *Archives of Neurology*, 41: 403-409, 1984.
- PIENIADZ, J.M., NAESER, M.A., KOFF, E., and LEVINE, H.L. CT scan cerebral hemispheric asymmetry measurements in stroke cases with global aphasia: Atypical asymmetries associated with improved recovery. *Cortex*, 19: 371-391, 1983.
- POIZNER, H., CLARK, M., MERIANS, A.S., MACAULEY, B., ROTH, L.J.G., and HEILMAN, K.M. Joint coordination deficits in limb apraxia. *Brain*, 118: 227-242, 1995.
- POIZNER, H., MACK, L., VERFAELLIE, M., ROTH, L.J.G., and HEILMAN, K.M. Three dimensional computergraphic analysis of apraxia. *Brain*, 113: 85-101, 1990.
- POIZNER, H., and SOECHTING, J. New strategies for studying higher level motor disorders. In D. Margolin (Ed.), *Cognitive Neuropsychology in Clinical Practice*. New York: Oxford University Press, 1992, pp. 435-464.
- POIZNER, H., WOOTEN, E., and SALOT, D. Computergraphic modeling and analysis: A system for tracking arm movement in three dimensional space. *Behavior Research Methods, Instruments, and Computers*, 18: 427-433, 1986.
- RAPCSAK, S.Z., OCHIPA, C., BEESON, P.M., and RUBENS, A.B. Praxis and the right hemisphere. *Brain and Cognition*, 23: 181-202, 1993.
- RAPCSAK, S.Z., ROTH, L.J.G., and HEILMAN, K.M. Apraxia in a patient with atypical dominance. *Brain and Cognition*, 6: 450-463, 1987.
- RAYMER, A.M., MAHER, L.M., MACAULEY, B., FOUNDAS, A.L., ROTH, L.J.G., and HEILMAN, K.M. Differences between transitive and intransitive gestures in limb apraxia. *Journal of the International Neuropsychological Society*, 3: 55, 1997.
- ROTH, L.J.G., and HEILMAN, K.M. Acquisition and retention of gestures by apraxic patients. *Brain and Cognition*, 3: 426-437, 1984.
- ROTH, L.J.G., HEILMAN, K.M., and WATSON, R.T. Pantomime comprehension and ideomotor apraxia. *Journal of Neurology, Neurosurgery and Psychiatry*, 48: 207-210, 1985.
- ROTH, L.J.G., MACK, L., VERFAELLIE, M., BROWN, P., and HEILMAN, K.M. Ideomotor apraxia: Error pattern analysis. *Aphasiology*, 2: 381-388, 1988.
- ROTH, L.J.G., OCHIPA, C., and HEILMAN, K.M. A cognitive neuropsychological model of limb praxis. *Cognitive Neuropsychology*, 8: 443-458, 1991.
- ROTH, L.J.G., RAYMER, A.M., and HEILMAN, K.M. Limb praxis assessment. In L.J.G. Roth and K.M. Heilman (Eds.), *Apraxia: The Neuropsychology of Action*. East Sussex, UK: Psychology Press, 1997, pp. 61-73.
- ROTH, L.J.G., RAYMER, A.M., OCHIPA, C., MAHER, L.M., GREENWALD, M.L., and HEILMAN, K.M. *The Florida Apraxia Battery: Experimental Edition*, 1992 (unpublished).
- SOECHTING, J., and ROSS, B. Psychophysical determination of coordinate representation of human arm orientation. *Neuroscience*, 13: 595-604, 1984.
- SOECHTING, J., and TERZUOLO, C. An algorithm for the generation of curvilinear wrist motion in an arbitrary plane in three-dimensional space. *Neuroscience*, 7: 431-437, 1976.
- STARKSTEIN, S.E., BERTHIER, M.L., and LEIGUARDA, R. Disconnection syndrome in a right-handed patient with right hemispheric speech dominance. *European Neurology*, 28: 187-190, 1988.

Anastasia Raymer, Ph.D., Dept. of ESSE, Child Study Center, Old Dominion University, 45th St and Hampton Blvd, Norfolk, VA 23529-0136 USA; e-mail: sraymer@odu.edu

(Received 20 July 1998; accepted 13 November 1998)