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Task Demands and Limb Apraxia in Stroke

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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; a composite score, an arithmetic combination of the five performance dimensions, was used as an index of the overall accuracy. Analyses revealed a comparable proportion of patients in each stroke group were classified as apraxic in the imitation condition, but a higher proportion of left stroke patients were apraxic in the pantomime condition. The severity of apraxia in each stroke group and the performance dimensions affected were, however, comparable. 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. © 2000 Academic Press

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, or poor comprehension of or attention to commands (Rothi & 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) distin-

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guished 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 and found apraxic impairments to be more severe when pantomiming gestures (Alexander, Baker, Naeser, Kaplan, & Palumbo, 1992; Lehmkuhl, Poeck, & Willmes, 1983; Poeck, Lehmkuhl, & Willmes, 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, Faglioni, & Sargato, 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 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, Motti, & Nichelli, 1980) showed that performance in these two conditions was not correlated and suggested that they engaged different processes underlying praxis. Like Liepmann, 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 physical instantiation 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 conceptual 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 conceptual system. Both routes to action are thought to map onto a later stage in the production system responsible for movement execution.

More recently Roy (Roy & Square, 1994; 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 conceptual system, affecting knowledge of tool function or knowledge of action, or in the early stages of the production system involving 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 conceptual or ideational processes; that is, apraxia on pantomime alone. A smaller difference between the stroke groups in the 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 led 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%. 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

TABLE 1
Participant Characteristics

Group	Age			Test onset (days since stroke)	
	N	*M*	*SD*	*M*	*SD*
Control	15	68.45	10.01	—	—
LHD	46	71.4	12.7	74.6	76.1
RHD	53	69.2	13.4	71.2	60.5

RHD. For example, Schnider et al. (1997) found that 45% (5/11) of patients with RHD fell in the apraxic range when pantomiming and imitating meaningful gestures. Our own recent work supports these observations. Using a detailed analysis of pantomime performance across five dimensions, Roy, Black, Blair, and Dimeck (1998) found that their RHD patients were significantly less accurate than controls and the frequency of apraxia in these patients was 30%. The present investigation was designed to extend our previous 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 the patients met the inclusion criteria, which were a unilateral hemispheric stroke and sufficient comprehension and stamina to complete the assessment.[1] The control group was matched as closely as possible to 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.

Gestural Tasks and Performance Scoring

Participants were required to pantomime and imitate eight transitive gestures which had been examined in our previous study of 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

[1] One of the patients with LHD was eliminated from the data analysis due to a severe comprehension impairment and agitation; hence only the data from 57 of the 58 patients were included in the data analyses.

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 we have noted elsewhere (Roy et al., 1998), the dimensions of repetitiveness and spatial location relative to the body (i.e., 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 nonrepetitive 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 our 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 were 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 interrater 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.

RESULTS

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.

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

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 2 means.

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, $F(1, 28) = 17.79$, $p < .01$.

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 three-group (control, LHD, and RHD) $\times$ two-condition (pantomime and imitation) mixed-factor ANOVA. In addition, a three-group (control, LHD, and RHD) $\times$ two-condition (pantomime and imitation) $\times$ five-dimension (location, posture, action, plane, and 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

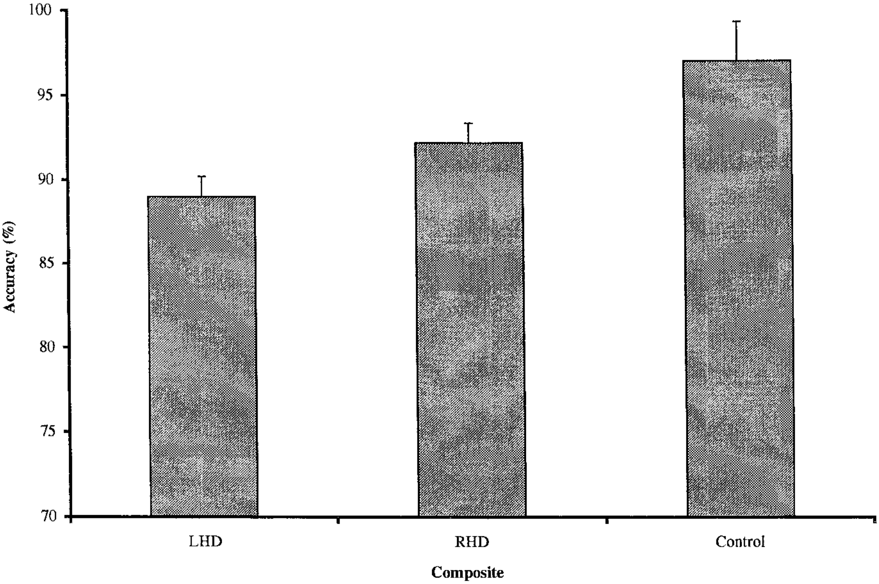

FIG. 1. Average composite score for patients with LHD and RHD and for controls.

Fig. 1 and see Table 3 for the distribution of composite scores in the three groups). 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 $\times$ 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 Fig. 2).

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 ($r = .498$, $p < .01$) or 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 condi-

TABLE 3
Composite Score Distribution of LHD, RHD, and Control Participants across Performance Conditions

Score	Pantomime			Imitation		
	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	—	—	—	—	—	—

tion (see Roy et al., 1998). The first cutoff score was equal to 1 standard deviation below the composite mean (I), and the second cutoff score was equal to 2 standard deviations below the composite mean (II). The cutoff scores were subsequently used to classify patients within each stroke group as nonapraxic (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, $c^2 = 4.01$, $p = .045$ (Table 4). In the imitation condition the distribution of patients in the two stroke groups did not differ significantly across the three categories, $c^2 = .98$, $p = .322$.

Comparisons between Apraxic and Nonapraxic 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 and those classified as nonapraxic in each stroke

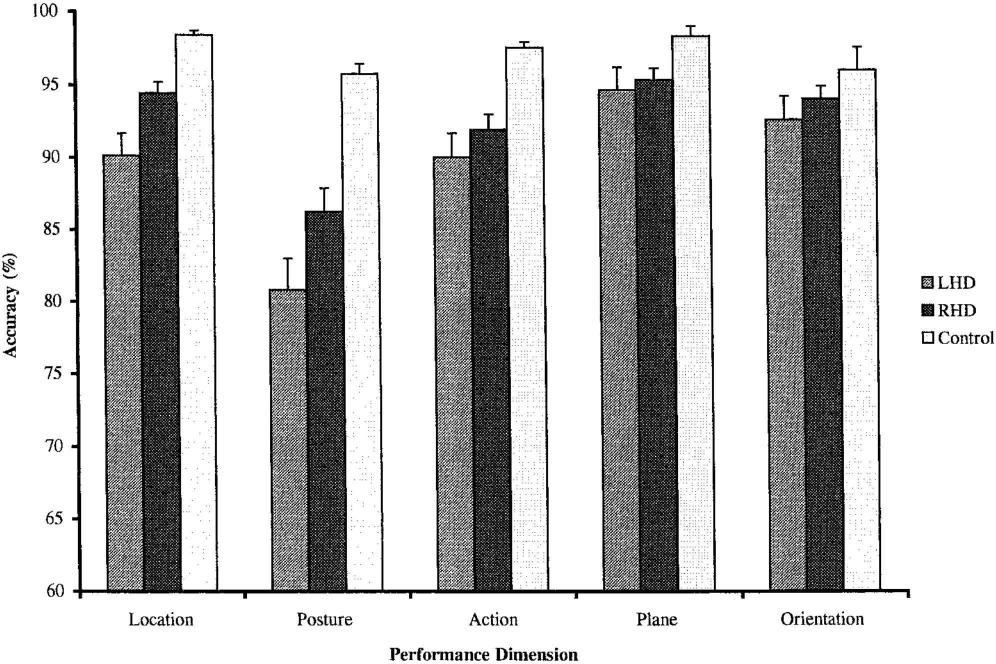

FIG. 2. Accuracy across performance dimensions for both stroke groups and controls.

group for each performance condition (see Tables 5 and 6). For the patients with LHD there was a main effect of group (apraxic vs nonapraxic) for both pantomime, $F(1, 44) = 30.79$, $p < .001$, and imitation, $F(1, 44) = 25.92$, $p < .001$), conditions and a group × 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

TABLE 4
Apraxia Severity as a Function of Stroke Group

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

TABLE 5
Gestural Performance of LHD Participants Classified as Apraxic and Nonapraxic

	Apraxic				Nonapraxic			
	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	87.90	7.84	94.78	2.28	97.43	1.24

TABLE 6
Gestural Performance of RHD Participants Classified as Apraxic and Nonapraxic

	Apraxic				Nonapraxic			
	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

in both the pantomime, $F(1, 51) = 47.21$, $p < .001$, and imitation, $F(1, 51) = 30.44$, $p < .001$), conditions and group × 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 effect demonstrated that the apraxics were less accurate than the nonapraxics on all performance dimensions, but this difference was largest for the posture dimension.

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 our most 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. We found a higher proportion of patients with RHD in the first group (less than two dimensions), but a higher proportion of patients with LHD in the second group (more then three dimensions). In the present analysis the average performance of patients categorized as nonapraxic in the pantomime and imitation conditions was used to define whether performance on a particular dimension was impaired in each of the patients classified as apraxic in the two performance conditions. 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 in the nonapraxic patients were classified as impaired. The results for pantomime and imitation were compared separately (see Table 7).

The pantomime data indicated that a higher proportion of patients in right stroke group exhibited impairments on two or fewer dimensions, while a greater proportion of LHD patients were impaired on three or more dimen-

TABLE 7
Number of Performance Dimensions Impaired in Each Stroke Group

Group	≤2		≥3	
	Pantomime	Imitation	Patomime	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%)

sions ($c^2 = 4.23$, $p = .04$). 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, $c^2 = 1.33$, $p = .249$.

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 in imitation ($P_A I_{NA}$), in imitation but not in pantomime ($P_{NA} I_A$), or in both pantomime and imitation ($P_A I_A$). Patients who fell into these three patterns were identified from the cutoff scores used to define apraxic categories (i.e., nonapraxic, borderline apraxic, and apraxic) in our 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.

We also compared performance accuracy between the two stroke groups within each pattern of apraxia (see Table 8 for composite scores of each

TABLE 8
Frequency and Composite Score Accuracy Data for Patients with LHD or RHD in Each Apraxic Category

Apraxic pattern	LHD Frequency (%)	LHD Pantomime accuracy	LHD Imitation accuracy	RHD Frequency (%)	RHD Pantomime accuracy	RHD Imitation accuracy
$P_{NA}I_{NA}$	16 (35)	95.58	97.57	23 (43)	94.57	97.63
P_AI_A	20 (43)	78.95	85.93	12 (23)	82.38	87.39
P_AI_{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

TABLE 9
Left Hemisphere Group Aphasia Classification

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

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) $\times$ 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 revealed that 48% (21/44) of the patients were aphasic.[2] 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% or 9/21) or the Broca's (24% 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 we first compared the frequency of apraxia in the patients with aphasia to that in the patients without aphasia. These analyses revealed a much higher frequency of apraxia among the patients with aphasia (57% or 12/21 for pantomime and 76% of 16/21 for imitation) than among the patients without aphasia (35% or 8/23 for pantomime and 43% or 10/23 for imitation), and the frequency of apraxia among the patients with aphasia averaged across performance conditions was 67%, a value comparable to that reported in the literature (e.g., Goldenberg, 1996; Lehmkuhl, Poeck, & Willmes, 1983; Wang & Goodglass, 1992).

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

[2] 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.

concert with these correlations the apraxic patients exhibited significantly lower aphasia quotients than the nonapraxic patients for both the pantomime condition (apraxic AQ = 71.04; nonapraxic AQ = 90.54), $F(1, 42) = 25.57$, $p < .001$, and the imitation condition (apraxic AQ = 76.07; nonapraxic 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, & Shewan, 1984; Lehmkuhl, Poeck, & Willmes, 1983; Square-Storer, Roy, & Hogg, 1990; Wang & Goodglass, 1992). Analyses of the component scores of the WAB AQ are beyond the scope of this article but are the focus of another report (Roy, Black, & Square, in preparation).

DISCUSSION

Left- versus Right-Hemisphere Stroke and Apraxia

This study was designed to compare the frequency and severity of apraxia in patients with LHD or RHD and to examine whether the difference between the stroke groups was greater in the pantomime or imitation conditions. Our prediction that the frequency and severity of apraxia would be greater in the patients with LHD was only partially borne out. Looking first at frequency the proportion of patients classified as apraxic was higher for those with LHD in both performance conditions, a finding which is consistent with many other studies of apraxia in stroke (e.g., Rothi & Heilman, 1997). However, this difference in proportion was significant only in the pantomime condition. As for the severity of apraxia while the patients with LHD were significantly less accurate than the controls in gesture performance, they were not significantly less accurate than the patients with RHD. Further, among those patients found to be apraxic, comparisons of performance accuracy as well as the performance dimensions affected revealed that the two apraxic stroke groups did not differ significantly.

Together these findings suggest that stroke to the left hemisphere does not cause greater impairments in praxis. How can these results be reconciled with the many other studies which have found a greater impairment with LHD? One explanation could be that the groups differed in the time since stroke. If the time since stroke were shorter for the RHD patients, they would have had potentially greater impairments in many cognitive and motor functions including praxis than might have been present with more recovery time, leading to their praxis performance being comparable to the patients with LHD. The two stroke groups overall did not differ in time since stroke, however, and analyses comparing the apraxic patients in each group also revealed no differences.

A second explanation may be that the left hemisphere in these patients with RHD might not be unaffected by the stroke. While our patients required a single stroke to be evident on CT, so that a definite structural lesion to the left hemisphere would be ruled out, it is possible that their left hemisphere was not functionally intact because of diaschisis, whereby left-hemisphere function was compromised by damage to the right hemisphere. Thus the left hemisphere's ability to control praxis may have been compromised due to some type of transcallosal interference. This explanation might be investigated through PET or fMRI activation studies where apraxic patients with RHD might show reduced ability to activate the left hemisphere compared to nonapraxic patients with RHD. Alternately, sodium amytal studies in such patients might reveal that suppressing the function of the right hemisphere would remove the left-hemisphere interference and thereby improve praxis performance.

The explanation noted above assumes that the apraxia in these patients with RHD does not arise from damage to the right hemisphere but rather from disruptions to the left hemisphere. In a sense then these patients are actually left-hemisphere dominant for praxis. An alternate explanation is that these apraxic patients may be representative of the very small group of right-handers who have praxis represented either bilaterally or lateralized to the right hemisphere. Considering the association between praxis and speech and language function this hypothesis could be confirmed by demonstrating that these patients also exhibit aphasic deficits. Unfortunately, our patients with RHD were not examined for aphasia. In our future work we will incorporate this assessment into our protocol so that we might address this prediction.

Neither of these explanations for the higher frequency and severity of apraxia in our patients with RHD seem satisfying because there is no evidence that our patients with RHD are in any way unique compared with those seen in other studies. That is, these mechanisms, transcallosal interference with left-hemisphere function and a ''crossed'' or bilateral cerebral representation of praxis, could have been operating in the patients observed in these other studies and yet the frequency and severity of apraxia was much lower than we observed. Thus there must be something else unique about our study which would have led to the higher frequency and severity of apraxia observed in our patients with RHD.

Possibly the precision afforded by our analyses of performance accuracy was sufficient to detect impairments in praxis in the patients with RHD not seen using other less sensitive scoring systems. Certainly other studies using detailed error analyses such as this one have found impairments in praxis with RHD (cf. Haaland & Flaherty, 1984; Roy et al., 1998; Schnider et al. 1997). However, it is not clear why such an increase in precision would have a selective effect on apraxia in patients with RHD. With better precision one might have expected a higher frequency and severity of apraxia in both stroke groups. Possibly the impairments seen with LHD are so readily observed that the precision afforded by our analysis system does not add appreciably to the detection of apraxia. The more subtle impairments seen with RHD, however, may require this precision to be detected and reliably measured.

Studies by Poizner (Poizner, Mack, Verfaellie, Rothi, & Heilman, 1990; Poizner, Merians, Clark, Rothi, & Heilman, 1997) using kinematic measures of performance, however, an even more precise system than ours for measuring the spatial and temporal details of movement in gesturing, have failed to show impairments in patients with RHD. This discrepancy may be due to the fact that these kinematic studies have typically examined only a small number of patients and only one or two gestures. A study of groups of patients with LHD or RHD by Hermsdorfer, Mai, Spatt, Marquardt, Veltkamp, and Goldenberg (1996) which examined the kinematics of a meaningless gesture akin to a salute, however, found marked abnormalities in the patients with LHD compared to those with RHD, a finding which supports Poizner's work using only a limited number of patients. Nevertheless, the patients with LHD in Poizner's studies have often been selected based on the presence of apraxia, while those with RHD have not been selected on this basis. Had these studies involved only patients with apraxia those apraxic patients with RHD might have shown impairments similar to those with LHD. Our analyses comparing performance between the LHD and RHD apraxic groups provides some support for this contention in that there was great similarity in the performance dimensions affected in each group.

In sum our findings that impairments to praxis are not selectively seen in patients with LHD is at variance with a large body of literature which links apraxia to the left hemisphere. However, our findings do replicate our other work using this system (e.g., Roy et al., 1998) as well as other studies using similar analysis systems (e.g., Haaland & Flaherty, 1984; Schnider et al., 1997), suggesting that much more work will be needed comparing different performance analysis systems in order to resolve this discrepancy.

Performance Conditions and Apraxia

Our second hypothesis, that the impairment in the patients with LHD relative to those with RHD should be greater in the pantomime than the imitation condition, was also only partially supported. Recall that De Renzi (Barbieri & De Renzi, 1988) found this larger impairment in the pantomime condition for patients with LHD and reasoned that this effect reflected the dominant role played by the left hemisphere in the ideational component of gesture performance. In the present study we did find that the proportion of apraxic patients with LHD relative to those with RHD was significantly greater in the pantomime but not in the imitation condition, consistent with what De Renzi (Barbieri & De Renzi, 1988) had observed. However, the performance of the apraxic patients with LHD was not significantly less accurate than the RHD group, suggesting a comparable severity of apraxia. Further, performance in the pantomime condition was significantly less accurate than in the imitation condition, indicating that, for both stroke groups, when gesture performance places demands on memory, performance is less accurate. Our observations of the frequency of apraxia, then, do provide support for De Renzi's proposal as to the selective role of the left hemisphere in the ideational component of praxis, but our findings on the severity of apraxia do not.

Further, the present findings do not concur with those of Schnider et al. (1997), who found that pantomime performance was less accurate than imitation but only for patients with LHD, suggesting that ideational processes were more affected with LHD. In their study, patients with RHD performed near ceiling levels in both performance conditions, thus a performance condition effect may not have been observed because their analysis system lacked sufficient sensitivity. Support for this contention is seen in the fact that their controls also performed at ceiling levels in both conditions, while performance of our controls did not reach ceiling; rather, the controls were less accurate in the pantomime than in the imitation condition. Therefore, it would seem that our analysis system was sensitive enough to detect performance difference between pantomime and imitation even among the control participants. Had such a system been used by Schnider et al. (1997) they might have been able to more adequately evaluate whether the performance difference between the pantomime and imitation conditions was truly larger in the LHD patients.

Patterns of Apraxia

Pantomime dissociated from imitation. The clearest evidence against the selective role of the left hemisphere in the ideational processes in gesture performance comes from our analyses of the patterns of apraxia described by Roy (1996). We predicted that the proportion of patients classified as apraxic in the pantomime condition alone should be much higher for the LHD patients (see Table 8), if LHD selectively affects ideational processes. De Renzi (Barbieri & De Renzi, 1988) observed a higher frequency of patients with LHD (12) than with RHD (2), demonstrating a dissociation in which apraxia was greater on pantomime than imitation. In contrast our data reveal that the proportion of patients showing a somewhat similar dissociation, apraxia in pantomime alone, was approximately the same in the two stroke groups (LHD = 5%; RHD = 6%).

The discrepancy between our data and those of De Renzi (Barbieri & De Renzi, 1988) may arise from the way in which this pattern was defined. In the present investigation this pattern was based on a clear dissociation where each patient falls in the apraxic range only on pantomime. In De Renzi's study (Barbieri & De Renzi, 1988) there was not a stipulation that patients were apraxic only on pantomime. Rather, the pattern was defined such that the difference between the two performance conditions was larger than that seen in the controls.

Given the above difference, it is possible that a number of the patients with LHD showing this pattern (pantomime more impaired than imitation) in De Renzi's sample may have been apraxic in both conditions but were just more impaired on pantomime than imitation. Support for this notion is seen in our pantomime data which can be separated into two subgroups of apraxic patients, one comprised of patients who are apraxic on pantomime alone and the other comprised of patients who are apraxic not only on pantomime but also on imitation. In the first subgroup reflecting apraxia on pantomime alone, approximately the same proportion of patients from each stroke group is represented. In the second subgroup reflecting an apraxic impairment on pantomime as well as on imitation the proportion of patients with LHD is larger (see Table 8). This observation suggests that the patients with LHD in De Renzi's (Barbieri & De Renzi, 1988) study who showed the dissociation between pantomime and imitation may have actually been apraxic on both conditions, since in our data it is only this subgroup of patients where those with LHD outnumber those with RHD. Such patients would not demonstrate as clear a dissociation as that seen in our patients who were apraxic only on pantomime. Considering Roy's model (1996) the pattern shown in such patients would seem not to be a ''pure'' conceptual or ideational problem (i.e., apraxia on pantomime alone), but rather one which also involves a significant executive disorder in that these patients are apraxic in both conditions.

Imitation dissociated from pantomime. A second pattern of apraxia described by Roy (1996) is one in which apraxia is seen on imitation but not on pantomime. A number of cases showing this pattern have been reported (e.g., Merians, Clark, Poizner, Macauley, Rothi, & Heilman, 1997; Ochipa et al., 1994). In our sample of lateralized stroke patients, it would appear that disruptions at this stage (reflecting disruptions in the analysis of visual gestural information or in the translation of visual gestural information into movement) occur with approximately equal frequency in each stroke group. These data support those of De Renzi (Barbieri & De Renzi, 1988), who also found approximately the same proportion of patients in each hemisphere group with apraxia greater on imitation. While the frequency of this pattern of apraxia may be the same for each stroke group in the present study, it is possible that the degree of the impairment as reflected in performance accuracy is greater in the LHD patients. Comparison of the composite scores between the two stroke groups, however, revealed no difference. Using both measures (frequency and accuracy), then, it appears that disruptions at this stage in gesture performance can arise from damage to either hemisphere.

The observation that the frequency of apraxia and the severity of the apraxic impairment is comparable in the two strokes groups for this pattern of apraxia reflecting impairments on imitation alone would not seem consistent with work by Schnider et al. (1997), who have shown that patients with LHD were more impaired than those with RHD at imitating gestures. Schnider et al. (1997) did not look at the frequency of apraxia, so it is difficult to compare our frequency data with their data, which focused on accuracy. Nevertheless, as noted for the pantomime data, the imitation data can be separated into two subgroups, one comprised of patients who are apraxic on imitation alone and the other comprised of patients who are apraxic on both conditions. In the first subgroup (apraxia on imitation alone), the proportion of patients in each stroke group is about the same. Whereas in the second subgroup the proportion of patients with LHD is much higher. The increased proportion of apraxic patients with left- relative to right-hemisphere damage in the imitation condition overall then arises from the larger number of LHD patients in the second subgroup.

Considering these two subgroups it would appear that the discrepancy between our finding and Schnider's (Schnider et al., 1997) may have arisen from differences in which subgroup was the focus of interest. In the present study only patients who were impaired on imitation alone were examined, while Schnider et al. (1997) looked at patients' performance on imitation regardless of how they performed on pantomime. The larger apraxic impairment seen in their LHD patients may not reflect an isolable deficit in the visual perceptual and visuomotor processes underlying gestural imitation as our pattern reflecting apraxia on imitation alone does. Rather, their apraxic patients are likely composed of the two subgroups we have identified, with the larger number likely being in the subgroup in which both imitation and pantomime are impaired. Moreover, since their controls performed at ceiling level on both conditions, virtually all of their LHD patients would fall into the latter subgroup, apraxic in both conditions, a pattern which we propose is more reflective of an impairment at a later stage in gesture performance associated with movement execution.

De Renzi (Barbieri & De Renzi, 1988) proposed that the pattern involving apraxia on imitation alone reflects an executive disorder. Roy (Roy & Square, 1994; Roy, 1996), however, argues that an executive disorder would likely affect performance in both pantomime and imitation leading to apraxia in both conditions. Thus, Roy (1996) has proposed that apraxia on imitation alone is more likely reflective of an impairment in either the ability to analyze visual gestural information or the ability to translate the visual gestural information into movement. Determining which of these processes is affected, Roy (1996) argues, would require examining the patient's performance on a gesture-recognition-discrimination task. If the disruption involves the analysis of visual gestural information, the patient should be impaired on the gesture-recognition-discrimination task. Our future work will address this question using various types of gesture recognition and discrimination tasks. Such tasks have played an important role in the study of apraxia (e.g., McDonald, Tate, & Rigby, 1994; Rothi, Heilman, & Watson, 1985; Rothi, Mack, & Heilman, 1986).

Goldenberg (Goldenberg, 1995, 1996; Goldenberg & Hagman, 1997) also has presented evidence questioning the proposal that a selective apraxia affecting imitation alone arises from a disorder in movement execution. If apraxia on imitation arises from or represents an impairment in movement execution, one would not expect dissociations between different gesture types. Rather, the apraxic impairment would affect all gestures to the same extent. Goldenberg, however, reports two cases with LHD who were impaired at imitating meaningless gestures but not meaningful gestures (Goldenberg & Hagman, 1997), and he has shown that patients with LHD are more impaired at imitating the proximal as opposed to the distal features of a hand/arm gesture.

One of these dissociations, that between meaningful and meaningless gestures, has been discussed by both Roy (1996) and Rothi et al. (1991, 1997). In the model developed by Rothi et al. (1991, 1997) the imitation of meaningful gestures involves a lexical route to action through input and output praxicons and with access to an action semantic system. Imitation of meaningless gestures is thought to involve a nonlexical route in which there is a direct link between perception of the gesture and the processes responsible for executing movement. Goldenberg (1996; Goldenberg & Hagman, 1997) questions the notion that imitation of meaningless gestures may involve such a direct route. He has shown that his patients with LHD were not only impaired at imitating meaningless gestures, but they also had a problem in moving the hand and arm of a mannikin into the gestural configuration presented by the examiner. From these correlative data Goldenberg argues that these patients have difficulty imitating meaningless gestures because of a basic disruption in ''knowledge about the structure of the human body.'' Given that these patients were not impaired in imitating meaningful gestures he conjectured that this knowledge of body schema is required primarily when imitating novel or meaningless gestures.

Imitating gestures, then, may not involve a direct route to movement execution but rather one through a component involving knowledge of body schema. This schema would appear to be more important for directing the accurate positioning of the arm (proximal) as opposed to the hand and fingers (distal), since it was only these more proximal features which were selectively impaired in the patients with LHD. Thus, imitation may place demands not only on the visual perceptual and visuomotor processes alluded to by Roy (1996) but also requires intact knowledge of body schema. Further evidence of the importance of this schema in imitation is seen in cases of autotopagnosia (De Renzi & Scotti, 1970; Poncet et al., 1971), who were unable to imitate meaningless gestures but could accurately perform meaningful gestures to pantomime.

Goldenberg's (1996; Goldenberg & Hagman, 1997) observation that primarily the more proximal aspects of a gesture were affected by LHD might be examined in our data by comparing performance accuracy on the location and posture dimensions. The location and posture dimensions are somewhat analogous to the proximal and distal aspects of movement, respectively.

Goldenberg's findings would predict that our patients with LHD should be more impaired than those with RHD on the location dimension. Our analyses of performance accuracy support this prediction in that the patients with LHD were more impaired than those with RHD on the location dimension but not on the posture dimension.

In the current study meaningful gestures, in particular transitive or tool-use gestures, were employed. Considering the dissociation between meaningful and meaningless gestures one might have expected no impairments in imitating meaningful gestures, since these gestures were spared in the cases described by Goldenberg and Hagman (1997). Many group studies like ours, however, have shown apraxic impairments on imitating both types of gesture (e.g., Belanger, Duffy, & Coelho, 1996; Haaland & Flaherty, 1984; Schnider et al., 1997). Thus, finding that our patients were impaired is not inconsistent with what other group studies have found, but the fact that Goldenberg and Hagman (1997) did observe such a dissociation points to the need for the type of pattern analysis used in the present study to identify individual cases or subgroups of patients who demonstrate such dissociations.

The dissociation between meaningful and meaningless gestures is thought to arise because they rely on different routes to action, a lexical route (meaningful gestures) and a nonlexical route (meaningless gestures). Goldenberg's (Goldenberg & Hagman, 1997) finding of an impairment for only meaningless gestures suggests a disruption to the nonlexical route to action and points to the advantage enjoyed by meaningful gestures due to the lexical support afforded through the action semantic system and the input and output praxicons, as described by Rothi et al. (1991, 1997). Is it reasonable to presume that one might observe cases who demonstrate a dissociation in the other direction where only meaningful gestures are impaired? Such a pattern could arise from a selective disruption to the lexical route to action. However, disruptions to the action semantic system, to the action input or output praxicons, or to communication among these components of the praxis system (Rothi et al., 1991, 1997), which could potentially underlie a selective impairment to imitation of meaningful gestures, would not likely affect imitation of these gestures. In the face of such disruptions to the lexical route, patients would likely just use the intact nonlexical route for imitating meaningful gestures. Some support for the use of this route in imitating meaningful gestures when faced with disruptions to the lexical route comes from cases in which patients are able to imitate gestures which they do not recognize (Rothi et al., 1986).

Although it seems unlikely one would see cases selectively impaired at imitating meaningful as opposed to meaningless gestures, one might use a type of lexical priming approach in the imitation condition to assess the integrity of the lexical route to action. That is, in imitating meaningful gestures it may be that certain patients have difficulty activating or using the lexical route. Priming such patients during imitation as to the identity of the gesture should enable them to perform the gesture more accurately if the action semantic system is intact. Confirmation of the integrity of action semantics could be ascertained through tests of gesture recognition and discrimination. These observations certainly attest to the complexity of the network involved in praxis and to the need for the continued development and use of innovative assessment approaches like those used by Goldenberg (Goldenberg, 1995, 1996; Goldenberg & Hagman, 1997), Rothi et al. (1991, 1997), Roy (Roy & Square, 1994; Roy, 1996), and others (e.g., Belanger et al., 1994; Duffy & Duffy, 1990) which attempt to identify disruptions in these various processes in gesture performance.

Concurrent apraxia on pantomime and imitation. The third pattern of apraxia reflects the co-occurrence of apraxia in the two conditions. This pattern appears to occur more frequently than the other two patterns. This high co-occurrence rate would appear to coincide with the finding that performance accuracy in the two conditions was significantly correlated in both stroke groups. These observations do not support De Renzi's (Barbieri & De Renzi, 1988) findings of no correlation between these conditions and his subsequent conclusion that the pantomime and imitation conditions tap into different stages in gesture performance. Rather, the correlation and the higher frequency for the co-occurrence of apraxia may reflect the fact, as Roy's model (1996) suggests, that performance in both conditions is dependent on the integrity of the later stage in the production system which controls movement execution.

This larger co-occurrence rate is particularly evident in the patients with LHD. The proportion of these patients who are apraxic in both conditions (43%) is much higher than apraxia in either condition alone (5% for pantomime alone and 17% for imitation alone). In those with RHD the proportion of patients with apraxia in both conditions (23%) is higher than the proportion who are apraxic to pantomime alone (6%) but approximately equal to the number who are apraxic to imitation alone (28%).

One of De Renzi's (Barbieri & De Renzi, 1988) studies concurs with these observations, although he examined the pattern of apraxias in a somewhat different manner. In his patients with LHD he observed that the proportion of patients with an apraxia of equal magnitude in both conditions (54%) was much greater than the proportion of patients who showed an apraxia which was greater in pantomime (22%) or imitation (14%). In his patients with RHD, however, the proportion of patients with an apraxia of equal magnitude in both conditions (24%) was greater than the proportion of patients who showed a greater apraxia in pantomime (5%) but, as we found, was approximately equal to the proportion of patients who showed a greater apraxia on imitation (26%).

These findings that the co-occurrence of apraxia on pantomime and imitation is much higher among patients with LHD concurs with our observation of a stronger correlation between the conditions in this stroke group and by inference indicates that the likelihood of a disruption at the movement execution stage appears to be much higher in these patients. This pattern reflecting disruption of movement execution might be expected in many movement disorders such as those affecting the basal ganglia. Indeed considerable research now indicates that apraxia is seen in such disorders as Parkinson's disease (Leiguarda, Pramstaller, Merello, Starkstein, Lees, & Marsden, 1997; Pramstaller & Marsden, 1996), although little work has systematically compared performance in the two conditions. Confirmation of this pattern of apraxia in patients with such disorders would indicate that damage to different brain areas can lead to an apraxia affecting the movement execution stage of gesture performance, and our analysis system would afford the opportunity to compare the performance dimensions affected in patients with lesions in these various brain regions.

Analysis of Performance in Apraxia

Our analyses of apraxia reflecting accuracy on a number of performance dimensions are similar to other systems which have also attempted to measure the quality of movement production in apraxia. For example, Rothi, Mack, Verfaellie, Brown, and Heilman (1988) examined spatial (four types including location and orientation of the hand), hand-posture (referred to as body-part-as-tool errors in which the patient's hand became the tool such as using the extended index finger as the toothbrush in pantomiming brushing teeth), and action (movement distortions and occurrence errors which involved repeating a single-cycle gesture or failing to repeat a multicycle gesture) errors. Haaland and Flaherty (1984) examined arm- and hand-position, hand-posture, and hand-orientation errors, while McDonald et al. (1994) examined spatial (hand orientation and location), action (unsustained action, clumsy, or awkward implementation), and hand-posture (body-part-as-object) errors. In concert with our findings all of these studies have shown significant impairments in patients with LHD relative to controls on all of these dimensions, and the one study which compared patients with LHD or RHD (Haaland & Flaherty, 1988) showed, as we have, that patients with RHD were equally apraxic.

The findings from the present study also largely concur with our recent study of apraxia in pantomiming gestures (Roy et al., 1998) where both stroke groups were most impaired on the location, posture, and action dimensions. Our observation that these three performance dimensions are affected to the same degree in pantomime and imitation also concurs with the findings of McDonald et al. (1994), who showed the pattern of errors were the same in pantomime as in imitation.

The major difference between our approach to examining praxis and the analyses used by others (e.g., Haaland & Flaherty, 1988) is that we measure the accuracy of each performance dimension and so can derive, in the composite score, an index of the overall accuracy in performing a gesture. The approach used by others typically involves recording the presence of various types of errors, and individual gestures are then scored as either correct (no errors) or incorrect (one or more errors). The presence of apraxia in patients is defined on the basis of the number of correct gestures relative to controls, and the quality of their apraxic performance is revealed in the number and types of errors. Our approach has the advantage that one can more precisely define the presence of apraxia and the severity of the apraxic impairment among those patients classified as apraxic. In its present form our approach has the disadvantage of focusing exclusively on what Heilman (Rothi et al., 1997) calls production errors as opposed to content errors such as substitutions which may reflect more conceptual problems in praxis. Our present analysis system also misses exemplars of particular types of production errors such as body-part-as-tool errors, a specific type of hand-posture error. We do in fact code these content and specific production errors (Roy et al., 1985), although we have not reported these in this investigation. The goal of our future work is to combine the precision of our movement analysis system with its focus on production errors with the qualitative features of an error notation system capable of identifying more conceptually based errors.

While we recognize the advantages of the precision of our movement analysis system, we also realize that our system may in some sense be too sensitive in that many central and peripheral disorders which disrupt the control of movement may be found to affect gesture performance. This sensitivity, however, may prove to be useful in discriminating the contribution of movement disorders such as tremor from disorders which might be more clearly identified as apraxic. For example, assuming one had a measure of a disorder such as tremor one could, through correlation analyses, estimate the contribution made by this tremor to gestural performance. Using the residual measure of performance accuracy after the effects of tremor are removed one could compare gestural performance among patients with different lesion sites. Gestural performance of patients with cortical lesions could then be more directly compared to patients with subcortical disorders such as Parkinson's disease, since the impact of hyperkinetic movement problems seen in these latter disorders would be largely eliminated.

One might argue that kinematic analyses such as those employed by Poizner's group (Merians et al., 1997; Poizner et al., 1990, 1997) would provide better descriptions of disorders in movement execution than the description afforded by our system. Work by Goldenberg (Hermsdorfer, Mai, Spatt, Marquardt, Veltkamp, & Goldenberg, 1996), however, has shown a dissociation between kinematic analyses and analyses such as ours which focus on observing errors. In examining patients with LHD imitating meaningless gestures he found two distinct groups. In one group the patients' kinematic movement profiles looked like those for the controls, but the final location of the hand in space was quite in error. The other group showed the opposite pattern; their kinematic profile was quite impaired relative to controls, although hand location was correct. These findings suggest that we must develop approaches which integrate error analyses reflecting in a sense the end product of the movement (e.g., hand location or posture achieved) with kinematic analyses which describe the characteristics of the movement path to achieve these end products. This goal of integration is consistent with the larger aim in neuropsychology to combine product and process analyses of performance (cf. Roy, 1990).

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