BRAIN AND COGNITION 27, 213–236 (1995)

Progressive Ideomotor Apraxia: Evidence for a Selective Impairment of the Action Production System

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We report a patient with slowly progressive bilateral limb apraxia associated with an asymmetrical focal degenerative process of the parietal lobes. Clinical assessment of praxis production suggested a striking deficit in controlling the spatiotemporal attributes of purposeful skilled limb movements, consistent with ideomotor apraxia. The precise nature of the action production impairment was further defined by objective three-dimensional computergraphic analysis of transitive movements which demonstrated significant kinematic deficits in spatial accuracy, timing, spatiotemporal coupling, and joint coordination. Gesture comprehension and discrimination were spared. Furthermore, detailed evaluation of the conceptual praxis system revealed that despite an almost complete inability to perform transitive movements accurately, abstract knowledge of tool function and action was remarkably well preserved. The critical dissociation between intact conceptual knowledge of action and impaired movement execution documented in this case points to a fundamental competence/performance dichotomy in apraxia and provides empirical support for cognitive models of praxis that divide the action system into distinct conceptual and production subcomponents. Within this theoretical framework, our patient's severe ideomotor apraxia is interpreted to represent a selective disruption of the action production system.

INTRODUCTION

Cognitive neuropsychological models of praxis divide the action system into conceptual and production subsystems (Roy & Square, 1985).

The three-dimensional motion analyses were supported in part by NIH Grant NS28665 and NSF Grant DBS92-13110 to Rutgers University. We thank Olga Fookson, Benjamen Liberman, Abhay Kothari, Maryann Clark, and Alma Merians for their help. Address correspondence and reprint requests to Steven Z. Rapcsak, M.D., Neurology Service (127), VA Medical Center, Tucson, AZ 85723.

0278-2626/95 $6.00

According to Roy and Square (1985), the conceptual system contains three types of abstract information relevant to praxis: knowledge of objects and tools in terms of their functions, "decontextualized" knowledge of action that is independent of objects or tools but into which appropriate objects and tools can be incorporated, and knowledge about the serial organization of single actions into a sequence. By contrast, the production system represents knowledge of action in sensorimotor form and includes action programs for skilled movements as well as mechanisms for translating these programs into motor activity. Peripheral sensorimotor processes involved in lower-level movement control are also included within the action production system.

The cognitive model of praxis outlined above provides a useful theoretical framework for interpreting the two major types of apraxic disorders encountered in patients with brain damage: ideational apraxia and ideomotor apraxia. According to the model, ideational apraxia results from a dysfunction of the conceptual praxis system. Impaired knowledge of tool function and action in patients with ideational apraxia is manifested by incorrect selection and conceptually inappropriate use of objects or tools (Morlaas, 1928; De Renzi, Pieczuro & Vignolo, 1968; De Renzi & Lucchelli, 1988; Ochipa, Rothi, & Heilman, 1989, 1992) and/or by a failure to perform in the correct sequence actions requiring the use of several objects to achieve an intended goal (Pick, 1905; Liepmann, 1920; Lehmkuhl & Poeck, 1981; Poeck, 1983). A genuine conceptual defect in ideational apraxia is strongly suggested by observations that patients with this disorder also perform poorly on various verbal or nonverbal tasks that tap knowledge of action but which do not require manipulation of actual objects (Lehmkuhl & Poeck, 1981; Roy, 1981; Ochipa, Rothi, & Heilman, 1989, 1992). Theoretically, patients with ideational apraxia should not have difficulty with movement execution per se, since in these patients the action production system is believed to be spared. Ideational apraxia is typically seen with lesions located in the posterior temporoparietal region of the left hemisphere (Liepmann, 1920; De Ajuriaguerra, Hécaen, & Angelergues, 1960; De Renzi & Lucchelli, 1988).

In contrast to ideational apraxia, ideomotor apraxia reflects a disruption of the action production system. Specifically, it has been proposed that ideomotor apraxia is caused by lesions that either damage visuokinesthetic engrams for skilled movements stored in the left parietal lobe or disconnect these engrams from motor association areas (Heilman, 1979; Heilman & Rothi, 1985). The information contained in visuokinesthetic engrams is thought to be critical for guiding the motor system in adopting the appropriate spatial positions of the relevant body parts over time (Heilman, 1979). Accordingly, the movement production impairment of patients with ideomotor apraxia is characterized predominantly by spatiotemporal errors (Heilman & Rothi, 1985; Rothi et al., 1988; Poizner et al., 1990). Since the conceptual praxis system is presumed to be intact, patients with ideomotor apraxia should not use objects and tools in a conceptually inappropriate fashion and should not have difficulty with the serial organization of action.

Although the division of the action system into distinct conceptual and production subcomponents appears theoretically sound, neuropsychological support for this proposed dichotomy is still relatively scarce and mostly comes from group studies that have found a rather loose association between ideational apraxia and ideomotor apraxia (De Renzi, Pieczuro, & Vignolo, 1968; Lehmkuhl & Poeck, 1981; De Renzi & Lucchelli, 1988; Ochipa, Rothi, & Heilman, 1992). In contrast, detailed single case reports documenting theoretically important functional dissociations between conceptual knowledge of action and the ability to execute skilled movements are few in number and seem to have involved patients with atypical cerebral dominance (Poeck & Lehmkuhl, 1980; Ochipa, Rothi, & Heilman, 1989). The reason for the relative dearth of well-documented cases with praxis impairment selectively limited to either the conceptual or the production system is in part anatomical, since the operations of both action systems depend critically on posterior left hemisphere cortical areas that are in close anatomical proximity and may thus be damaged simultaneously. Other possible reasons include the long-standing controversy concerning the nature of ideational apraxia and the related lack of consensus about testing procedures most appropriate for assessing the integrity of the conceptual praxis system. Last, but not least, patients with posterior left hemisphere damage are frequently aphasic, and comprehensive assessment of the action system in these patients is often fraught with considerable methodological difficulties.

In this report we describe a patient who presented with slowly progressive bilateral limb apraxia without aphasia, in association with a focal degenerative process of the parietal lobes. Severe ideomotor apraxia, characterized by a striking impairment in controlling the spatiotemporal aspects of transitive limb movements, was documented both by clinical examination and by objective three-dimensional computergraphic analysis of movement errors. Detailed evaluation of the conceptual praxis system, however, revealed that abstract knowledge of tool function and action was remarkably preserved. Based on these findings, we propose that our patient's apraxia was due to a selective impairment of the action production system.

CASE REPORT

GW is a 61-year-old right-handed woman, who originally presented to us in 1989 with a 4- to 5-year history of progressive inability to carry out purposeful skilled movements with her upper extremities. She had the impression that she could not make her hands do what she wanted and complained of severe "clumsiness" in all manual activities, especially when using the left upper extremity. She stated that even simple, routine motor tasks were no longer "automatic" and required deliberate effort and attention on her part. GW's manual difficulties were clearly apparent in everyday activities and severely interfered with her ability to use household objects. For instance, she had to rely on other people to help her get dressed and needed assistance in preparing meals and in cutting the food on her plate. GW spontaneously commented that since her illness she had to give herself verbal directives while using objects and had to talk her way through familiar action routines.

In addition to the difficulties she experienced in using her hands, GW also complained of profound spatial disorientation. She had in fact been involved in several automobile accidents which, according to her, had all resulted from her inability to judge accurately the positions of other cars on the road. She complained of not being able to find her way to the cashier in her local supermarket and of "constantly getting lost between the aisles." She claimed she could not judge the position of her body correctly with respect to other objects in the environment and would repeatedly bump into things. She frequently missed the chair when attempting to sit down and even had trouble correctly orienting her body to lie down in bed. In contrast to her severe spatial impairment, GW denied any language difficulties.

Neurological examination at the time of her initial presentation revealed intact visual fields, although left-sided visual extinction was apparent on double simultaneous stimulation. Extraocular movements were full, but she had difficulty in directing saccades accurately to targets presented in the visual periphery. Although she could touch objects presented in central vision fairly accurately, she occasionally misreached for targets presented in peripheral vision while fixating centrally. She could point correctly to named body parts both with eyes open and with eyes closed.

Except for mild rigidity at the left shoulder, tone was normal in all extremities. Muscle strength was intact. Rare choreo-athetoid movements were observed in the left arm while at rest but not during attempted movements. Pain, temperature, light touch, and vibration sense were intact, although left-sided tactile extinction was demonstrated on double simultaneous stimulation. Position sense was diminished in the limbs bilaterally. However, stereognosis and graphesthesia were preserved. Deep tendon reflexes were symmetrical and the plantar responses were flexor.

Magnetic resonance imaging (MRI) scan revealed striking focal atrophy of the posterior–superior parietal lobes, more pronounced on the right side (Figs. 1 and 2). By contrast, the frontal, temporal and occipital areas appeared to be relatively spared. Single-photon emission computed to-

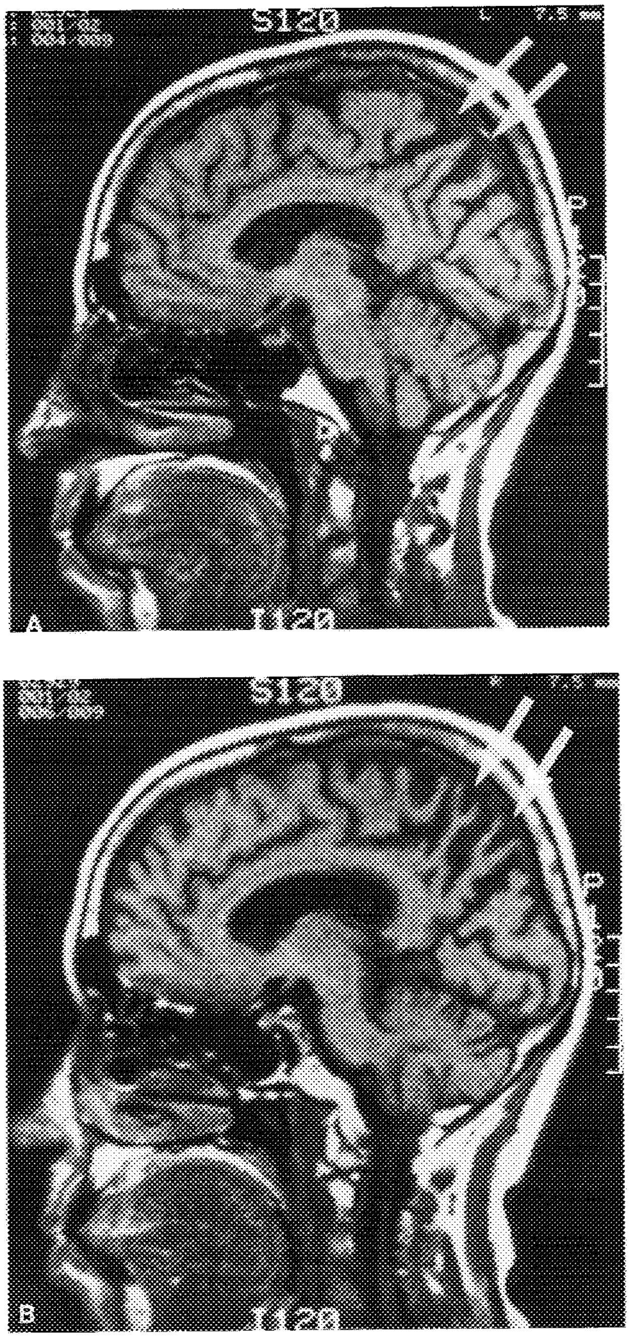

FIG. 1. (A,B) Sagittal MRI scans taken from slightly to the left and to the right of midline showing focal parietal atrophy in the left and right hemispheres (arrows).

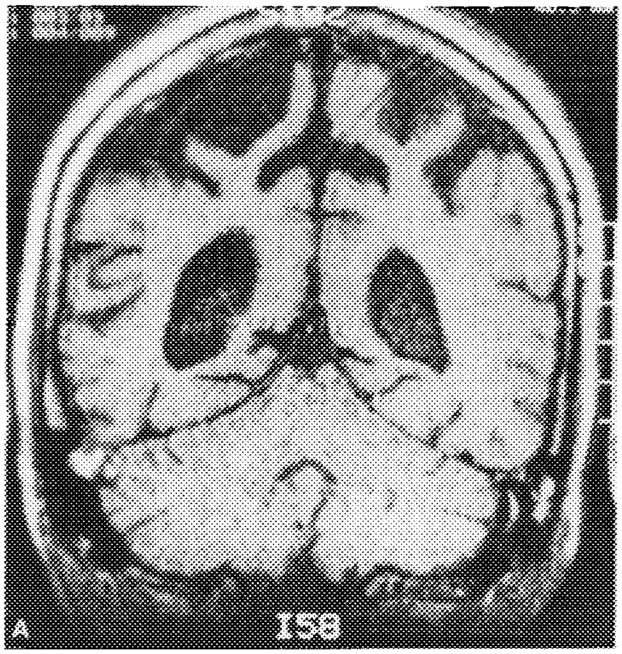

FIG. 2. (A,B,C) Coronal MRI scan demonstrating asymmetrical bilateral atrophy of the posterior–superior parietal regions.

mography (SPECT) demonstrated more extensive posterior cortical dysfunction than what was apparent by MRI. The area of diminished metabolic activity revealed by SPECT involved the entire temporo-parietal area on the right side and on the left side extended into the region of the inferior parietal lobule.

NEUROPSYCHOLOGICAL EVALUATION

GW's performance on the WAIS-R (Wechsler, 1981) yielded a Verbal IQ of 101 and a Performance IQ of 66, with a Full Scale IQ of 86. On the Wechsler Memory Scale-R (Wechsler, 1987), GW obtained an MQ of 103, with subtest scores consistent with intact verbal (Verbal Memory Index = 120) but impaired visual (Visual Memory Index = 75) memory. It should be noted that GW's lower visual memory score on this test was in large part due to her severe constructional apraxia. Memory functions were further evaluated with the Warrington Recognition Memory Test (Warrington, 1984). On the verbal subtest GW achieved a score of 45/50 and on the faces subtest a score of 48/50, both within normal range. GW correctly recognized 15/15 famous faces.

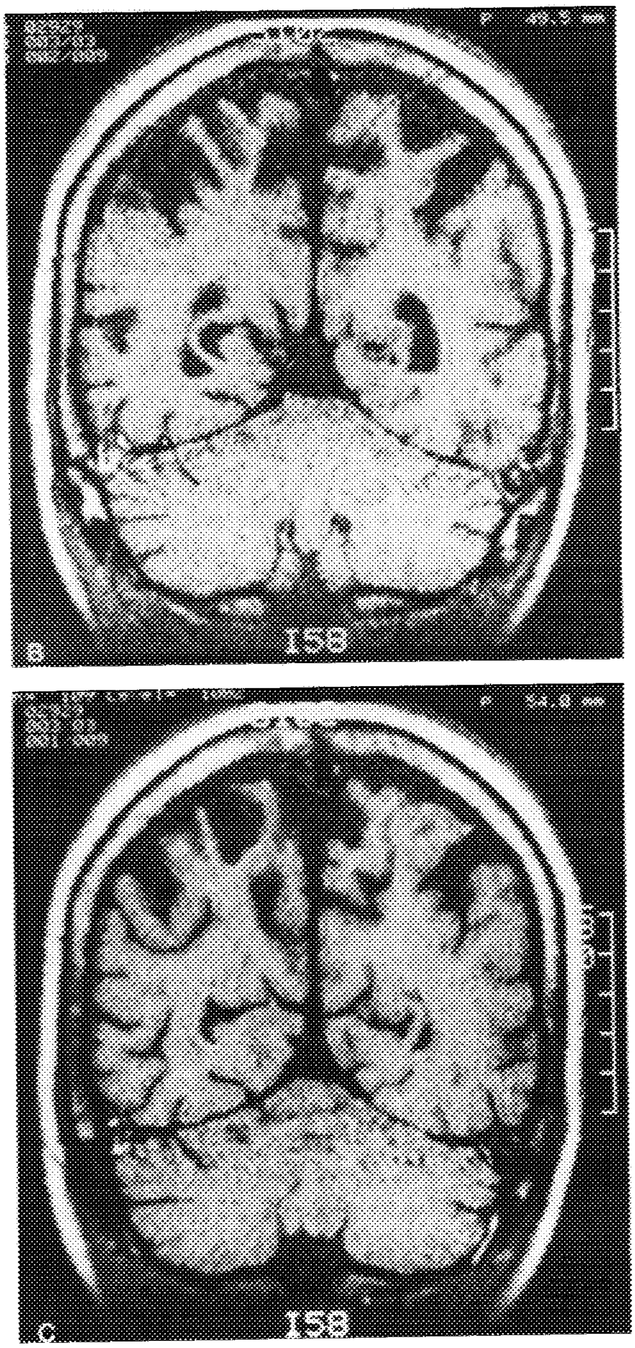

Fig. 2—*Continued*

Language functions were formally assessed with the Western Aphasia Battery (Kertesz, 1982). GW obtained an Aphasia Quotient of 99.7, thus scoring in the non-aphasic range. Her performance on the Boston Naming Test (Kaplan, Goodglass, & Weintraub, 1983) was also within normal limits (57/60). GW had no difficulty in comprehending written sentences, but she would sometimes lose her place in the text while reading. On the Battery of Adult Reading Functions (Rothi, Coslett, & Heilman, 1984), she correctly read all regular words, irregular words, and nonwords. She could also correctly spell these words to dictation. Although she generally produced well-formed letters, she had a tendency to write on the right side of the page and had difficulty keeping her lines straight.

In sharp contrast with her preserved language abilities, GW's performance on several visuospatial tasks was significantly impaired. For instance, on the Benton Judgment of Line Orientation (1983) and the Benton Visual Form Discrimination (1983) tests her scores fell within the moderately to severely defective range. However, on the Benton Facial Recognition Test (1983) she scored within normal range (Corrected Long Form Score = 44). GW exhibited severe constructional apraxia and was unable to draw or copy even simple figures accurately. Line bisection tasks revealed inconsistent left-sided neglect, but performance on a line cancellation test was normal.

EVALUATION OF THE ACTION SYSTEM

Action Production

Clinical Assessment

Procedure: Transitive movements. GW's ability to perform transitive movements was evaluated using a modified version of the Florida Apraxia Screening Test (Rothi & Heilman, 1984). GW was asked to demonstrate the use of 15 common household tools in the following four experimental conditions: on verbal command, on visual command (i.e., pantomiming the use of an object that she was allowed to see but not handle), on imitation, and with the actual objects.

Serial actions. In addition to evaluating the use of single objects, we also investigated performance on seven serial action tasks requiring the use of several objects to achieve an intended goal (making coffee using an electric coffee maker, lighting a candle, mailing a letter, opening a can of food and putting the contents on a plate, looking up a number in the phone book and dialing it, opening a bottle and pouring a drink, lighting a cigarette). All the necessary objects were placed on the table and GW was verbally requested to perform a given task.

Scoring. Performance on all praxis production tasks was videotaped and was scored independently by two investigators. Transitive movements were first scored as either correct or incorrect. Qualitative analysis of movement errors was subsequently carried out using the classification system developed by Rothi et al. (1988). In the serial action tasks, we scored the number of component actions correctly performed in the appropriate sequence. Sequence errors, omissions and conceptually inappropriate use of objects were recorded, but spatiotemporal movement errors in manipulating the various objects were ignored.

Results: TRANSITIVE MOVEMENTS. GW was unable to produce even a single transitive gesture correctly with either hand on verbal command, visual command or imitation. She used 3/15 objects correctly with her right hand and 1/15 with the left. Qualitative analysis revealed that spatial errors (i.e., internal configuration, external configuration and movement errors) were the most common in all conditions, although the temporal aspect of the movement was also frequently defective. Taken together, spatiotemporal errors accounted for 90% of all praxis production errors. The remaining errors (10%) were classified as body-part-as-object errors. Content errors (i.e., a correctly executed movement which, however, is not appropriate for the target object) and perseverations were not observed. It is notable that although GW was overall slightly more successful with real objects, her performance in manipulating actual tools was also characterized by prominent spatiotemporal movement errors. Furthermore, she often had difficulty in correctly positioning her hands to grasp the tools and in orienting tools appropriately both with respect to her body and with respect to the location of the imagined recipient of the tool's action in extrapersonal space.

SERIAL ACTIONS. In performing the seven serial action tasks, GW made two sequence errors (e.g., dialing the phone number before picking up the receiver), both of which she spontaneously detected and corrected. She also made a single error of omission which she failed to correct spontaneously. Conceptually inappropriate use of objects was not observed. Some hesitations were apparent, especially when carrying out longer action sequences, and it was noted that GW was at times trying to talk her way through the task.

Three-Dimensional Computergraphic Analysis of Transitive Movements

Precise information regarding the spatial and temporal characteristics of skilled movements is difficult to obtain from visual inspection alone. To better define the nature of GW's praxis production errors, three-dimensional computergraphic analysis of transitive movements was undertaken. This technique has already been used successfully for the objective analysis of movement errors in patients with ideomotor apraxia following left hemisphere lesions (Poizner et al., 1989, 1990; Poizner & Soechting, 1992).

Three-dimensional movement data were acquired for transitive gestures made in a series of conditions in which contextual cues were introduced in a graded fashion. Movements were made to verbal command, imitation, with tool present, with the object of the tool's action present and with both tool and the object provided. Analyses were performed on a variety of transitive gestures, including slicing food, erasing a blackboard, hammering a nail, and unlocking a door with a key. We present below kinematic analyses of one of these gestures; however, the conclusions apply to GW's production of other transitive gestures as well.

Procedure. The gesture of slicing a large object of food (such as a loaf of bread or a turkey breast) to verbal command was selected to illustrate the nature of GW's movement production errors. This gesture has certain readily definable spatial requirements. A successful slicing movement requires that the shape of the trajectory at the hand be linear and planar. Furthermore, the gesture requires a cyclic forward and backward motion which has a sharp reversal and overlapping planes of movement.

GW's performance was contrasted with that of eight normal right-handed control subjects. To allow for further comparisons with data obtained from patients with ideomotor apraxia following left hemisphere lesions who were evaluated using the same procedure (Poizner et al., 1989, 1990; Poizner & Soechting, 1992), GW and all normal subjects used their left hand to perform the gesture. The slicing gesture was repeated four times in order to obtain measures of movement variability.

Three-dimensional data acquisition and reconstruction. Two commercially available optoelectric cameras (WATSMART, Northern Digital, Inc.) directly sensed the positions of four infrared emitting diodes which were secured to the subject's left arm at the shoulder, elbow, wrist, and hand. A microcomputer synchronized the sequential activation of the diodes with the digitizing of the camera signals. The position of each of the four joints was sampled at 100 Hz and low pass filtered with a modified Butterworth filter using a cutoff frequency of 8 Hz. Limb trajectories were recorded from neighboring views so that three-dimensional coordinates could be reconstructed. The data were analyzed on a Silicon graphics IRIS 4D/80GT workstation using customized software for the interactive manipulation and dynamic display of the reconstructed trajectories (Poizner, Wooten, & Salot, 1986; Jennings & Poizner 1988; Kothari, Poizner, & Figel, 1992). For analysis, the slicing motion was divided into individual movement cycles, each consisting of one forward and backward trajectory path.

Kinematic analyses. Kinematic analyses were performed on the trajectories of the wrist, and on the angular motions of the shoulder and elbow joints. We turn first to movement at the wrist, which represents the combined action of shoulder and elbow motions. Algorithms were written to capture specific trajectory features of spatial accuracy, temporal attributes, and spatiotemporal relationships. Medians and the Mann–Whitney U test were used for statistical analysis, since these statistics are relatively unaffected by single outlier values, and equal data sets and stringent assumptions about the distribution of the values are not required for statistical comparisons. An α level of $p < .01$ was selected due to the number of comparisons computed.

SPATIAL ACCURACY. Spatial accuracy was defined by three spatial features: plane of motion, degree of movement planarity, and movement amplitude. The *plane of motion* was measured by computing the best-fitting plane of motion for the wrist trajectory for each cycle of movement using a least squares regression to the plane equation. To specify the plane's orientation in three-dimensional space, the direction vector perpendicular to each plane (plane normal) was calculated. The anterior–posterior component of the plane normals significantly differed between GW and the control subjects ($U_{118,14} = 111$, $p < .0001$). This difference in the plane of motion at the wrist was due to a substantial component of the movement occurring in the frontal plane for GW; control subjects restricted their movements to the sagittal plane. In order to quantify the degree of *movement planarity* (as opposed to specifying the orientation of the plane of movement), the standard deviation of the distances of individual coordinate values from the best-fitting plane was computed and normalized to the amplitude of the movement (length of major axis). GW's movements were significantly less planar than those of the control subjects ($U_{118,14} = 1454$, $p < .0001$). Finally, the amplitude of GW's movements was less than that of the control subjects (median amplitude per cycle of movement = .233 meters for GW, .41 meters for controls, $U_{118,14} = 1215$, $p < .005$).

TEMPORAL ATTRIBUTES. The peak velocity of GW's movements was considerably slower than that of the control subjects (median peak velocity = .35 meters/sec for GW, .95 meters/sec for controls, $U_{118,14} = 1548$, $p < .0001$).

SPATIOTEMPORAL ATTRIBUTES. Movement trajectories may be described in terms of their spatial path and the time sequence along that path. In normal movements ranging from handwriting to point-to-point movements to three-dimensional scribbling in the air, a close association exists between spatial and temporal movement attributes: as the speed of the hand decreases, the curvature, or degree of bending, of the path increases (Viviani & Terzuolo, 1982; Morasso, 1983). The upper panels of Fig. 3 present tangential velocity and radius of curvature during the course of one movement produced by GW and by a control subject. Figure 3 shows that the control subject's movement has smooth sinusoidal variation in velocity and varies in proportional fashion with curvature (the radius of curvature, the inverse of curvature is plotted so that both curves can be presented on the same graph). GW's velocity profile, in contrast, is highly

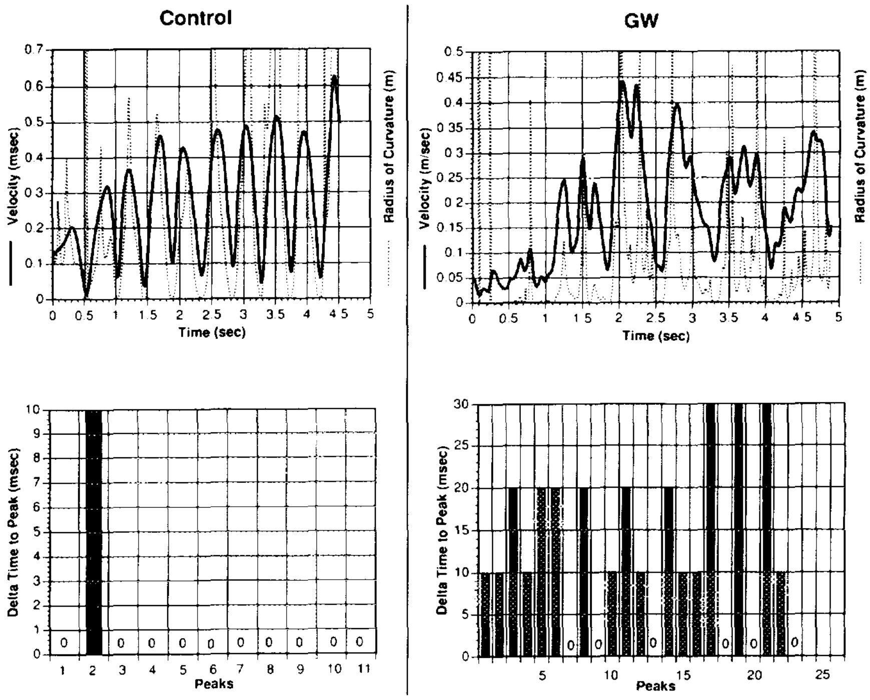

FIG. 3. Velocity-curvature decoupling in GW. Tangential wrist velocity and radius of curvature are plotted in the upper panels. Time correspondences between velocity minima and radius of curvature minima are plotted in the lower panels.

irregular and non-sinusoidal and is less coupled with radius of curvature. To capture the linkage between velocity and radius of curvature, a computer algorithm was written to locate and mark tangential velocity minima and radius of curvature minima. The difference in time between each velocity minimum and the nearest radius of curvature minimum was taken as a measure of velocity–curvature decoupling. Time differences of zero reflect tight spatiotemporal coupling, whereas larger time differences reflect greater spatiotemporal decoupling. These time differences are presented in the lower panel of Fig. 3 and indicate marked decoupling of velocity and curvature in GW. Across all trials and subjects, velocity–curvature was significantly more decoupled in GW than in the control subjects ($U_{79,259} = 5042$, $p < .0001$).

INTERJOINT RELATIONS. The angular orientation of the upper arm and of the forearm was calculated, as was the angle of flexion and extension of the elbow. The parameters chosen were the angular elevation (θ and β) and yaw (η and α) of the upper arm and forearm, as defined in Fig. 4 (see Soechting & Terzuolo, 1986, for a detailed description of these

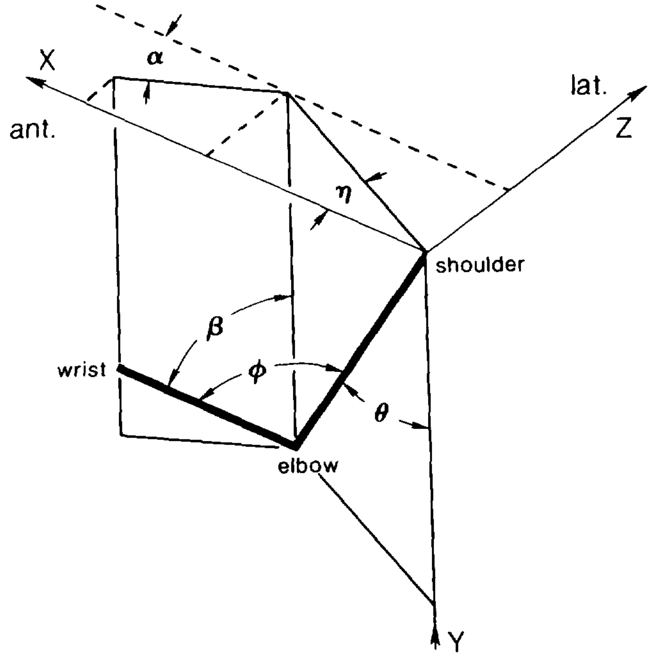

FIG. 4. Parameters used to define the angular orientation of the arm. The angles θ and β represent the angular elevation of the arm and forearm and are measured in a vertical plane relative to the vertical (*Y*) axis. The yaw angles η and α are measured in the horizontal plane from the anterior (*X*) direction. Reprinted from J. F. Soechting and C. A. Terzuolo, *Neuroscience*, **19**, 1393–1405, copyright 1986, with kind permission from Elsevier Science Ltd, The Boulevard, Langford Lane, Kidlington OX5 1GB, UK.

angles). Angular elevation is measured in a vertical plane relative to the vertical axis and yaw in the horizontal plane relative the the anterior direction. These angles were identified previously psychophysically as the preferred coordinate system for the recognition of the orientation of the arm in space (Soechting & Ross, 1984).

The top panels of Fig. 5 present the variation in alpha and eta over time, that is, variation in motions of the forearm and upper arm in the horizontal plane, for GW and for a control subject. The top panels of Fig. 5 show that GW's joint motions were less sinusoidal than that of the control subject, and that the relative amplitudes of forearm and upper arm motions were apportioned differently from that of the control subject. Whereas α decreased over a somewhat large range for GW, it varied sinusoidally over much smaller ranges for the control subject. In contrast, η varied over smaller ranges for GW than for the control subject. The frequency of the variation in this upper arm motion, however, was similar in the two subjects. In order to quantify the relation among amplitudes

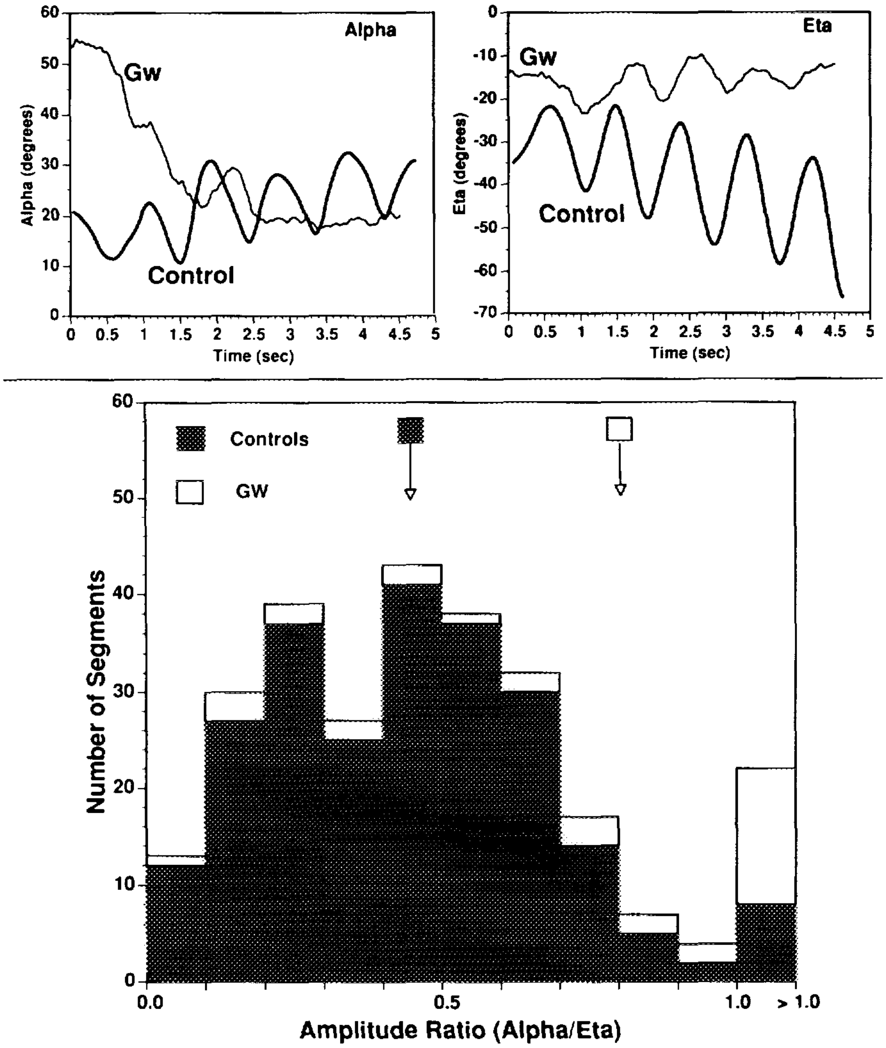

FIG. 5. Top panel. Variation in motions of the forearm and upper arm in the horizontal plane for GW and for a control subject. Bottom panel. Relative amplitudes of forearm and upper arm motion in the horizontal plane, across all segments and replications of the "slice" gesture for GW versus the eight control subjects. Arrows provide median amplitude ratios. Note that GW apportions the arm angles in different relative amplitudes than the control subjects.

for the arm angles, the angles were first segmented. In this step, an initial set of boundary positions were defined to break up the arm angle functions into short segments that can be fit with sine waves. A computer algorithm then moved the segment boundaries to the left and to the right along the time axis to reduce the error of the fit of sine waves to the data. This error reduction procedure was performed iteratively by gradually reducing the time interval over which a given boundary was adjusted. In this manner, the algorithm narrowed in on the segment boundaries that maximized the fit of sine waves to the data (Soechting, 1983; Soechting & Ross, 1984; Soechting, Lacquaniti, & Terzuolo, 1986; Poizner & Soechting, 1992).

With the data fitted with sine waves, relative amplitudes of the arm angles could be calculated. The lower panel of Fig. 5 presents a histogram of the relative amplitudes of the two arm angles, forearm yaw to upper arm yaw, across segments for all replications of the slicing gesture for GW versus that for all eight control subjects. Ratios of arm angles are taken to normalize for differences in arm size and in absolute size of movements. The arrows in Fig. 5 indicate median ratios. The lower panel of Fig. 5 shows that the control subjects had a median amplitude ratio of approximately .5, indicating that the control subjects had roughly twice the displacement of the upper arm in the horizontal plane than displacement of the forearm in the horizontal plane. The lower panel of Fig. 5 further shows that GW had much higher ratios, with median forearm yaw to upper arm yaw being approximately .8 ($U_{34,238} = 2064$, $p < .0001$). Thus, control subjects coordinate shoulder and elbow motions to keep the forearm in the sagittal plane, despite the upper arm's moving out of that plane. GW, in contrast, moved her arm more as a single unit rather than properly coordinating shoulder and elbow motions and thus did not produce the appropriate trajectory path at the wrist.

Summary of data from three-dimensional computergraphic analyses. Although we only provided detailed analysis of a single gesture here, it should be noted that transitive movements across *all* testing conditions, including the full context condition (i.e., both the tool and the object of the tool's action present), were characterized by similar spatial and temporal errors. In general, GW's movements were incorrectly oriented in space and inappropriately changed planar orientation within a movement. In addition to problems with spatial accuracy, movement timing was also markedly disrupted. GW exhibited a very slow buildup of hand velocity, reflecting a delay in initiating the movement, as well as a very irregular, non-sinusoidal velocity profile. Furthermore, there was evidence for a substantial decoupling of spatiotemporal movement attributes (hand velocity and trajectory curvature) and for defective joint coordination. The kinematic deficits that GW demonstrated in spatial accuracy, timing, spatiotemporal coupling and joint coordination closely matched the types of deficits we have previously documented in left-hemisphere-damaged patients with ideomotor apraxia (Poizner et al., 1989, 1990; Poizner & Soechting, 1992).

Action Recognition and Discrimination

GW's ability to recognize pantomimed actions was evaluated by asking her to name the 15 transitive gestures from the Florida Apraxia Screening Test (Rothi & Heilman, 1984) when these were performed by the examiner. Her performance on this task was flawless.

Action discrimination was tested by asking GW to select the correct transitive gesture from among three gestural foils that included spatial, body-part-as-object and content errors. She responded correctly on 14/15 (93%) trials, and her only error consisted of selecting a body-part-as-object action foil.

Conceptual Knowledge of Tool Function and Action

The following verbal and nonverbal tests were designed to assess abstract conceptual knowledge of tool function and action. Unlike the action production tasks described above, these tests *did not* require GW to perform gestures or to manipulate actual tools or objects.

Knowledge of Tool Function

Identifying tools from verbal functional descriptions. GW was asked to name household tools in response to verbal descriptions of their functions (e.g., tell me what you use for cutting the meat on your plate). In another version of this task she was asked to select the appropriate tool from among four foils, in response to a verbal description of the tool's function. There were 10 trials in each condition. GW's performance was flawless on both versions of this test.

Tool function identification. GW was asked to describe verbally the function of visually presented tools. In another version of this test she was asked to verbally identify the function of household tools named by the examiner. There were 10 trials in each condition. GW correctly responded on all trials in both conditions.

Tool selection task. Knowledge of tool function was further evaluated by presenting GW with 10 partially completed tasks (e.g., a partially sawed board) and asking her to select from an array of five tools the one appropriate for completing the task. Her performance on this test was flawless.

Knowledge of Action

Verbal description of actions required for tool use. GW was asked to verbally describe the actions involved in using the 15 household tools that were previously used in evaluating her ability to produce transitive movements. GW's verbal descriptions suggested that despite her severe inability to execute transitive movements accurately, she had preserved conceptual knowledge of the types of actions required for tool use (e.g., "I pick up the hammer with my hand, put the handle in my palm and then use it to pound a nail by repeatedly swinging it in an arc through the air until it lands on the nail").

Alternate tool selection task. Conceptual knowledge of action is to a certain extent independent of the tools with which the action is usually associated. For instance, pounding a nail is usually associated with using a hammer, but pliers might also be used to accomplish the task if a hammer was not available. Decontextualized knowledge of action that is independent of tools but into which appropriate tools can be incorporated (Roy & Square, 1985) was evaluated with an alternate tool selection task. GW was presented with a partially completed task (e.g., a nail partially driven into a piece of wood) and an array of five tools that included four foils and one tool that could be used to complete the task given its structural attributes (e.g., pliers), although the tool was not usually used for that purpose. GW selected the correct tool alternative on 10/10 trials.

Knowledge Relevant to the Serial Organization of Action

Verbal description of serial actions. In this task GW was asked to verbally describe all the steps involved in the seven serial action tasks that she previously attempted to perform. She readily described all the necessary steps in their correct order.

Picture arrangement. GW was given seven sets of four to six color photographs. Each set contained pictures depicting the component actions involved in one of the seven serial action tasks that she was previously asked to perform. The photographs for each serial action task were laid out on a table in random order and GW was asked to arrange the action pictures in their correct sequence. GW performed flawlessly on this task.

DISCUSSION

The insidiously progressive limb apraxia in GW was caused by an asymmetrical focal degenerative process that involved predominantly the posterior parietal regions of the brain. Bilateral and frequently asymmetrical posterior cortical atrophy has been described previously in association with slowly progressive apraxia (De Renzi, 1986; Dick et al., 1989; Piccirilli, 1990; Léger et al., 1991; Caselli et al., 1992). The nosological status of asymmetrical cortical degeneration remains uncertain, since pathological examination of brains with posterior cortical atrophy have produced variable histological patterns (Ross et al., 1990).

Apraxia is not uncommon in senile dementia of the Alzheimer type (Della Sala, Lucchelli, & Spinnler, 1987; Rapcsak, Croswell & Rubens, 1989; Ochipa, Rothi & Heilman, 1992). Furthermore, in Alzheimer's disease the degenerative process has a well-known predilection for the posterior temporo-parietal cortical regions (Brun & Gustafson, 1976; Brun & Englund, 1981; Kemper, 1984). However, it is unlikely that GW suffered from Alzheimer's disease, given the striking sparing of language, verbal intelligence, and memory functions and the preservation of insight, judgment, and personality 4 to 5 years after the onset of her illness. The fact that slowly progressive limb apraxia can present as a relatively isolated neuropsychological deficit in the setting of posterior cortical atrophy, without the general intellectual decline and memory loss that characterizes dementia, has been documented in other cases as well (De Renzi; 1986; Dick et al., 1989; Piccirilli, 1990; Léger et al., 1991).

Detailed evaluation of the action system in GW revealed evidence of severe bilateral limb apraxia. In pantomiming transitive movements, she was unable to produce even a single gesture correctly with either hand and she only improved minimally with the use of actual objects. Visual inspection of her gesture production errors suggested a severe breakdown of the spatiotemporal aspects of purposeful skilled movements and this clinical impression was subsequently confirmed and objectively defined by three-dimensional computergraphic analysis of transitive movements. Prominent spatial errors included inappropriate positioning of the hands for grasping the objects, incorrect planar orientation of the movement both with respect to the body and the target of the movement in extrapersonal space, and a disruption of the normal spatial movement trajectory. Control over temporal variables such as movement initiation, fluidity and timing was also severely defective. Finally, there was a substantial decoupling of the normally tight relationship between specific spatiotemporal movement attributes (hand velocity and trajectory curvature) and a significant deficit in joint coordination. Although GW's spatiotemporal movement errors were qualitatively very similar to those observed in patients with ideomotor apraxia following unilateral left hemisphere lesions (Rothi et al., 1988; Poizner et al., 1989, 1990; Poizner & Soechting, 1992), the overall severity of her limb apraxia was somewhat unusual. However, a virtually complete inability to perform skilled movements has also been described in other cases of progressive limb apraxia associated with bilateral posterior cortical degeneration (De Renzi, 1986; Dick et al., 1989; Piccirilli, 1990). The unusual severity of apraxia in these patients may be related to the bilaterality of the pathological process and the inexorably progressive nature of the underlying disease.

Spatiotemporal errors in ideomotor apraxia are thought to result from the destruction of visuokinesthetic engrams or, alternatively, they may reflect a disconnection of these engrams from motor association areas

(Heilman, 1979; Heilman & Rothi, 1985). Heilman (1979) proposed that visuokinesthetic engrams for skilled movements were located in the dominant inferior parietal lobule (IPL) (Brodmann's areas 39, 40). By MRI, the atrophic process in GW's left hemisphere was confined mostly to the superior parietal lobule (SPL) (Brodmann's areas 5 and 7), although SPECT imaging revealed that the area of cortical dysfunction also extended into the region of the IPL. While the association of ideomotor apraxia with left IPL damage is well-established (Faglioni & Basso, 1985), it should be noted that limb apraxia has also been reported following a focal vascular lesion that involved the SPL (Heilman et al., 1986). Furthermore, at least in one case of progressive limb apraxia the bilateral degenerative process appeared to have been confined to the SPL both by CT and by SPECT (Dick et al., 1989). The SPL is reciprocally interconnected with motor association areas (Petrides & Pandya, 1984; Pandya & Yeterian, 1985). Converging evidence from neurophysiological studies in primates and neuropsychological investigations in humans with focal brain damage suggests that the superior parietal regions play a critical role in transforming visuospatial information relevant to reaching and other spatially directed complex limb movements into somesthetic codes suitable for directing the motor system (Mountcastle et al., 1975; Hyvärinen, 1982; Jeannerod, 1988). Cerebral blood flow and positron emission tomography (PET) activation studies in normal subjects have provided further evidence that the SPL is involved in the integration of spatial attributes during selection of hand movements in response to both external and internal cues (Roland et al., 1980; Roland, 1984; Deibert et al., 1991; Grafton et al., 1992). Heilman et al. (1986) proposed that the role of the SPL in controlling learned skilled limb movements is to translate the spatiotemporal information contained in visuokinesthetic engrams into somesthetic spatial codes, which in turn can be used to activate the appropriate premotor and motor neurons responsible for movement execution. Taken together, the neuroimaging data and the analysis of movement errors in GW suggest that her severe limb apraxia may have been caused by damage to visuokinesthetic engrams in the IPL, or it may have been related to damage to the SPL resulting in an inability to transcode stored spatiotemporal patterns for transitive movements into somesthetic codes suitable for guiding the motor system in movement execution, or, most likely, it reflected a combination of both mechanisms. Within the framework of the Roy and Square (1985) model, GW's ideomotor apraxia is consistent with a disruption of the praxis production system, since this subcomponent of the action system encompasses both the action programs for skilled movements and the appropriate mechanisms for translating these programs into motor activity.

Heilman et al. (1982) postulated that there may be two forms of ideomotor apraxia following left hemisphere damage. They suggested that apraxic patients with posterior parietal lesions which damaged the visuokinesthetic engrams were also impaired in comprehending action pantomimes and in discriminating correct gestures from incorrect ones, whereas apraxic patients with more anterior lesions that disconnected these engrams from motor association areas were impaired in gesture production only. However, recent models of praxis (Rothi, Ochipa, & Heilman, 1991) have posited that the system involved in comprehension and discrimination of action pantomimes is distinct from the gesture production system. The sparing of transitive gesture recognition and discrimination in GW despite an almost complete inability to execute transitive movements accurately is consistent with the proposed separation of action production and comprehension systems. Alternatively, it may be that gesture recognition is simply an easier task than gesture production. Consequently, damaged or degraded visuokinesthetic engrams could still support gesture recognition and discrimination even when correct gesture production is no longer possible.

Although GW made numerous spatiotemporal errors in performing transitive movements, she did not produce content errors and was never observed to use tools in a conceptually inappropriate fashion. This particular aspect of her performance pointed to the possibility that despite the severe ideomotor apraxia, the conceptual praxis system may have been preserved. Our clinical impression was subsequently confirmed by a series of verbal and nonverbal tests which were designed to probe the types of abstract knowledge attributed to the conceptual praxis system in the Roy & Square (1985) model of action. A common feature of these tasks was that, unlike the action production tests, they did not require GW to perform gestures or to manipulate actual tools. On tasks of this nature, GW was able to demonstrate intact conceptual knowledge of tools in terms of their functions and associative relationships. Furthermore, knowledge of the types of actions required for tool use and "decontextualized" knowledge of action that is independent of tools but into which appropriate tools can be incorporated were both found to be well preserved.

At first glance, GW's occasional errors in performing serial action tasks with real objects might be interpreted to represent a mild form of ideational apraxia. According to some investigators (Pick, 1905; Liepmann, 1920; Lehmkuhl & Poeck, 1981; Poeck, 1983), ideational apraxia is manifested by an inability to perform in the correct order serial actions requiring the use of several objects to achieve an intended goal. The performance of patients with ideational apraxia on such tasks is said to be characterized by sequence errors and omissions (Liepmann, 1920; Poeck, 1983, 1985). Although a limited number of sequence errors and omissions were indeed observed when GW performed serial actions, we were able to demonstrate that these errors took place despite an apparent preservation of abstract conceptual knowledge relevant to the serial organization of single actions into a sequence. GW's performance was flawless when verbally describing serial actions and when arranging action photographs in their correct sequence. This is clearly different from patients with "true" ideational apraxia who seem to have a genuine conceptual defect and, consequently, also perform poorly on action sequencing tasks that do not require manipulation of actual objects (Poeck & Lehmkuhl, 1980; Lehmkuhl & Poeck, 1981; Roy, 1981).

Sequence errors and omissions are known to occur in normal subjects engaged in performing highly familiar tasks, and these slips of action have often been attributed to lapses of attention (Reason, 1979, 1984; Roy, 1982). According to Reason (1979, 1984), the attentional demands associated with routine tasks are usually minimal and only require that occasional "spot checks" be made on the progress of the activity at critical choice points in the action sequence. Errors can occur when attention is diverted from these critical choice points by some other mental activity or when it is inappropriately directed to a particular aspect of performance that does not ordinarily demand attention. We propose that an inappropriate deployment of attention was also responsible for GW's occasional sequence errors and omissions in performing serial actions. Recall her complaint that using her hands in routine manual tasks was no longer "automatic" and demanded constant attention and deliberate effort on her part. Since GW had to focus an inordinate amount of attention on motor execution, an aspect of performance that does not ordinarily require conscious attention and is usually carried out under "open loop" control, she may not have had the necessary resources or the appropriate mechanisms to switch her attention back to the unfolding action sequence at critical choice points. When asked to verbally describe serial actions or arrange action photographs in their correct sequential order, the attentional demands on movement execution were effectively removed and under these circumstances GW's performance was normal. That a failure of attention rather than a conceptual defect was responsible for GW's errors in serial action tasks is also supported by the observation that she was able to spontaneously detect and correct most of these errors. GW's apparent inability to direct attention appropriately to all relevant aspects of routine serial action tasks may have reflected a reduction of attentional capacity caused by damage to the parietal lobes.

The critical dissociation between preserved conceptual knowledge of action and impaired movement execution documented in GW points to a fundamental competence/performance dichotomy in apraxia and provides strong empirical support for the proposed separation of the action system into distinct conceptual and production subcomponents (Roy & Square, 1985). Our results are consistent with the notion that ideomotor apraxia and ideational apraxia are qualitatively distinct and autonomous neuropsychological entities and militate against claims that ideational apraxia is simply a more severe form of ideomotor apraxia (Sittig, 1931; Zangwill, 1960). Finally, the dissocation between severe ideomotor apraxia and completely intact language in GW corroborates the view that praxis and language are subserved by independent left hemisphere neuronal systems.

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