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EFFECT OF LATERALIZED CEREBRAL DAMAGE UPON CONTRALATERAL AND IPSILATERAL SENSORIMOTOR PERFORMANCE

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EFFECT OF LATERALIZED CEREBRAL DAMAGE UPON CONTRALATERAL AND IPSILATERAL SENSORIMOTOR PERFORMANCE

by

Jim Hom

A Dissertation Submitted to the Faculty of the

DEPARTMENT OF PSYCHOLOGY

In Partial Fulfillment of the Requirements
For the Degree of

DOCTOR OF PHILOSOPHY

In the Graduate College

THE UNIVERSITY OF ARIZONA

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THE UNIVERSITY OF ARIZONA
GRADUATE COLLEGE

As members of the Final Examination Committee, we certify that we have read the dissertation prepared by Jim Hom

entitled Effect of Lateralized Cerebral Damage upon Contralateral and Ipsilateral Sensorimotor Performance

and recommend that it be accepted as fulfilling the dissertation requirement for the Degree of Doctor of Philosophy.

Ralph M. Reitan	1-19-81 Date
Robert Lansing	1-19-81 Date
George Hohmann	1-19-81 Date
Peter Madsen	1/19/81 Date
Lewis Hertz	1-19-81 Date

Final approval and acceptance of this dissertation is contingent upon the candidate's submission of the final copy of the dissertation to the Graduate College.

I hereby certify that I have read this dissertation prepared under my direction and recommend that it be accepted as fulfilling the dissertation requirement.

Ralph M. Reitan	1-19-81
Dissertation Director	Date

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ABSTRACT

A large body of human brain-behavior research has focused upon sensorimotor processes and their relation to higher mental functioning. Semmes et al. (1960) have presented evidence to suggest that sensorimotor functions of the two cerebral hemispheres are not mirror images of each other. These investigators found that lesions of the left hemisphere resulted in sensorimotor deficits in the ipsilateral as well as the contralateral hand, while a much lower incidence of ipsilateral sensorimotor deficits was found with right cerebral hemisphere lesions. In contrast to these findings of left hemisphere predominance for ipsilateral sensorimotor functioning, Boll (1974) demonstrated that a greater impairment of both contralateral and ipsilateral sensorimotor functioning resulted from right cerebral hemisphere lesions than left cerebral hemisphere lesions.

Information gathered from previous investigations has been primarily based upon either a single homogeneous lesion group or heterogeneous lesion groups. In addition, research concerned with the study of lesions of the human brain is plagued with the problem of localizing the actual area of damage. The present study was designed to investigate the differential effect of type of lesion on sensorimotor functioning. Also, the sensorimotor functioning of an entire cerebral hemisphere was evaluated rather than an assumed area of damage. The present study investigated the extent of sensory-perceptual, tactile-perceptual, motoric and psychomotor performance

deficits from three types of naturally occurring damage to the left and right cerebral hemispheres.

One hundred and fifty right-handed adult patients with definite neurological diagnoses of cerebrovascular, neoplastic, or traumatic brain lesions were used in this investigation. The patients had sustained cerebral damage principally to either the right or left hemisphere. Six naturally occurring lesion groups were composed:

1. cerebrovascular - right hemisphere;
2. cerebrovascular - left hemisphere;
3. neoplastic - right hemisphere;
4. neoplastic - left hemisphere;
5. traumatic - right hemisphere;
6. traumatic - left hemisphere.

Each patient's sensorimotor abilities were assessed using a selection of tests from the Halstead-Reitan Neuropsychological Test Battery for Adults representing motor, psychomotor, sensory-perceptual, and tactile-perceptual functioning. A 3 x 2 x 2 multivariate analysis of variance and a series of posteriori Hotelling T^2 tests were employed to compare the interhemispheric and intrahemispheric contralateral and ipsilateral sensorimotor performances of the three lesion groups.

The results of the analyses indicated that, in general, the cerebrovascular group was most impaired, followed by the neoplastic group, with the trauma group demonstrating the least impairment of sensorimotor functioning. Furthermore, greater sensorimotor deficits were associated with lesions lateralized to the right cerebral hemisphere than similar lateralized lesions of the left hemisphere.

Intrahemispheric comparisons of contralateral and ipsilateral sensorimotor performances showed greater sensorimotor deficits with contralateral performances than ipsilateral performances for damage lateralized to either the right or left hemisphere. Analyses of interhemispheric comparisons yielded poorer sensorimotor performances associated with both the contralateral and ipsilateral performances of lesions lateralized to the right cerebral hemisphere than with lesions lateralized to the left cerebral hemisphere.

In general, a similar pattern of right cerebral hemisphere predominance for contralateral and ipsilateral sensorimotor functioning was found for each of the three lesion groups, as in the overall analysis of combined lesion groups. However, the consistency of the pattern varied according to lesion type.

The results were discussed in terms of several important methodological considerations necessary for the appropriate study of sensorimotor functioning in brain-damaged patients. Specifically, the findings of previous studies are considered in light of such factors as type of lesion, localization of damage, method of analysis, hand preference, and types of sensorimotor measures.

INTRODUCTION

Much research has been generated concerning the differential role each hemisphere plays in human behavior. The majority of the eivdence has been derived from studies comparing the effects of disease or damage of the left or right cerebral hemisphere in terms of performance on tasks of verbal or spatial abilities (Carmon and Benton, 1969; Costa and Vaughan, 1962; DeRenzi, Faglioni and Scotti, 1968; Heilbrun, 1956; Klove and Reitan, 1958; McFie and Piercy, 1952; Milner, 1954; Reitan, 1955a; Reitan and Fitzhugh, 1971; Reitan and Tarshes, 1959; Vaughan and Costa, 1962; and Weinstein, 1962). Evidence from these studies has suggested that damage to the left cerebral hemisphere resulted in performance decrements associated with verbal information and language skills. On the other hand, damage to the right cerebral hemisphere affected performance on tasks concerning spatial relationships and spatial abilities.

A large body of human brain-behavior research has also focused upon sensorimotor processes, such as sensory-perceptual, tactile-perceptual, and motoric functioning, and their relation to higher mental functioning. Semmes et al. (1960), using data from gunshot-wound patients, presented evidence to suggest that sensorimotor functions of the left cerebral hemisphere are not mirror images of those of the right hemisphere. These investigators found that for the right hand, sensorimotor deficits were specifically associated with lesions of the sensorimotor area within the left cerebral hemisphere, whereas no specific area within the right hemisphere was associated with sensorimotor deficits of the left hand.

The work of Semmes et al. (1960) and a later paper by Semmes (1968) suggest that the cerebral hemisphere are organized so that the sensorimotor functions are diffusely represented in the right hemisphere and more focally represented in the left hemisphere. This general conclusion was based upon results derived from tests of sensory threshold discriminations of two-point discrimination, touch-pressure, point localization, and sense of passive movement (Semmes et al., 1960); motor reactions of strength of grip and presence of increased or pathological reflexes in the fingers; and complex functions, such as spatial orientation (Semmes, 1968). In addition, Teuber (1962) and Weinstein (1962) provide an excellent review of some of their previous work concerning the relationship of each cerebral hemisphere to different sensorimotor abilities. Certain visual, auditory and tactile sensory symptoms were found to be more frequent or profound with lesions of the right cerebral hemisphere as compared to the left hemisphere.

The extensive work of Semmes et al. (1960) has also provided evidence which questions the widely accepted relationship of contralateral cerebral representation and performance of left- and right-sided sensorimotor functions. Electrophysiological studies on animals (e.g., cats, rabbits, sheep and monkeys) have demonstrated the existence of ipsilateral sensory and motor representations as well as contralateral representations (Nakahama, 1958; Patton, Towe and Kennedy, 1962; and Woolsey and Fairman, 1946). Semmes et al. (1960) observed that left hemisphere lesions resulted in sensorimotor deficiencies in the ipsilateral as well as the contralateral hand, while a much lower incidence of ipsilateral sensorimotor deficit was found with right cerebral hemisphere lesions. Further support for ipsilateral sensorimotor defects is evidenced by studies concerning unilateral lesions in man (Vaughan and Costa, 1962; Wyke, 1966; 1971) and in monkeys (Glees and Cole, 1952; Semmes and Mishkin, 1965).

Strong support for the findings by Semmes et al. (1960) of asymmetry of ipsilateral sensorimotor processes is provided by the work of Vaughan and Costa (1962). A significantly higher incidence of ipsilateral somesthetic and motor defects was found in subjects with left cerebral hemisphere damage than in those with right-sided damage, despite the fact that the right cerebral lesion group appeared, on the basis of electroencephalographic evidence, to have more subjects with severe and extensive lesions. In a comparative study of postural arm drift in patients with unilateral cerebral lesions, Wyke (1966; 1971) also found bilateral impairment of static arm posture and rapidity of repetitive movements produced by left- sided cerebral lesions. Further, right-sided cerebral lesions produced abnormal arm drift and impairment in the rapidity of repetitive movements which were restricted to the contralateral arm.

In contrast to the aforementioned studies, Corkin, Milner and Rasmussen (1964) found no significant asymmetry of ipsilateral somatosensory deficit with unilateral cerebral damage. Using methods similar to those of Semmes et al. (1960), these investigators found that bilateral somatosensory deficits appeared to occur with equal frequency in patients with unilateral cortical lesions of either the left or right hemisphere. Further contradictory evidence has been demonstrated by Carmon (1971) and Finlayson (in press). These studies presented evidence which indicates that neither contralateral nor ipsilateral motor deficits are associated more frequently with lesions of the right or left cerebral hemisphere.

These differences in findings may be partially accounted for by the types of lesions the patient samples had in each of these studies. In the Corkin et al. (1964) investigation, the results were based upon the sensorimotor functioning of patients who had cerebral excisions due to surgery for focal epilepsy. According to these authors, these surgical lesions were probably of a milder nature, in terms of depth of lesion, than those of the patients with penetrating head wounds of the Semmes et al. (1960) study. Both the Carmon (1971) and Finlayson (in press) studies also had different patient samples than the Semmes et al. study. The patients in the Carmon (1971) study had either localized vascular or tumor lesions. An equal sample of cerebrovascular, neoplastic, and trauma brain lesions was used in the Finlayson (in press) investigation.

Another source of variance in the findings of left hemisphere predominance for ipsilateral sensorimotor functioning was demonstrated by Boll (1974). Employing three of the Reitan-Klove measures of sensory-perceptual skills in adults, Boll showed that damage to the right cerebral hemisphere resulted in greater impairment of both contralateral and ipsilateral tactile-perceptual performance than left cerebral damage. Moreover, damage to the right cerebral hemisphere significantly impaired overall tactile-perceptual performance more than similar damage occurring in the left hemisphere.

Existing anatomical evidence indicates the similarity in the sensory and motor representations in the left and right human cortex (Bonin, 1962). The variable findings of the previously mentioned studies concerning sensory-perceptual functioning suggest the need for further study. In addition, these studies show a need for exploration of the functional organization of other sensorimotor capabilities in terms of contralateral and ipsilateral performance. Information gathered from previous investigations has been primarily based upon either a single homogeneous lesion group or heterogeneous lesion groups. Little consideration has been given to the effect of the type of lesion on the right and left cerebral hemispheres with respect to contralateral and ipsilateral performances. The present study investigated the extent of sensory-perceptual, tactile-perceptual, motoric and psychomotor performance deficits from three types of naturally occurring damage to the left and right cerebral hemispheres, utilizing a broad range of sensorimotor measures. Specifically, this study investigated the following:

1. Differential effect of cerebrovascular, neoplastic and traumatic lesions upon sensorimotor functioning;
2. Differential sensorimotor performances associated with lateralized cerebral lesions of the left and right hemispheres;
3. Differential sensorimotor performance of the contralateral and ipsilateral body sides associated with lateralized cerebral lesions of the left and right hemispheres; and
4. Differential effect of type of lesion upon sensorimotor functions associated with the contralateral and ipsilateral sides of the body.

The various measures of sensorimotor functioning were derived from selected tests in the Halstead-Reitan Neuropsychological Test Battery for Adults. (See Variables section for a description of the tests.) These tests afforded the best opportunity to accomplish the experimental aims of the present study. Extensive research has demonstrated that the tests included in the Halstead-Reitan Neuropsychological Test Battery are quite sensitive to the biological integrity of the cerebral hemispheres. The test battery has been developed to reflect a full range of functions and abilities of the human brain. Also, the battery includes general indicators of brain function as well as specific indicators that assess the differential functions of both hemispheres and the integrity of particular areas within each cerebral hemisphere.

Research concerned with the study of lesions of the human brain are plagued with the problem of localizing the actual area of damage. The studies of Semmes et al. (1960) and others have attempted to relate deficiencies of sensorimotor functioning to focal lesions. However, their findings were based upon an unwarranted assumption of localized lesions (Reitan, 1961). Naturally occuring lesions ("accidents of nature" or even accidents of man) most likely involve damage to extensive areas rather than to a pre-selected or defined area. In fact, most of the patients in the Semmes et al. study had large and variable areas of cerebral damage rather than having lesions restricted to one circumscribed location.

The strategy used in the present experimental design did not attempt to determine the specific areas of involvement but instead, through the use of a large sample of patients, assumed a distribution of lesions affecting different areas within the cerebral hemisphere. The evaluation of sensorimotor functioning of this distribution was accomplished by a broad range of sensorimotor measures which represent different areas within the cerebral hemisphere. Thus, the sensorimotor functioning of an entire cerebral hemisphere, rather than an assumed area of damage, was evaluated with regard to the effects of a lesion.

Sensorimotor functioning is represented in different areas within a given cerebral hemisphere. Furthermore, the homologous areas of the other cerebral hemisphere are assumed to represent the same sensorimotor functioning. Motor functioning has been primarily associated with the precentral motor strip and adjacent areas of the anterior portion of the cerebral hemispheres. The parietal area is involved with tactile-perceptual abilities. Sensory-perceptual functioning is represented in the temporal, occipital, and parietal areas of the cerebral cortex according to the sense modality involved. The measures used in the present study reflect the cerebral organization for sensorimotor functioning and also the fundamental components of the nervous system. Certain of the measures were primarily concerned with sensory input as related to brain functions, and others relate brain functions to output or motor capabilities.

The sensory-perceptual and tactile-perceptual functions were represented by the Reitan-Klove Sensory-Perceptual Examination and the Tactile Form Recognition Test. The Sensory-Perceptual Examination consists of tests which evaluate the perception of double simultaneous stimulation through the sensory avenues of touch, audition, and vision. These sensory input procedures reflect the activities of the parietal, temporal, and occipital areas of the cerebral hemispheres, respectively. In addition to sensory-perceptual measures, the tactile-perceptual functioning of the parietal regions are evaluated through the measurement of tactile finger localization abilities, finger-tip number writing perception, and tactile form recognition. The major emphasis of each of the above procedures is on sensory- and tactile-perception as related to brain functions with minimal output or response requirement. The output or motor component of nervous system functioning as related to the brain was represented by the Finger Oscillation Test and Strength of Grip Test. Both of these tests related very closely to the integrity of the motor system of the cerebral hemispheres and have a minimal afferent component.

For each of the above measures, both a right and left body side performance were obtained. In addition, the patients in the present study had lesions lateralized to one or the other cerebral hemisphere. As a result, the contralateral and ipsilateral sensorimotor performances of lateralized brain lesions could be assessed in terms of the two cerebral hemispheres and even for homologous areas of the two hemispheres.

The above sensorimotor measures basically reflect the integrity of particular areas of the brain and were considered to be relatively pure measures of either sensory or motor functioning. The Tactual Performance Test, on the other hand, integrates both the input and output components of sensorimotor functioning with that of a central processing problem-solving requirement. The Tactual Performance Test is a problem-solving task which depends upon complex manipulatory skills and sophisticated sensory- and tactile-perceptual functioning. This measure is a general indicator of the integrity of sensorimotor functioning and, in its problem-solving elements, appears to involve the functioning of the whole brain (Reitan, 1955b). Initially, in the performance of the test, information is fed to the cerebral hemisphere across from the hand performing the task. However, the information and processing is not restricted to that hemisphere because of the inter-hemispheric connections of the anterior and posterior commissures and the corpus callosum. The entire brain is called upon to process and integrate, thus contributing to the solution of the problem-solving component of the task. Thus, the dependent variables used in this study assessed the integrity of both cerebral hemispheres, not only in terms of the input and output sensorimotor efficiencies of each individual hemisphere but also in terms of the functioning of both together as a central processing problem-solving unit.

Finlayson (in press) suggested that hand preference is a confounding factor in the interpretation of motor deficits associated with lateralized lesions of the right and left cerebral hemispheres. Differences in magnitude in the performances for the two hands associated with lateralized lesions of the cerebral hemispheres may be enhanced or attenuated depending upon the hand preferences of the patients. In order to overcome the possibility that hand preference may confound the results of this study, a T-score conversion, described in the Data Analysis section of this paper, was employed for the right and left side sensorimotor performances.

METHOD

Subjects

The 150 subjects in the present study were adult patients with damage principally involving one cerebral hemisphere or the other. In accordance with the first aim of this study, only patients with definite neurological diagnosis of cerebrovascular, neoplastic, or traumatic brain lesions were used in this investigation. Furthermore, these patients had sustained cerebral damage principally to either the right or left hemisphere. The combination of type of lesion with side of cerebral damage permitted the composition of six naturally occurring lesion groups:

1. Cerebrovascular - right hemisphere damaged;
2. Cerebrovascular - left hemisphere damaged;
3. Neoplasm - right hemisphere damaged;
4. Neoplasm - left hemisphere damaged;
5. Trauma - right hemisphere damaged;
6. Trauma - left hemisphere damaged.

These brain-damaged subjects were chosen from the extensive files maintained by Ralph M. Reitan at the University of Arizona, Tucson, Arizona. For each subject, a neurological diagnosis was established by extensive neurological examination, including electroencephalography, cerebral angiography, pneumoencephalography, brain scan (as clinically needed), and autopsy reports, when available. Half of the subjects had lesions which principally involved the left hemisphere (n = 75), while the other half had lesions of the right hemisphere (n = 75). No attempt was made to select subjects in terms of specific areas of involvement because of the difficulty in achieving accuracy in this respect when using naturally occurring lesions. However, the large number of subjects in each group should have allowed chance factors to operate in producing inter-group comparability.

All subjects in the study were right-handed. The subjects were equivalent according to age, gender, and education within each of the neurological diagnostic groups. No attempt was made to match these variables among each of the three neurological diagnostic groups. The inherent problem of patient availability and the normal incidence of these naturally occurring lesions complicates matching among the different lesion categories and would cause an artificial result in the composition of certain groups. For example, matching by age between head injury and cerebrovascular groups would require composition of an "old" head injury group or a "young" cerebrovascular group.

Table 1 gives the means and standard deviations for age and education. Inspection of the table reveals no apparent differences for the right and left cerebral hemispheres within each neurological lesion group on the age and education measures. However, a difference in age is indicated for the traumatic brain lesion group as compared to either the cerebrovascular or neoplastic lesion groups. Also, the mean level of education for the neoplastic lesion group apparently differs from that of the cerebrovascular and traumatic brain lesion groups.

TABLE 1

Age and Education Means and Standard Deviations for the Three Neurological Diagnostic Groups

Neurologic Group	N	Age		Education	
		$\overline{X}$	SD	$\overline{X}$	SD
Cerebrovascular	50	47.38	12.59	11.84	3.80
Right Hemisphere	25 (M=18, F=7)	48.16	12.29	12.00	3.28
Left Hemisphere	25 (M=21, F=4)	46.60	13.08	11.67	4.35
Neoplasm	50	46.22	11.81	10.18	3.67
Right Hemisphere	25 (M=16, F=9)	49.52	11.38	10.32	4.08
Left Hemisphere	25 (M=17, F=8)	42.92	11.53	10.04	3.28
Trauma	50	31.14	14.49	11.92	2.95
Right Hemisphere	25 (M=17, F=8)	28.56	13.20	12.12	2.33
Left Hemisphere	25 (M=22, F=3)	33.72	15.51	11.72	2.49

Two univariate analyses of variance (ANOVA) were computed to compare the patient groups according to lesion type and damaged hemisphere for the age and education measures (Tables 2 and 3). Confirming the above observations, within each neurological diagnostic group, the age, gender, and level of education did not significantly differ for the left or right cerebral hemisphere groups. Furthermore, no significant differences were found for these variables between the right hemisphere-damaged group and left hemisphere-damaged group of the entire sample.

The apparent differences observed by inspection of the means in Tables 2 and 3 were confirmed by the two ANOVAs and posteriori Scheffe tests for multiple comparisons. Significant differences were found among the lesion groups on the age measure and on the education measure. The age level of the trauma group was found to be significantly lower than the other two lesion groups (Scheffe tests: trauma vs. cerebrovascular, $F=39.59$, $df=2/144$, $p<.01$; trauma vs. neoplasm, $F=34.13$, $df=2/144$, $p<.01$). For the education measure, the neoplastic lesion group was significantly lower as compared to either the cerebrovascular group (Scheffe test: $F=5.35$, $df=2/144$, $p<.01$) or the trauma group (Scheffe test: $F=6.04$, $df=2/144$, $p<.01$).

The age differences such as those found in the present study have previously been noted for the different neurological diagnostic categories. The lower age level of the trauma group as compared to the cerebrovascular or neoplastic lesion groups reflects the typical age-incidence distribution for traumatic lesions (Dikmen and Reitan,

TABLE 2

Summary of ANOVA on Age by Type of Lesion
and Damaged Hemisphere

Source of Variation	df	SS	MS	F	p
Within Cells	144	23984.64	166.56		
Lesion	2	8208.16	4104.08	24.64	< .00001
Hemisphere	1	37.50	37.50	.23	<.64 (NS)
Lesion x Hemisphere	2	870.24	435.12	2.61	<.08 (NS)
Total	149	33100.54			

TABLE 3

Summary of ANOVA on Education Level by Type of Lesion and Damaged Hemisphere

Source of Variation	df	SS	MS	F	p
Within Cells	144	1764.72	12.26		
Lesion	2	93.21	46.61	3.80	< .03
Hemisphere	1	4.17	4.17	.34	<.56 (NS)
Lesion x Hemisphere	2	.17	.09	.007	<.99 (NS)
Total	149	1862.27			

1976, 1978; Jennett, 1975; Jennett and Bond, 1975; and Jennett et al., 1976). A trauma lesion group that was equivalent in age to the cerebrovascular or neoplastic groups would be unrepresentative of the trauma lesion population.

Level of education differences of the magnitude indicated in Table 1 previously have been found not to demonstrate a significant differential effect upon performances of intellectual and neuropsychological measures. Finlayson, Johnson, and Reitan (1977) compared the effect of different levels of education of brain-damaged adults and non-brain-damaged controls upon Wechsler-Bellevue and Halstead-Reitan Neuropsychological Test measures. The brain-damaged adults were divided into three groups based upon their level of education:

1. Grade school group: $\overline{X}$ = 7.82 years of education; SD = 1.63;
2. High school group: $\overline{X}$ = 12.0 years of education; SD = 0.0
3. University group: $\overline{X}$ = 17.06 years of education; SD = 1.78.

No significant differences were found between the grade school and high school levels of the brain-damaged patients on any of the intellectual or neuropsychological measures. Level of education did have an effect upon the university-educated brain-damaged individuals as compared to the two lower education brain-damaged groups on the Wechsler-Bellevue measures. Similarly, although to a lesser degree, the university-educated brain-damaged group was affected on the Halstead-Reitan

Neuropsychological variables. The university-educated brain-damaged persons tended to have a higher level of performance on all measures. Although statistically significant differences were present for the level of education among the groups in the present study, the findings of the Finlayson et al. (1977) suggest that these differences would have a minimal influence on the results of this study.

Selection of the brain-damaged subjects was as follows. A master list for each of the diagnostic categories to be used in the study was compiled by the author. This list contained a summary of the neuropsychological test data under investigation and also the neurological diagnostic criteria for each subject. Only cases having well-established neurological diagnoses were included in this study. Those subjects missing a significant proportion of the neuropsychological data or having some ambiguity regarding the validity of the neurological diagnostic criteria were excluded.

After the compilation of the master list, the neurological diagnostic criteria for each subject were pulled from the original file and brought to Dr. Reitan. He then reviewed only this neurological information and decided whether the subject's neurological diagnosis was sufficiently established for inclusion in the study. Thus, subjects were selected for the study solely on the basis of neurological diagnostic information, without reference to the neuropsychological test performance. Each subject was selected in this manner until each diagnostic group had been appropriately completed.

The following is a list of the subjects chosen for each neurological diagnostic group:

1. Cerebrovascular: n=50 (39 males; 11 females)
   A. Cerebrovascular accident: n=41 (21 left hemisphere; 20 right hemisphere)
   B. Vascular anomaly, such as aneurysm or arteriovenous malformation: n=9 (4 left hemisphere; 5 right hemisphere)
2. Neoplastic: n=50 (33 males; 17 females)
   A. Rapidly-growing intrinsic tumor, such as glioblastoma multiforme: n=28 (12 left hemisphere; 16 right hemisphere)
   B. Slowly-growing intrinsic tumor, such as low-grade astrocytoma and ependymoma: n=22 (13 left hemisphere; 9 right hemisphere)
3. Trauma: n=50 (39 males; 11 females)
   A. Penetrating head injury: n=8 (5 left hemisphere; 3 right hemisphere)
   B. Closed head injury: n=42 (20 left hemisphere; 22 right hemisphere)

Total: 150 brain-damaged subjects.

Variables

A selection of tests from the Halstead-Reitan Neuropsychological Test Battery for Adults representing motor, psychomotor, tactile-perceptual, and sensory-perceptual functioning was used in this study.

The following is a brief description of the sample of tests which were used. A more complete description can be found in Reitan and Davison (1974).

The first two measures are principally dependent upon motor functions and have a minimal sensory component.

1. Finger oscillation test (TAP). This test is a measure of motor speed performance. The subject is required to tap as fast as he/she can, using the index finger of each hand on a specially designed manual tapper. The subject is given five consecutive ten-second trials, first with the preferred hand and then with the non-preferred hand. The scores on this test are the average times for each hand.

2. Strength of grip test (GRIP). The second test of motor abilities measures the grip strength of each hand, using a Smedley Hand Dynamometer. The dynamometer is adjusted to suit the size of the subject's hand. Scores recorded are the average of two trials for each hand.

The third test depends upon both sensory and motor functions and also entails a problem-solving component.

3. Tactual performance test (TPT). This test measures psychomotor skills in a problem-solving context. The subject is blindfolded before the test begins and never sees the stimulus material. The task requires that the blindfolded subject fit blocks into their proper spaces on a modified Seguin-Goddard form board. First, the preferred hand is tested. Then, after completion and without prior warning, the non-preferred hand is tested. Finally, again without

prior warning, both hands are tested. Scores are recorded as the time required to complete the task for each trial.

The following three tests measure tactile-perceptual functioning in which motor responses are minimal.

4. Tactile finger recognition (FA). With the subject's eyes closed, he/she is required to identify individual fingers on each hand following tactile stimulation. A system for reporting the finger touched is worked out with the subject prior to the beginning of the test. Each finger on each hand receives a total of four trials of tactile stimulation, yielding a total of 20 trials on each hand. The scores reported are the number of errors for each hand.

5. Finger-tip number writing perception (FTW). On this test, the subject is required to identify numbers written on the finger tips of each hand. The subject's eyes are closed during this procedure. Each finger on each hand receives a total of four trials. The number of errors on each hand is the score reported.

6. Tactile Form Recognition (TFR). This test requires the subject to feel plastic chips of different geometric shapes (circle, square, cross and triangle) with one hand, and to identify the shapes by pointing with the other hand to chips of the same shape on a display panel placed in front of him/her. The chip that is being felt is out of the subject's sight. Each hand is given eight trials, and the total number of errors for each hand is recorded.

The final set of tests measures sensory-perceptual functioning with minimal motor response required.

7. Tactile, auditory and visual imperception tests (TAC, AUD, VIS). These three separate tests measure a subject's sensory-perceptual abilities in the tactile, auditory and visual sensory modalities. Initially, for each sensory modality test, the subject is stimulated in order to determine the minimal stimulus necessary to achieve consistently correct responses. Then, for each modality, the subject receives trials of unilateral stimulation for each side of the body and trials of bilateral simultaneous stimulation. The scores reported are the total number of imperceptions.

The tests described above were administered on an individual basis by technicians thoroughly trained in the data collection procedures. These technicians were not informed of the neurological diagnoses nor of the design of this study. As previously noted, the three neurological diagnostic groups were composed without reference to the subjects' neuropsychological test performances.

Data Analysis

To allow for parametric statistical analyses, the combined raw score distributions for the three neurological diagnostic groups for each variable were transformed into two T-score distributions. One T distribution consisted of the combination of the raw score performances of the right body side, and the other was composed of the raw score performances of the left body side. Both distributions were converted to a mean of 50 and a standard deviation of 10. The reason for the

T-score conversion was two-fold. First, this conversion facilitated visual inspection of the differences between groups, cerebral hemispheres and body performances for the different sensorimotor measures. Second, the problem of absolute magnitude differences for the right and left body side performances due to hand preference was eliminated. T-scores were then reassembled into the three neurological diagnostic groups. Interhemispheric and intrahemispheric comparisons of the contralateral and ipsilateral body performances of the three groups on all of the variables were made by a 3 x 2 x 2 multivariate analysis of variance (MANOVA; Wilks Lambda test). Specifically, comparisons were performed on the sensorimotor deficits of the right and left sides of the body, resulting from cerebrovascular, neoplastic, and traumatic lesions in the left and right cerebral hemispheres.

A series of posteriori comparisons using the Hotelling T^2 test, a multivariate analogue of the Student t test, were computed in order to test the equality of means for significant effects and interactions derived from the MANOVA. A Bonferroni procedure was employed to correct for the increased incidence of Type I errors resulting from such a series of comparisons (Myers, 1979). The required adjustment was based upon the following formula:

$$\frac{\alpha_{EC}}{k}$$

where α_{EC} is the significance level per comparison, and k is the number of comparisons. In the present study, the probability levels of significance for all multiple posteriori comparisons using the Hotelling T^2

have been adjusted by the Bonferroni procedure. As a result, a more conservative level of significance was used for each comparison, and all resulting non-significant comparisons have been identified in the tables.

RESULTS

A 3 x 2 x 2 MANOVA was conducted for the evaluation of the type of lesion, damaged cerebral hemisphere, and side of body performance on each of the sensorimotor measures. The results are presented in Table 4.

Comparison by Lesion Type

The analysis comparing the differential effect of cerebrovascular, neoplastic, and traumatic lesions on the sensorimotor measures showed a significant difference among the three groups ($F=2.26$, $df=18/272$, $p<.003$). Mean T-scores based on the combined performances for the two sides of the body on each of the sensorimotor measures for the three lesion groups are provided in Table 5 and graphed in Figure 1. In general, the mean sensorimotor performances of the cerebrovascular group were the poorest, with the performances of the neoplastic group following closely. The traumatic lesion group clearly demonstrated the best performance of the three lesion groups. Statistical comparison of the three groups using Hotelling's T^2 test yielded a significant difference between the cerebrovascular and traumatic lesion groups ($F=2.71$, $df=9/189$, $p<.005$; see Table 6). Similar analyses comparing the neoplastic group with the cerebrovascular ($F=1.29$, $df=9/189$, $p<.24$) or the trauma group ($F=2.23$, $df=9/189$, $p<.02$) failed to reach significance. However, the mean T-score performances of the neoplastic group were consistently lower than those

TABLE 4

Summary of MANOVA

Source of Variation	df	F	p
Lesion	18/272	2.26	< .003
Hemisphere	9/136	4.36	<.00005
Side	9/136	.002	<1.0 (NS)
Lesion x Hemisphere	18/272	1.22	<.25 (NS)
Lesion x Side	18/272	1.28	< .20 (NS)
Hemisphere x Side	9/136	16.48	<.00001
Lesion x Hemisphere x Side	18/272	2.86	< .0002

TABLE 5

Mean T-Scores and Standard Deviations for the Combined Performances of the Two Sides of the Body on Each of the Sensorimotor Measures for the Three Neurological Diagnostic Groups

Measure	Cerebrovascular		Neoplasm		Trauma	
	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD
Motor						
TAP	47.81	11.54	49.81	9.78	52.38	7.84
GRIP	48.48	10.76	49.14	9.04	52.39	9.73
Psychomotor						
TPT	48.31	10.61	48.40	9.92	53.29	8.57
Sensory-Perceptual						
TAC	48.31	11.20	48.92	11.09	52.75	6.38
AUD	50.51	8.15	49.37	10.57	50.38	9.80
VIS	50.17	9.06	48.07	13.02	51.79	6.37
Tactile-Perceptual						
FA	47.85	12.14	49.33	8.80	52.83	7.90
FTW	47.80	11.12	49.21	9.40	52.99	8.63
TFR	46.85	12.32	50.24	9.70	52.89	6.00

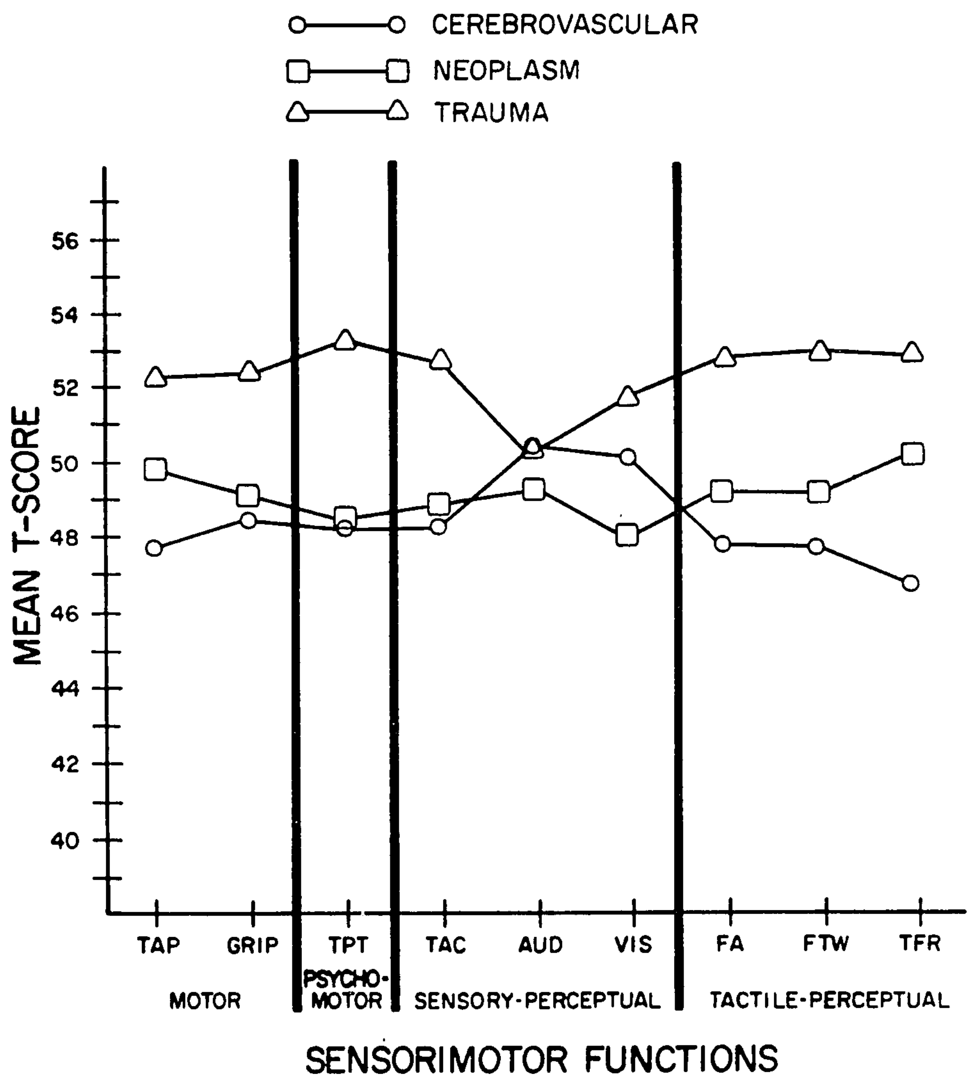

Figure 1. Mean T-Scores for the Combined Performances of the Two Sides of the Body on Sensorimotor Measures among Patients with Lateralized Cerebrovascular, Neoplastic, and Traumatic Cerebral Lesions

TABLE 6

Hotelling T^2 for Pairwise Comparison of Equality of Multivariate Means with Bonferroni Adjustment

Source of Variation	Pairwise Comparison	Bonferroni Adjustment	T^2	df	F	p
Lesion		.017				
	Cerebrovascular-Neoplasm		12.20	9/189	1.29	< .24 (NS)
	Cerebrovascular-Trauma		25.59	9/189	2.71	< .005
	Neoplasm-Trauma		21.04	9/189	2.23	< .02 (NS)
Hemisphere x Side		.013				
	Rt Hemis Left Side - Rt Hemis Rt Side		60.41	9/140	6.35	< .0001
	Left Hemis Rt Side - Left Hemis Left Side		65.88	9/140	6.92	< .0001
	Rt Hemis Left Side - Left Hemis Rt Side		24.60	9/140	2.59	< .009
	Rt Hemis Rt Side - Left Hemis Left Side		56.31	9/140	5.92	< .0001
Lesion x Hemisphere x Side		.0042				
Cerebro-vascular:	Rt Hemis Left Side - Rt Hemis Rt Side		69.63	9/40	6.45	< .0001
	Left Hemis Rt Side - Left Hemis Left Side		55.68	9/40	5.16	< .0001
	Rt Hemis Left Side - Left Hemis Rt Side		31.96	9/40	2.96	< .009 (NS)
	Rt Hemis Rt Side - Left Hemis Left Side		60.15	9/40	5.57	< .0001
Neoplasm:	Rt Hemis Left Side - Rt Hemis Rt Side		20.81	9/40	1.93	< .08 (NS)
	Left Hemis Rt Side - Left Hemis Left Side		24.28	9/40	2.25	< .04 (NS)
	Rt Hemis Left Side - Left Hemis Rt Side		24.08	9/40	2.23	< .04 (NS)
	Rt Hemis Rt Side - Left Hemis Left Side		33.20	9/40	3.07	< .007 (NS)
Trauma:	Rt Hemis Left Side - Rt Hemis Rt Side		10.09	9/40	0.93	< .51 (NS)
	Left Hemis Rt Side - Left Hemis Left Side		40.94	9/40	3.79	< .002
	Rt Hemis Left Side - Left Hemis Rt Side		15.37	9/40	1.42	< .21 (NS)
	Rt Hemis Rt Side - Left Hemis Left Side		143.54	9/40	13.29	< .0001

of the traumatic group. Based upon the Bonferroni procedure, the level of significance of the above comparisons was .017 (α_{EC}=.05; k=3).

Comparison of Right and Left Hemispheres

The evaluation of the differential sensorimotor performances associated with lateralized cerebral lesions of the left and right hemispheres revealed a highly significant difference ($F=4.36$, $df=9/136$, $p<.00005$). Inspection of the mean T-scores for the combined performances of the two sides of the body in Table 7 and Figure 2 demonstrates the nature of the effect of lateralized cerebral lesions of the left and right hemispheres on the sensorimotor measures. Greater sensorimotor deficits were associated with lesions lateralized to the right cerebral hemisphere than similar lesions lateralized to the left hemisphere.

Intrahemispheric Comparisons of Contralateral and Ipsilateral Performances

Table 8 gives the mean T-score performances and standard deviations of the contralateral and ipsilateral body performances for patients with right or left cerebral hemisphere lesions. Inspection of Figure 3 indicates that contralateral body performances were lower than the ipsilateral body performances. Furthermore, both the contralateral and ipsilateral body performances of patients with lesions lateralized to the right cerebral hemisphere were lower than comparable contralateral and ipsilateral body performances of patients with lesions lateralized to the left cerebral hemisphere.

TABLE 7

Mean T-Scores and Standard Deviations for the Combined Performances of the Two Sides of the Body on Each of the Sensorimotor Measures among Patients with Right and Left Cerebral Hemisphere Lesions

Measure	Right Hemisphere		Left Hemisphere	
	$\bar{X}$	SD	$\bar{X}$	SD
Motor				
TAP	49.21	9.61	50.79	10.32
GRIP	48.02	9.03	51.99	10.51
Psychomotor				
TPT	48.04	10.18	51.96	9.41
Sensory-Perceptual				
TAC	48.48	10.28	51.51	9.46
AUD	47.56	11.24	52.62	6.60
VIS	48.47	10.32	51.55	9.36
Tactile-Perceptual				
FA	49.25	9.56	50.75	10.35
FTW	48.77	10.13	51.22	9.71
TFR	49.72	9.65	50.26	10.31

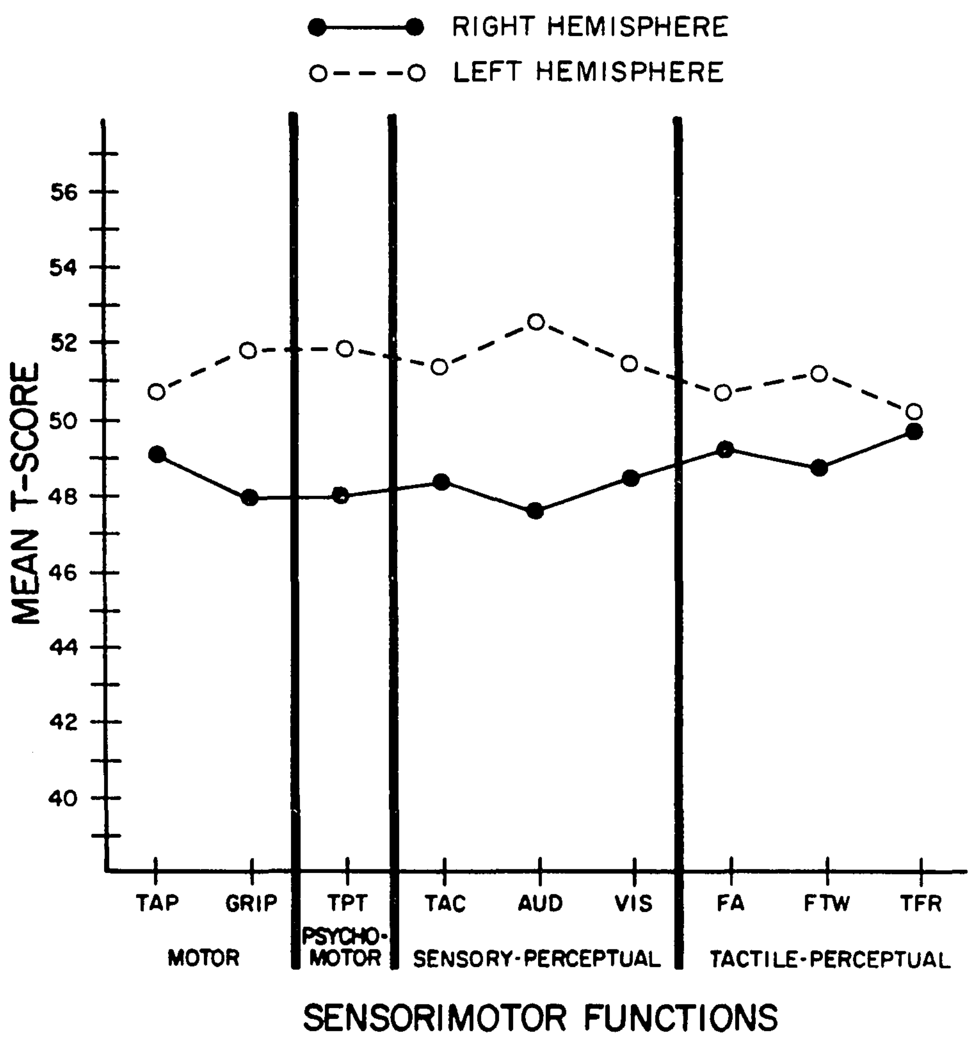

Figure 2. Mean T-Scores for the Combined Performances of the Two Sides of the Body on Sensorimotor Measures among Patients with Right and Left Cerebral Hemisphere Damage

TABLE 8

Mean T-Scores and Standard Deviations of Contralateral and Ipsilateral Body Performances on Each of the Sensorimotor Measures among Patients with Lateralized Cerebral Lesions

Measure	Rt Hemisphere Left Side		Rt Hemisphere Right Side		Left Hemisphere Right Side		Left Hemisphere Left Side	
	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD
Motor								
TAP	45.08	10.75	53.34	5.97	46.66	11.96	54.92	6.05
GRIP	44.43	8.94	51.60	7.63	48.40	11.75	55.58	7.65
Psychomotor								
TPT	44.47	10.45	51.61	8.58	48.39	11.07	55.53	5.48
Sensory-Perceptual								
TAC	45.54	12.47	51.43	6.31	48.57	12.54	54.44	2.33
AUD	46.08	12.20	49.04	10.06	51.27	7.92	53.97	4.61
VIS	45.35	12.51	51.58	6.17	48.47	12.50	54.62	0.94
Tactile-Perceptual								
FA	45.76	11.50	52.74	5.20	47.28	12.60	54.23	5.70
FTW	46.03	11.42	51.52	7.81	48.48	11.65	53.96	6.24
TFR	45.73	12.30	53.72	1.97	46.25	13.00	54.28	3.54

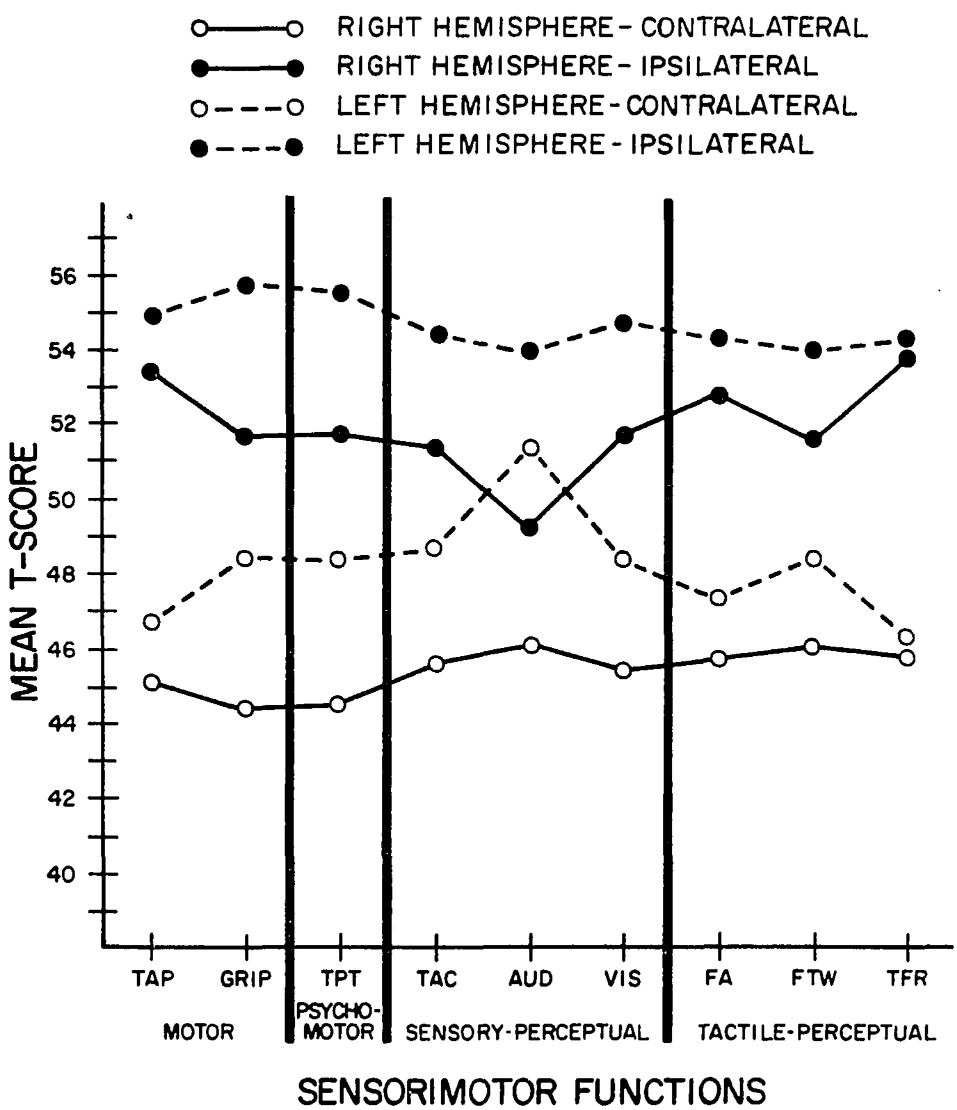

Figure 3. Contralateral and Ipsilateral Mean T-Score Performances on Sensorimotor Measures among Patients with Right and Left Cerebral Hemisphere Lesions

Results of the overall multivariate analysis of the differences between the contralateral and ipsilateral body performances of lateralized right and left cerebral lesions yielded a difference beyond the .00001 level. Further statistical analyses of this interaction, using pairwise comparisons, confirmed the above observations (see Table 6). For the right hemisphere, the contralateral body performances were significantly lower than ipsilateral performances ($F=6.36$, $df=9/140$, $p<.0001$). Similarly, for the left hemisphere, greater sensorimotor deficits were associated with contralateral as opposed to ipsilateral performances ($F=6.92$, $df=9/140$, $p<.0001$).

Interhemispheric Comparisons of Contralateral and Ipsilateral Performances

Further analysis yielded a significant difference for the comparison of contralateral body performances associated with right and left cerebral hemisphere lesions ($F=2.59$, $df=9/140$, $p<.009$). Right hemisphere lesions consistently produced greater sensorimotor deficits with contralateral performances than the contralateral performances of left hemisphere lesions. Comparison of ipsilateral body performances associated with right and left cerebral hemisphere lesions revealed the same pattern ($F=5.92$, $df=9/140$, $p<.0001$). Poorer sensorimotor performances were associated with the ipsilateral performances of lesions lateralized to the right cerebral hemisphere than the ipsilateral performances of lesions lateralized to the left cerebral hemisphere.

Analysis of the Interaction of Lesion, Hemisphere, and Side of Body

Statistical evaluation of the contralateral and ipsilateral body performances for lateralized cerebral lesions of the three different neurological diagnostic categories yielded a significant difference ($F=2.86$, $df=18/272$, $p<.0002$). A series of multiple comparisons with the three different lesion groups were made to determine the source of the statistical significance found with the above MANOVA. For each of the three neurological diagnostic groups, comparisons were made in terms of the contralateral and ipsilateral performances associated with lateralized cerebral lesions. A more conservative level of significance was required based upon the Bonferroni procedure ($\alpha=.0042$). For the cerebrovascular group, Table 9 and Figure 4 indicate a similar pattern of contralateral and ipsilateral performance deficits as were found in the analysis of the combined lesion groups. Contralateral performances of either the right or left cerebrovascular lesion groups produced greater sensorimotor deficits than the ipsilateral performances ($F=6.45$, $df=9/40$, $p<.0001$; $F=5.16$, $df=9/40$, $p<.0001$, respectively; see Table 6). For contralateral performances, the comparison of the right and left cerebrovascular lesion groups failed to reach statistical significance at the adjusted significance level ($F=2.96$, $df=9/40$, $p<.009$). However, in terms of ipsilateral performances, comparison of the two damaged hemisphere groups yielded a significant difference ($F=5.57$, $df=9/40$, $p<.0001$). Right cerebrovascular lesions produced greater sensorimotor deficits with ipsilateral performances than ipsilateral performances

TABLE 9

Mean T-Scores and Standard Deviations of Contralateral and Ipsilateral Body Performances on Each of the Sensorimotor Measures among Patients with Lateralized Cerebrovascular Lesions

Measure	Rt Hemisphere Left Side		Rt Hemisphere Right Side		Left Hemisphere Right Side		Left Hemisphere Left Side	
	$\overline{X}$	SD	$\overline{X}$	SD	$\overline{X}$	SD	$\overline{X}$	SD
Motor								
TAP	42.59	10.56	54.53	5.50	39.46	12.34	54.65	7.68
GRIP	41.96	8.77	51.70	8.10	44.00	12.21	56.29	6.85
Psychomotor								
TPT	41.63	10.00	54.91	3.61	42.26	11.73	54.44	6.68
Sensory-Perceptual								
TAC	41.15	13.66	50.53	6.88	47.86	13.46	53.70	3.60
AUD	45.44	12.55	50.00	6.93	52.22	3.70	54.40	2.99
VIS	44.28	12.80	51.81	1.81	50.24	10.61	54.36	1.26
Tactile-Perceptual								
FA	41.98	12.99	51.83	5.10	42.56	16.30	55.03	3.56
FTW	43.79	12.83	51.21	8.27	42.24	12.33	53.96	4.91
TFR	39.41	13.01	53.94	1.15	40.00	15.43	54.04	2.19

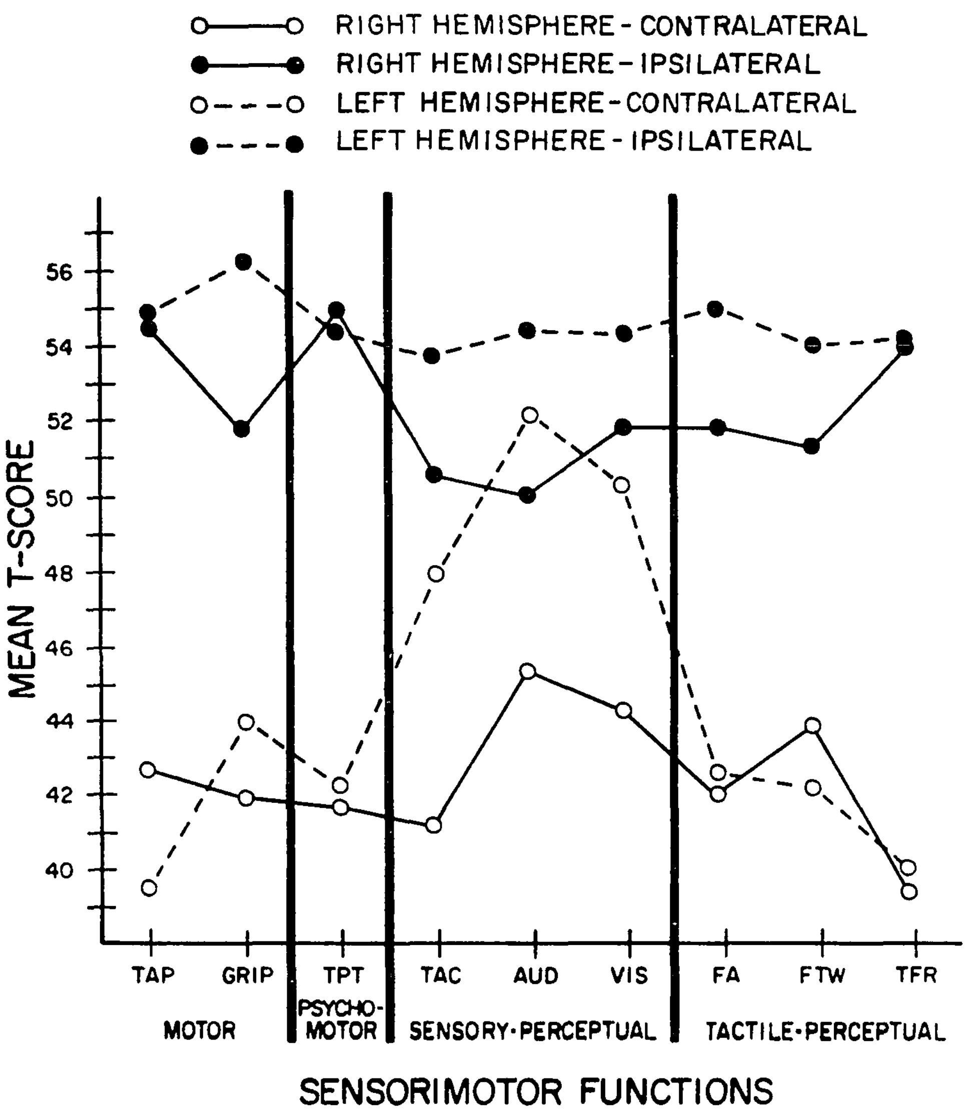

Figure 4. Contralateral and Ipsilateral Mean T-Score Performances on Sensorimotor Measures among Patients with Right and Left Cerebrovascular Lesions

of left cerebrovascular lesions. Although non-significant, the comparison of contralateral performances showed a similar pattern.

None of the comparisons involving the contralateral and ipsilateral performances of lateralized neoplastic lesions reached statistical significance (see Table 6). However, examination of Table 10 and Figure 5 shows a similar pattern of ordering for contralateral and ipsilateral performances associated with lateralized neoplastic lesions as in the cerebrovascular lesion comparisons. Contralateral and ipsilateral performances of the right neoplastic lesion group had lower mean values in 16 of 18 intrahemispheric and interhemispheric comparisons.

For the comparisons involving lateralized traumatic lesions, an ordering similar to those found for the cerebrovascular and neoplastic lesion groups appeared for the contralateral and ipsilateral performances (Table 11 and Figure 6). In all 18 comparisons, the group with right cerebral lesions actually had the lower mean score. However, statistical comparisons yielded significance only for the comparisons of contralateral versus ipsilateral performances of the left traumatic lesion group ($F=3.79$, $df=9/40$, $p<.002$) and the comparison for ipsilateral performances of the right versus left hemisphere lesion groups ($F=13.29$, $df=9/40$, $p<.0001$). For the left hemisphere lesion group, contralateral sensorimotor performances were significantly poorer than the ipsilateral sensorimotor performances. Also, the ipsilateral sensorimotor performances associated with right hemisphere traumatic

TABLE 10

Mean T-Scores and Standard Deviations of Contralateral and Ipsilateral Body Performances on Each of the Sensorimotor Measures among Patients with Lateralized Neoplastic Lesions

Measure	Rt Hemisphere Left Side		Rt Hemisphere Right Side		Left Hemisphere Right Side		Left Hemisphere Left Side	
	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD
Motor								
TAP	44.41	10.57	51.60	7.22	48.62	11.43	54.62	6.36
GRIP	44.15	8.62	50.89	6.99	48.02	10.44	53.48	7.39
Psychomotor								
TPT	42.80	9.21	47.72	9.91	47.40	10.55	55.69	4.73
Sensory-Perceptual								
TAC	44.88	12.73	50.89	7.21	45.36	14.93	54.57	1.55
AUD	44.16	12.02	48.52	11.06	50.10	11.07	54.72	3.52
VIS	43.27	13.09	50.24	10.54	43.90	17.94	54.86	0.00
Tactile-Perceptual								
FA	44.79	9.61	51.40	5.89	48.56	9.40	52.56	8.16
FTW	44.47	9.97	48.86	8.34	50.64	9.90	52.85	7.70
TFR	46.93	11.86	53.94	1.66	46.31	12.56	53.77	5.69

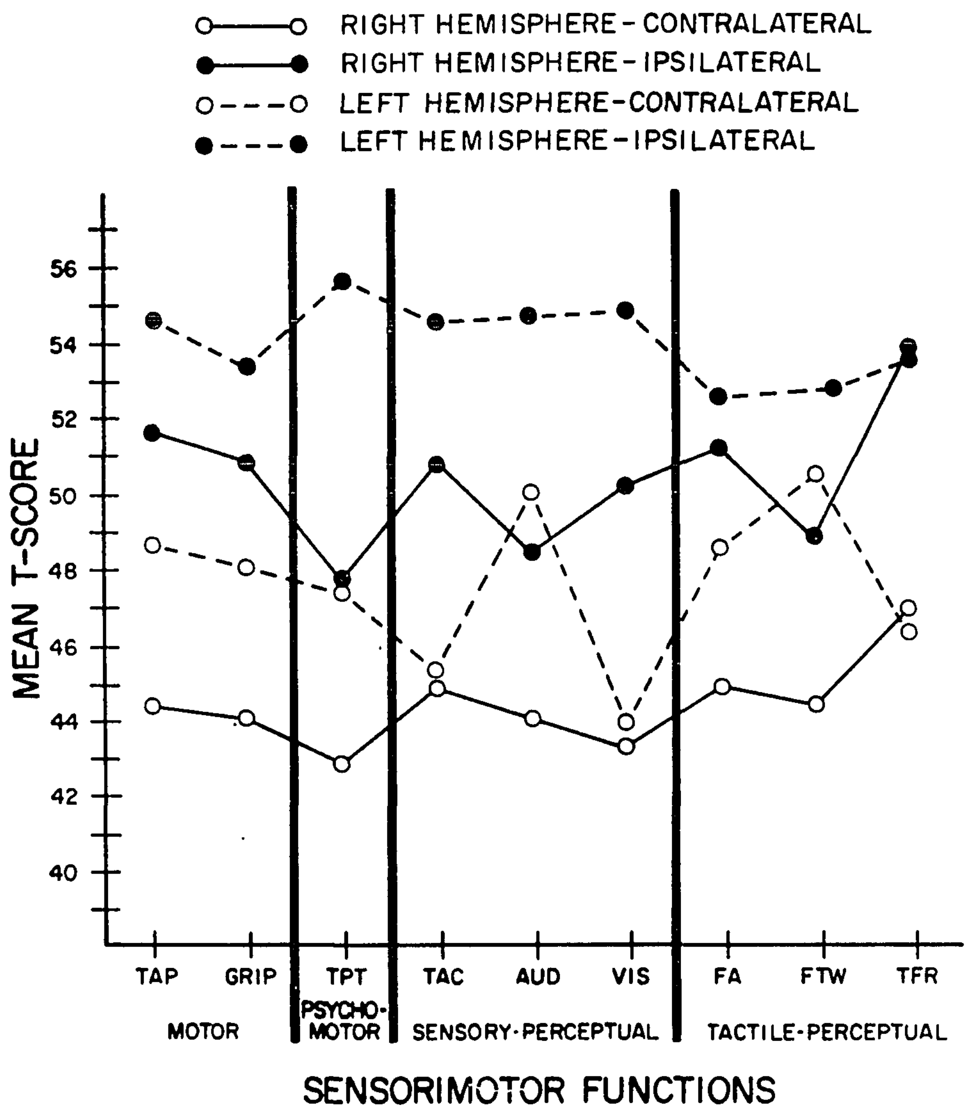

Figure 5. Contralateral and Ipsilateral Mean T-Score Performances on Sensorimotor Measures among Patients with Right and Left Neoplastic Lesions

TABLE 11

Mean T-Scores and Standard Deviations of Contralateral and Ipsilateral Body Performances on Each of the Sensorimotor Measures among Patients with Lateralized Traumatic Lesions

Measure	Rt Hemisphere Left Side		Rt Hemisphere Right Side		Left Hemisphere Right Side		Left Hemisphere Left Side	
	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD
Motor								
TAP	48.24	10.75	53.90	4.75	51.88	8.46	55.50	3.62
GRIP	47.18	8.99	52.22	8.03	53.19	11.08	56.96	8.48
Psychomotor								
TPT	48.97	10.94	52.18	9.38	55.52	5.98	56.48	4.82
Sensory-Perceptual								
TAC	50.59	9.15	52.86	4.48	52.50	7.30	55.07	0.62
AUD	48.64	12.07	48.62	11.84	51.48	7.41	52.80	6.48
VIS	48.51	11.45	52.70	0.00	51.28	3.77	54.66	1.00
Tactile-Perceptual								
FA	50.50	10.35	55.00	3.82	50.71	9.93	55.10	4.08
FTW	49.83	10.78	54.49	5.80	52.56	10.29	55.07	5.84
TFR	50.84	9.29	53.27	2.75	52.44	6.68	55.02	0.70

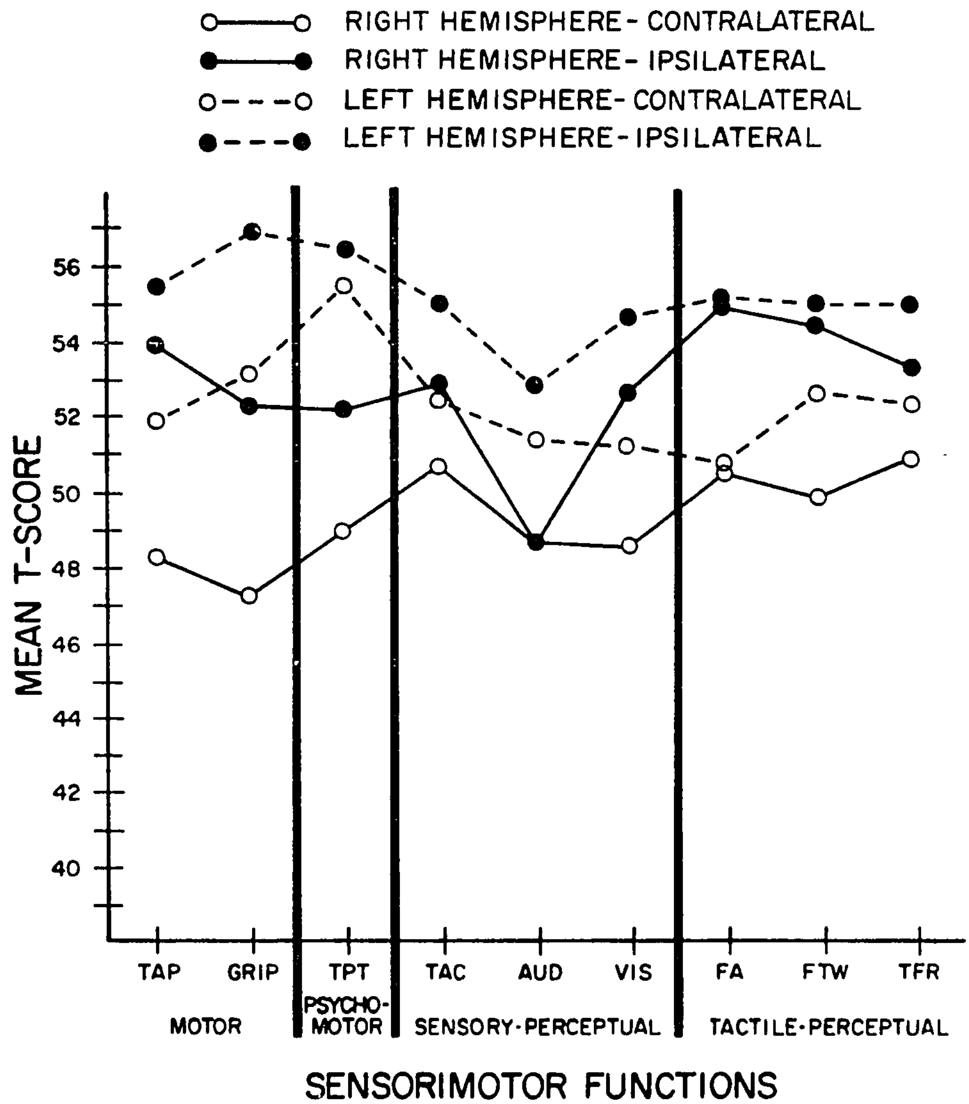

Figure 6. Contralateral and Ipsilateral Mean T-Score Performances on Sensorimotor Measures among Patients with Right and Left Traumatic Lesions

lesions were significantly poorer than the same ipsilateral sensorimotor performances of left hemisphere traumatic lesions.

The Appendix contains a summary of the 3 x 2 x 2 univariate ANOVAs for each individual sensorimotor measure used in this study. This information is offered as a supplement to the above findings and is not the major focus of the present investigation. As in the multivariate analysis, each ANOVA compares the contralateral and ipsilateral body performances of patients with lateralized cerebral lesions within three neurological diagnostic groups. The figures already presented have been organized so as to facilitate visual inspection of the ordering pattern of these individual sensorimotor measures.

DISCUSSION

The results of the present investigation clearly demonstrate the effect of lateralized cerebral lesions upon the contralateral and ipsilateral performances of a constellation of sensorimotor functions. Intrahemispheric comparisons of contralateral and ipsilateral sensorimotor performances coincide with the established predominance of contralateral projections of the classic somatosensory and motor pathways. The contralateral performances showed greater sensorimotor deficits than ipsilateral performances for damage lateralized to either the right or left hemisphere. These results are consistent with findings of previous studies (Boll, 1974; Finlayson, in press; Reitan and Fitzhugh, 1971; Semmes et al., 1960; Vaughan and Costa, 1962).

Differential sensorimotor functioning was demonstrated for lateralized cerebral lesions. Cerebral lesions lateralized to the right hemisphere were associated with poorer sensorimotor performances than cerebral lesions lateralized to the left hemisphere. Similar findings have been reported by Boll (1974). Vaughan and Costa (1962) also found a greater overall impairment of function with right lesions, although they also reported a greater incidence of ipsilateral sensorimotor deficit associated with left cerebral lesions.

Interhemispheric comparisons of contralateral and ipsilateral sensorimotor performances significantly differentiated the two cerebral hemispheres. For the contralateral performances, lesions lateralized to the right cerebral hemisphere were associated with greater sensorimotor performance deficits than lesions lateralized to the left hemisphere. Right-sided cerebral lesions resulted in greater impairment of sensorimotor functioning on the left side of the body than did left-sided cerebral lesions with the right body side. This result confirms the findings of Boll (1974) and Semmes et al. (1960).

Ipsilateral sensorimotor functioning was affected in a manner similar to contralateral sensorimotor functioning. Again, right-sided cerebral hemisphere lesions produced greater ipsilateral sensorimotor performance deficits than left-sided cerebral lesions did. Along with the findings of Boll (1974), this result is in contrast to the findings of Semmes and others who had reported that the left cerebral hemisphere is predominant, in comparison with the right hemisphere, for ipsilateral sensorimotor functions.

These discrepant results may be accounted for by various aspects of the experimental design used in this study. The studies of Semmes et al. (1960) and others, who found predominance of the left cerebral hemisphere for ipsilateral sensorimotor functions, were based upon analyses of incidence or frequency of occurrence of sensorimotor deficit. Analysis of data in terms of discrete categories is inherently less sensitive to the actual distribution from which the data are drawn. In contrast, the analyses of data in the present study were made not just in terms of the occurrence of sensorimotor deficits but were evaluated with regard to their severity. As a result, the present findings are based upon a more powerful data base and employed more sensitive methods of analysis. Therefore, these findings and those of Boll

(1974) are more likely to reflect the effect of lateralized lesions upon sensorimotor functioning than are those of Semmes et al. (1960), Vaughan and Costa (1962) and Wyke (1966, 1971). The right cerebral hemisphere, not the left, is predominant for both contralateral and ipsilateral sensorimotor functioning.

Other features in the present experimental design which may account for the differences in the results of the present study from previous studies are in terms of the patient sample and the measures of sensorimotor functioning employed. The evidence presented by Semmes et al. (1960) was solely based upon the performances of patients with long-standing penetrating head injuries caused by high-velocity missiles inflicted during combat. A high proportion of patients in the Wyke (1966, 1971) studies had either meningiomas or temporal lobectomies. Varying types of cerebral lesions demonstrate different relationships in terms of pathological effects and neuropsychological measurements (Reitan, 1966). The question of the differential effect of varying neurological diagnostic groups was investigated in the present study, which used equal representation of patients with cerebrovascular, neoplastic, and traumatic brain lesions. The results confirm the hypothesis of differential effects and relationships among different lesion types. Differential sensorimotor functioning among the cerebrovascular, neoplastic, and traumatic lesion groups was shown. The sensorimotor functioning of patients with cerebrovascular lesions was significantly more impaired than that of patients with traumatic lesions. Based upon mean performances, the sensorimotor functioning of neoplastic lesion patients occupied a middle position between cerebrovascular and traumatic lesions. Traumatic brain lesions clearly demonstrated the least amount of sensorimotor deficit.

Additional analysis in terms of differential contralateral and ipsilateral sensorimotor functioning further demonstrated the differential effect of lesion type. In general, a similar pattern of right cerebral hemisphere predominance for contralateral and ipsilateral sensorimotor functioning was indicated for each of the three lesion groups, as in the overall analysis of combined lesion groups. However, the consistency of the pattern varied according to lesion type. Cerebrovascular lesions demonstrated the strongest example of the pattern while the neoplastic and traumatic lesions demonstrated less of the pattern.

Another important feature of the present study relates to the problem of hand preference confounding the results. Finlayson (in press) dealt with this problem by comparing the hand performances of brain-damaged patients to normative or control values for each hand measure. Comparisons of the resulting difference scores failed to differentiate between the right and left cerebral lesion groups for contralateral and ipsilateral comparisons. The procedure used by Finlayson assumes that hand preference characteristics of brain-damaged patients are similar to control or normative groups. Such an assumption may not be justified. In fact, the hand preference characteristics of a brain-damaged patient may be differentially affected by such factors as type of lesion and/or side of cerebral damage.

The procedure used in the present study makes no assumptions about the hand preference characteristics of the brain-damaged patients. Any differential effects due to hand preference have been adjusted by the T-score conversion procedure. Absolute magnitude differences between the right and left hand due to hand preference characteristics have been eliminated. As a result, a more direct measure of contralateral and ipsilateral sensorimotor functioning associated with lateralized cerebral lesions has been obtained.

Previous studies investigating the differential effect of lateralized lesions upon sensorimotor abilities have used only a small number of sensorimotor measures (Boll, 1974; Finlayson, in press; Semmes et al., 1960; Vaughan and Costa, 1962; Wyke, 1966; 1971). In contrast, the present study utilized a constellation of sensorimotor functioning, including motor, sensory-perceptual, tactile-perceptual, and psychomotor abilities. Through the use of the MANOVA procedure, the effect of lateralized cerebral lesions upon the entire constellation of sensorimotor abilities was simultaneously analyzed. As a result, the findings of the present study demonstrate the very powerful effect that lateralized cerebral lesions have upon sensorimotor functioning.

In concordance with previous studies (Boll, 1974; Semmes et al., 1960), the evidence presented in the present study clearly indicates that sensorimotor functions of the two cerebral hemisphere are not merely mirror images of each other. In fact, damage to the right cerebral hemisphere leads to greater sensorimotor impairment than does damage to the left cerebral hemisphere. Apparently, the human brain has a functional organization in which the right cerebral hemisphere is predominant in terms of sensorimotor processes.

The findings of the present study have definite implications concerning the theory of hemispheric specialization and organization proposed by Semmes (1968). Semmes interpreted her findings as representing a focally-organized left cerebral hemisphere composed of a high degree of convergence of "like" elements and a diffusely-organized right cerebral hemisphere depending on a convergence of "unlike" elements. However, her findings were based upon a problematic assumption. The experimental design of the Semmes et al. (1960) study assumed an appropriate classification of the patient sample into localizable areas of cerebral damage, with essentially comparable damage in each cerebral hemisphere. As noted earlier in this paper and in the thorough critique by Reitan (1961), this assumption is unwarranted. In addition, the findings of the present investigation are clearly in contrast to those found by Semmes et al. (1960). The right cerebral hemisphere, not the left, is predominant for both contralateral and ipsilateral sensorimotor functioning. In light of these two criticisms, it is very difficult to accept the theory of hemispheric specialization proposed by Semmes as representing the actual organization of the cerebral hemispheres.

The neuropsychological investigation of sensorimotor functions has important implications upon higher level mental functioning. The studies of Boll, Berent and Richards (1977), Fitzhugh, Fitzhugh and Reitan (1962), and Reitan (1970) have shown that impairment of sensorimotor functions has profound association with intellectual and cognitive functions and has some relationship to emotional adjustment. Reitan (1970) compared the intellectual and cognitive functioning of a group of adult brain-damaged patients with relatively intact sensorimotor functioning to a group with impaired sensorimotor functioning. It was found that the impaired group was seriously deficient in comparison with the intact group on intelligence measures, measures of concept formation and abstract functioning, measures requiring perception and coordination of verbal and non-verbal auditory information, and measures of general alertness and coordination. In addition, the impaired group had a more pathological profile in terms of affective behavior than the intact sensorimotor group.

These findings have been extended to include the sensorimotor functioning in children. Boll, Berent and Richards (1977) demonstrated that tactile-perceptual functioning exerts a powerful influence upon the adequacy of a broad range of human adaptive abilities in both brain-damaged and normal children. The aforementioned studies provide strong evidence for the importance of sensorimotor functioning in relation to human brain-behavior relationships.

Finally, in the current investigation, the different measures of sensorimotor functioning were studied as a single constellation. However, of equal importance is the effect of lateralized lesions upon each individual sensorimotor skill or smaller related combinations of sensorimotor functions. For example, Boll, Berent and Richards (1977) related tactile-perceptual abilities to higher level mental functioning. Further detailed investigation is necessary to determine these dimensions of sensorimotor functioning.

APPENDIX

SUMMARY OF ANOVAS FOR EACH SENSORIMOTOR MEASURE

Measure	Source of Variation	df	SS	MS	F	p <
TAP						
	Between Groups	144	7251.94	50.36		
	Side	1	.00023	.00023	0.00	.99
	Lesion x Side	2	100.59	50.30	1.00	.37
	Hemisphere x Side	1	5125.17	5125.17	101.77	.00001
	Lesion x Hemis x Side	2	1099.18	549.59	10.91	.00004
	Within Groups	144	14608.29	101.45		
	Lesion	2	1051.12	525.56	5.18	.007
	Hemisphere	1	186.79	189.79	1.84	.18
	Lesion x Hemisphere	2	369.07	184.53	1.82	.17
	Total	299	29792.15			
GRIP						
	Between Groups	144	5723.24	39.74		
	Side	1	.00019	.00019	0.00	.99
	Lesion x Side	2	61.46	30.73	0.77	.46
	Hemisphere x Side	1	3858.68	3858.68	97.09	.00001
	Lesion x Hemis x Side	2	589.72	294.86	7.42	.00086
	Within Groups	144	17445.72	121.15		
	Lesion	2	873.74	436.87	3.61	.0296
	Hemisphere	1	1183.84	1183.84	9.77	.002
	Lesion x Hemisphere	2	74.24	27.12	0.31	.736
	Total	299	29810.64			
TPT						
	Between Groups	144	6968.24	48.39		
	Side	1	.00023	.00023	0.00	.99
	Lesion x Side	2	110.38	55.19	1.14	.32
	Hemisphere x Side	1	3823.04	3623.04	79.00	.00001
	Lesion x Hemis x Side	2	1428.35	714.18	14.76	.00001
	Within Groups	144	14119.31	98.05		
	Lesion	2	1623.42	811.71	8.28	.0004
	Hemisphere	1	1156.40	1156.40	11.79	.00078
	Lesion x Hemisphere	2	565.82	282.91	2.89	.059
	Total	299				
TAC						
	Between Groups	144	12172.08	84.53		
	Side	1	.00389	.00389	0.00	.99
	Lesion x Side	2	142.92	71.46	0.85	.43
	Hemisphere x Side	1	2593.43	2593.43	30.68	.00001
	Lesion x Hemis x Side	2	450.34	225.17	2.66	.07
	Within Groups	144	12431.80	86.33		
	Lesion	2	1159.73	579.87	6.72	.002
	Hemisphere	1	685.78	685.78	7.94	.006
	Lesion x Hemisphere	2	137.00	68.50	0.79	.45
	Total	299	29773.08			

Measure	Source of Variation	df	SS	MS	F	p <
AUD						
	Between Groups	144	11255.78	78.17		
	Side	1	1.24	1.24	0.016	.90
	Lesion x Side	2	45.73	22.87	0.29	.74
	Hemisphere x Side	1	603.02	603.02	7.71	.006
	Lesion x Hemis x Side	2	194.73	97.37	1.25	.29
	Within Groups	144	13045.45	90.59		
	Lesion	2	77.89	38.94	0.43	.65
	Hemisphere	1	1918.60	1918.60	21.18	.00001
	Lesion x Hemisphere	2	92.76	46.38	0.51	.60
	Total	299	27235.20			
VIS						
	Between Groups	144	11400.07	79.17		
	Side	1	.11136	.11136	0.001	.97
	Lesion x Side	2	176.79	88.40	1.12	.33
	Hemsiphere x Side	1	2874.08	2874.08	36.30	.00001
	Lesion x Hemis x Side	2	340.67	170.34	2.15	.12
	Within Groups	144	13373.51	92.87		
	Lesion	2	696.46	348.23	3.75	.03
	Hemisphere	1	711.23	711.23	7.66	.006
	Lesion x Hemisphere	2	52.20	26.10	0.28	.75
	Total	299	29625.12			
FA						
	Between Groups	144	9493.53	65.93		
	Side	1	.01541	.01541	0.00	.99
	Lesion x Side	2	85.71	42.86	0.65	.52
	Hemisphere x Side	1	3643.92	3643.92	55.27	.00001
	Lesion x Hemis x Side	2	668.49	334.25	5.07	.007
	Within Groups	144	14314.27	99.40		
	Lesion	2	1308.71	654.36	6.58	.002
	Hemisphere	1	169.94	169.94	1.71	.19
	Lesion x Hemisphere	2	70.34	36.17	0.36	.70
	Total	299	29756.93			
FTW						
	Between Groups	144	6737.88	46.79		
	Side	1	.00276	.00276	0.00	.99
	Lesion x Side	2	174.04	87.02	1.86	.16
	Hemisphere x Side	1	2255.40	2255.40	48.20	.00001
	Lesion x Hemis x Side	2	627.30	313.65	6.70	.002
	Within Groups	144	17842.74	123.91		
	Lesion	2	1439.20	719.60	5.81	.004
	Hemisphere	1	449.09	449.09	3.62	.06
	Lesion x Hemisphere	2	274.16	137.08	1.11	.33
	Total	299	29799.81			
TFR						
	Between Groups	144	9665.59	67.12		
	Side	1	.02613	.02613	0.00	.98
	Lesion x Side	2	2.87	1.44	0.02	.98
	Hemisphere x Side	1	4810.25	4810.25	71.66	.00001
	Lesion x Hemis x Side	2	1757.62	878.81	13.09	.00001
	Within Groups	144	11592.37	80.50		
	Lesion	2	1837.26	918.63	11.41	.00003
	Hemisphere	1	21.97	21.97	0.27	.60
	Lesion x Hemisphere	2	55.32	27.66	0.34	.71
	Total	299	29743.28			

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