Assessment of cognitive asymmetries in brain-damaged and normal subjects: validation of a test battery

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SUMMARY A test battery designed to assess cognitive functions normally related to the left and right cerebral hemispheres was validated on 30 patients with unilateral (16 right, 14 left) lesions. The tests were preselected to reflect typical functioning of the hemispheres according to general agreement in the literature. A Cognitive Laterality Quotient (CLQ) was calculated from the difference in performance between the “right” and “left” test batteries and, therefore, reflected the relative functioning attributed to the right and left hemispheres. Using the CLQ measurement and a control group of 30 non-neurological patients matched for age and education, 28 out of 30 brain-damaged patients (93 %) were categorised correctly according to side of lesion; the other two were considered to have either abnormal lateralisation (one was left handed) or asymmetrical premorbid cognitive profiles. Using only one (paired) test whose two subparts were designed to vary only slightly in task requirements to measure either right or left functioning, 29 out of 30 patients were correctly categorised. It is suggested that the concept of *relative* assessment of basic cognitive functions is more fruitful than *general* assessment of intellectual functions for use in diagnosis and rehabilitation of neurological patients or normal subjects with developmental or acquired behavioural cognitive abnormalities.

Deficits in cognitive functioning after cerebral pathology are found in tests of memory (Schacter and Crovitz, 1977), intelligence (Fogel, 1964; Piercy, 1964), response time (Blackburn and Benton, 1955; Boller *et al.*, 1970), and other objective measures of mental functions (Harness *et al.*, 1976). Interpretations of deficits in a brain-damaged population are limited, however, since comparisons with normal performance do not take into account the interaction of brain disease with the patient's general cognitive functioning (Piercy, 1969). These measures can be quite informative when considered in the context of the patient's premorbid intellectual skills, but this information is often lacking. Test batteries especially designed to measure cognitive behaviour can avoid partly the problem of making valid comparisons with normal groups by allowing the patient to be his own control, since he would display a cognitive profile reflecting different relative performance among

subtests of the cognitive battery (Chapman and Wolff, 1959). The advantage of the profile approach is that a patient's cognitive status is described more completely but with minimal dependence on premorbid information, or complications of interpretation as a result of the general effects of deterioration (Benton, 1974).

The main problem is to decide which battery of tests gives the best profile of cognitive function. The battery presented here was constructed by working backwards from empirical evidence, and is designed to compare functions in the two anatomically and functionally distinct cerebral hemispheres (Bogen, 1969). Whereas most other test batteries are combined post hoc to estimate left and right cerebral functions, these tests were selected from those which have already shown preferential performance by processes attributed to the left or the right cerebral hemisphere. For example, tests of the left hemisphere function include verbal (Benton, 1968), sequential (Carmon and Nachshon, 1971), analytical (Levy-Agresti and Sperry, 1968), and time-dependent (Gordon, 1974) processing. Right hemisphere tests would require skills in synthesis (Levy-Agresti and Sperry, 1968),

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completion of forms (Nebes, 1974), recognition of faces (De Renzi and Spinnler, 1966; Benton and Van Allen, 1968), orientation in space (Benton, 1969; Benton *et al.*, 1975a), and recognition of patterns (Meier and French, 1965). The relative evaluation of right and left hemispheres has two major advantages. First, since each patient serves as his own control, a cognitive profile of certain functions relative to others reduces the importance of general deterioration and overall performance. Secondly, a difference score calculated for the relative functioning of each hemisphere (Gordon, 1979) provides a useful diagnostic tool for assessing the intellectual capacity of the patient as well as further direction for therapy.

The method of measuring right-left mental functioning using tests of lateralised cognitive functions is demonstrated in the present report on patients with verified left and right unilateral brain damage and compared with a baseline determined from a matched control group. The tests of the battery have been chosen with two ideas in mind. On the one hand, it was desirable to use tests that have already been standardised and used on clinical populations, to avoid dangers inherent in new test construction. However, when comparing the performance of the two hemispheres, variation in performance of a test based on widely different test materials or instructions should be avoided. Therefore in addition to standardised tests, the present battery included matched paired tests in which each of the two subtests used the same stimuli but with a slightly altered method of presentation so as to favour the specific functions of one or the other cerebral hemisphere. The present data validate both the standard and matched pair tests for the measurement of right and left hemisphere functions.

Subjects and methods

Fourteen left and 16 right hemisphere-damaged

patients were referred by the neurological or neurosurgical units for cognitive evaluation. All patients had unilateral lesions as verified by cerebral computerized tomography or surgical evidence. One left and two right hemisphere-damaged patients had a contralateral homonymous hemianopia. Their performances did not differ significantly from the mean performance of the respective groups. No significant differences were found between the right and left groups according to locus or type of lesions, or according to handedness, sex, age, and years of schooling (Table 1).

A control group of 30 patients resident in the hospital for non-neurological disorders were also tested to provide the baseline measure. The control patients were selected to match the age ($\bar{x}=43.46$ years; $SD=16.45$) and educational range ($\bar{x}=11.9$ years; $SD=3.2$) of the combined hemispheric groups. The average age and educational levels did not differ significantly for the two groups.

The test battery included two right-left hemisphere paired tests and an additional two left and three right hemisphere standardised, unpaired tests.

PAIRED TESTS

Light sequence-pattern test

The *light sequence test* (adapted from Carmon and Nachshon, 1971) was designed to measure left hemisphere function. The stimuli were back-illuminated squares (50mm×50mm), presented on 300mm×300mm opalescent screen that had been subdivided into a 5×5 matrix. For the sequence test, the corner and centre squares were blocked out leaving eight squares to form a diamond shaped pattern (Fig. 1a). A trial consisted of one sequential illumination of either three, four, or five squares in a preprogrammed order. The stimulus sequence was followed by a second presentation in the same spatial location but either in the same or different sequential order. The subject's task was to report whether the

Table 1 Detailed specifications of the right and left damaged groups

Site of damage*				Aetiology			Sex		Handedness		Age (yr)	Years of schooling
	Anterior	Middle	Posterior	Tumour	CVA	Others	Male	Female	Right	Left	Mean (SD)	Mean (SD)
Right damaged group	7	9	0	12	2	2	5	11	14	2	46.75 (17.86)	11.75 (3.55)
Left damaged group	9	4	1	13	1	0	6	8	13	1	41.00 (14.32)	12.64 (2.20)
Total	16	13	1	25	3	2	11	19	27	3	$t=0.963$ NS	$t=0.813$ NS

*Anterior: frontal; fronto-temporal. Middle: parietal; temporal; fronto-parietal; parieto-temporal. Posterior: parieto-temporo-occipital. CVA: cerebrovascular accident (stroke).

(a)

(b)

Fig. 1 Apparatus for the light sequence-pattern paired test (a) light sequence test, (b) light pattern test.

second sequence was the same or different from the first. The duration of each light in the sequence was 500 ms followed by a 500 ms interval between lights.

The light pattern test was designed to measure right hemisphere functioning. The same screen was used for this test as was used for the light sequence, except that the whole 5×5 matrix of squares was displayed (Fig. 1b). In each trial, a pattern of six to eight squares was illuminated simultaneously for 500 ms. Approximately three seconds after exposure, a card was handed to the subject. The card contained a pattern of black squares on a white background that corresponded to the pattern of lights flashed on the screen. No frame or matrix landmarks were present on the

card although the card's orientation was fixed. The subject was to say whether the pattern flashed card was the same or different from the pattern flashed on the screen.

In both versions there were 18 trials where same and different responses were interspersed unpredictably throughout. The score for each test was the total number of correct responses. Two training trials were presented before each test version.

Letter search-recognition test (adapted from Faglioni et al., 1969)

The letter search test was designed to assess left hemisphere functions. The subject was presented with

a 50mm × 280mm rectangular card with three (Hebrew) letters in cursive script written at the top. Underneath these stimulus letters, 10 five-letter meaningful words were presented in print, one below the other, down the length of the card. All six possible combinations of the three letters appeared in six different words of the list; three other words contained only two of the letters; and in one word, none of the three letters appeared. The word with the correct combination of letters was unpredictably located between the third and eighth word, inclusively. The subject's task was to locate and point to the correct word as quickly as possible.

The letter recognition test was designed to test the right hemisphere. A similar rectangular card was presented but with only one Hebrew letter printed at the top. Underneath, 10 single letters were listed one below the other, just as the words had been on the previous test. The difference on this test, however, was that the stimulus letter was slightly tilted to one side and camouflaged within a background of distracting symbols. The subject's task was first to recognise the letter, and then to point, as quickly as possible, to the matching letter from among 10 listed in the column below.

Eight different trials were included in each version of this test. The response time to each card was measured by a stop watch, but a single score was obtained for each version by calculating the median of the times at which a correct response was made. One training card was presented before each test.

UNPAIRED TESTS: LEFT HEMISPHERE

Digit span

This test was taken directly from the Wechsler Adult Intelligence Scale (WAIS) (Wechsler, 1955). A series of digits of increasing length (3, 4, . . .) was presented orally at a rate of about one digit per second. In the first part of the test the subject repeated the series verbatim until he reached his maximum level; in the second part he repeated the digits in the reverse order. The score was the sum of the highest level attained in each part.

Verbal fluency (Benton and De S. Hamsher, 1976)

The subject was requested to write as many words as possible in one minute's time that started with a given letter of the Hebrew alphabet. Proper names and multiple word forms—for example, plurals, tenses and so on—were not permitted. This test was repeated twice more, each time with a different letter. The letters were chosen according to a relatively high (but not the highest) frequency of words that start with each letter. The score was the total number of words from all three parts.

UNPAIRED TESTS: RIGHT HEMISPHERE

Block design

This test was taken from the WAIS (Wechsler, 1955) using the standard administration and scoring. Cubes (30mm on a side) differently painted red and white on each of their faces, were presented for construction of mosaic patterns presented on a stimulus card. Six patterns required four blocks, and four patterns required nine blocks. The constructions were scored for correctness within a time limit plus bonus points for fast constructions of the more difficult patterns.

Object assembly

This test was also taken from the WAIS (Wechsler, 1955). Four sets of cardboard puzzle pieces were presented to be assembled into the proper object forms. The productions were scored for correctness and speed of completion.

Facial recognition test (Benton et al., 1975b),

A full face photograph of a man or woman served as the test item. The subject was requested to identify the same face from among six response choices which were also photographs of faces but viewed from different angles or in different light conditions. In the first six trials one face was to be chosen from among the six. In the remaining 16 trials the test face was to be found three times among the six. The score was the number of correct faces identified (50% maximum).

GENERAL PROCEDURE

The subjects sat in a comfortable chair, in a quiet room. Administration of the battery of tests began with the letter search and the letter recognition matched pair test. Facial recognition was given next, followed in order by digit span, block design, object assembly, and word fluency. The paired light sequence and light pattern tests were presented last. Unlimited break times were allowed between the tests upon signs of fatigue or at the patient's request. Breaks never exceeded 10 minutes, and the entire test battery never exceeded 70 minutes including breaks. Hand laterality was assessed by a standard questionnaire (Oldfield, 1971).

Results

Patients with left hemisphere damage performed poorly on virtually all the left hemisphere tests but performed normally on right hemisphere tests. Precisely the reverse was seen in right hemisphere patients, who performed normally on left hemisphere tests but poorly on right hemisphere tests. By comparison, the control group of non-neurological

patients performed in the normal range on both left and right hemisphere tests (Table 2). The patients with left hemisphere damage virtually equalled the performance of the control group on all but one of the right hemisphere tests and scored lower on each of the left hemisphere tests. Conversely, the patients with right hemisphere damage performed as well as the control subjects on each of the left hemisphere tests but did worse than the control group on right hemisphere tests.

In order to assess the power of the test battery to differentiate between the different damaged hemispheres and the control groups, the score of each subject on each subtest was "corrected" using the deviation of this score from the mean score for all subjects in terms of the number of standard deviations. Thus, a standard (Z) score was calculated for each subject for each test:

$$Z_{ij} = \frac{X_{ij} - \mu_i}{\sigma_i}$$

where X_{ij} is the (jth) subject's score on a particular (ith) test, μ_i is the mean of the "population" (30 brain-damaged and 30 control patients), and σ_i is the standard deviation of the population. A measure of right hemisphere ability can be obtained by combining the scores for the right hemisphere tests into a single score simply by finding the average of the Z scores for that hemisphere:

$$A = \frac{1}{n_{Ri}} \sum Z_{Ri}$$

where A is the average for the right hemisphere, n_{Ri} is the number of right hemisphere tests, and Z_{Ri} is the Z score for the ith right hemisphere test. A similar score can be calculated to measure left hemisphere performance:

$$P = \frac{1}{n_{Li}} \sum Z_{Li}$$

The average left hemisphere performance, P, for left hemisphere-damaged patients was -0.798 while the average for right hemisphere performance, A, was

-0.09 in the same patients. Conversely, the average right hemisphere performance, A, for patients with right hemisphere damage was -0.629, while the average left hemisphere performance, P, was +0.205. A significant interaction ($F = 56.20$, $p < 0.001$) between the A and the P scores and the side of lesion was found using analysis of variance (ANOVA) repeated measures. There was no significant difference over all subjects in performance of the right (A) or left (P) test batteries but there was a difference in overall performance where the brain-damaged groups performed below the control group ($t = 4.27$, $p < 0.001$). Subsequent *t* tests confirmed a significant difference between A and P scores for each group (left damaged: $t = 7.83$; right damaged: $t = 5.01$; $p < 0.001$, two-tailed), but in opposite directions (Fig. 2).

The A and P values were then used to derive a single score, constructed not so much to determine the overall ability of a subject but rather to assess his relative ability in left-right hemispheric functions (Bogen *et al.*, 1972). In the present formulation this

Fig. 2 Diagram of right (A) and left (P) performance for the left damaged, right damaged, and control groups.

Table 2 Raw mean performance and standard deviations of the control, left hemisphere-damaged and right hemisphere-damaged groups for the right and the left hemisphere tests

Group	Test	Left hemisphere tests				Right hemisphere tests				
		Letter search (I/RT)	Lights sequential span (No. correct)	Digit (Scaled score)	Word fluency	Letter recognition (I/RT)	Light pattern (No. correct)	Block design (Scaled score)	Object assembly (Scaled score)	Facial recognition
Left hemisphere-damaged	$\bar{X}$	0.0916	11.72	7.78	16.36	0.2084	15.18	9.28	7.78	44.69
	SD	0.05	3.46	3.00	12.23	0.11	2.64	3.00	3.50	5.00
Control	$\bar{X}$	0.1893	14.32	10.50	33.27	0.3050	15.12	11.76	10.83	45.31
	SD	0.09	3.43	2.71	14.00	0.15	2.37	2.76	3.38	4.00
Right hemisphere-damaged	$\bar{X}$	0.1808	14.36	10.69	27.78	0.1153	12.64	8.69	6.69	41.37
	SD	0.097	2.31	2.75	11.96	0.12	3.22	2.39	2.91	4.14

score, which we call the Cognitive Laterality Quotient (CLQ) (Gordon and Melamed, 1978), is simply the difference in the measures for the two hemispheres: $CLQ = A - P$. Patients with left hemisphere damage would be expected to have CLQs greater than zero while patients with right hemisphere lesions would have negative CLQs. Non-neurological subjects would fall near zero. The validity of the test battery can be assessed by predicting the side of the lesion on the basis of the CLQ score. Accordingly the numbers of subjects with CLQs less than (an arbitrary) -0.5 or greater than 0.5 or in the middle region were tabulated (Table 3). No subjects with left hemisphere damage had a CLQ less than -0.5 and no subjects with right hemisphere damage had a CLQ greater than 0.5 . Most of the control subjects (63%) fell within the centre region while only a minority (27%) of the unilateral patients did. Despite the arbitrary cut-off points for the CLQ this crude distribution was nevertheless different from chance ($\chi^2 = 40.33$, $p < 0.005$ (df = 4), two-tailed), and correctly sorted the two lesion and control groups into their respective categories more than 67% of the time. The separation of the groups is clearer in more continuous representation of the distribution (Fig. 3).

Standardisation of the subtests will give this battery an even higher value. The Z scores would be then calculated relative to the normal performance, and the CLQ would become an effective measurement of cognitive functions for each patient. Whereas a

group of 30 control patients is rather small, its normal performance on the already standardised tests implies that the group may nevertheless be a good sample of the population. When A, P, and CLQ were recalculated, using the mean scores and SD of the control group only, the same relationship was found where P was lower for left hemisphere patients, A was lower for right hemisphere patients, and the resulting CLQ was positive for the left-damaged patients and negative for the right-damaged patients (see Table 4). The difference was significant ($t = 7.46$, $p < 0.001$). A measure of total cognitive performance (CTQ) can also be assessed by adding the performances for the left and right hemisphere: $CTQ = A + P$. Both groups showed, as expected, a significant deficit relative to the control group, but the decline was not different between the groups ($p > 0.20$) ($t = 4.270$, $p < 0.001$).

In this new calculation of the CLQ where the control group is used as an estimate of the population, nearly all (93%) the patients were correctly categorised. All 16 right damaged patients had $CLQ < 0$, and 12 out of 14 left damaged patients had $CLQ > 0$. One of the two misclassified patients was left handed.

In the event that a long testing session was not practical, an assessment was made on the validity of the paired tests for the light-sequence-patterns test. For left damaged patients the score for the sequential

Table 3 Frequency of control, left hemisphere-damaged and right hemisphere-damaged subjects with CLQ above +0.5, below -0.5, and between ± 0.5

Score	Left hemisphere damage	Control	Right hemisphere damage	
CLQ < -0.5	0	5	11	16
-0.5 < CLQ < +0.5	3	19	5	27
CLQ > +0.5	11	6	0	17
Total	14	30	16	60

Table 4 Mean performance of the left hemisphere-damaged and right hemisphere-damaged group on the right hemisphere tests (A), the left hemisphere tests (P), the relative performance (A-P), and the total performance (A+P).

	A (SD)	P (SD)	CLQ (SD)	CTQ (SD)
Left hemisphere-damaged (N = 14)	0.517 (0.76)	-1.048 (0.66)	+0.531 (0.42)	-1.566 (1.36)
Right hemisphere-damaged (N = 16)	1.139 (0.58)	-0.55 (0.68)	1.085 (0.71)	-1.194 (1.046)

Fig. 3 Distribution of subjects according to their CLQ.

version was significantly lower than for the pattern ($t=2.43$, $P<0.05$, $df=10$) while for the right damaged group the scores were reversed ($t=3.33$, $P<0.01$, $df=13$). The predictive ability of this test turned out to be good where 29 out of 30 patients were correctly classified. The predictive ability of the other paired test—letter search-recognition—failed to be convincing, (23 out of 30) although the relative value of the means was in the correct direction (Fig. 4).

Discussion

Poor performance on a battery of left hemisphere tests characterised patients with verified left hemisphere lesions while patients with right hemisphere lesions performed barely below the normal average on the same tests. Conversely, most tests designed to measure right hemisphere functions were performed just below the normal average by patients with left hemisphere lesions but quite poorly by patients with verified right hemisphere damage. The test batteries thus appear to be valid measures of right and left hemispheric functions, having been selected for this purpose.

An important concept in this method of measuring brain functions is to assess the relative performance of right and left hemispheres in a single measurement rather than to compare each of the measures separately to a control group. While it is true that a standard score based on a control group was calculated for each subtest, it is the relationship among these scores, reflected by the Cognitive Laterality Quotient (CLQ), that is used to assess cognitive functioning. Any general loss of function is “subtracted out” by the relative measure, which gives the present formulation its diagnostic value and therapeutic usefulness. For example, any particularly intelligent patient who would perform above average on both test batteries, or any particularly unintelligent patient who would perform below average on both batteries would

nevertheless reflect the same cognitive bias determined by the value of the CLQ.

Accordingly, correct classification was obtained in 28 out of 30 (93%) of the patients, where $CLQ<0$ for right damaged patients and $CLQ>0$ for left damaged patients. The failure to classify two of the patients, in spite of the verified unilateral damage, emphasises an important point: this battery of tests cannot (even theoretically) be used as a reliable tool for localising brain damage. In the first place, cortical damage may always be bilateral so the CLQ can only indicate the side of the most damage. Secondly, the ideal or “normal” division of cognitive functions into the left or right hemisphere (Bever, 1975) differs among non-right handers, women, and (possibly) inverted writers, not to mention subjects with early brain injury. The final complication in using the CLQ as a localising measure is the lack of knowledge of the subject’s premorbid cognitive profile. A right hemisphere lesion in a person who is considerably more skilful in global, spatial, orientational processes may cause only a partial loss of these functions so that they may still be superior to the logical, analytical functions of the left hemisphere. Therefore, the contribution of a neuropsychological measure for the diagnosis and treatment of patients is less valuable for localisation or measurement of intelligence than for description of cognitive abilities.

An example of how the cognitive profile can be helpful in retraining specific cognitive functions can be seen in the acquisition of reading ability in an alexic woman (Carmon *et al.*, 1977). This patient had a left hemisphere stroke which produced alexia with agraphia but only a mild anomia. Cognitive testing revealed good performance of right hemisphere tests and poor performance on nonverbal, left hemisphere tests as may be expected from the pathology. Successful retraining in reading progressed through methods that favoured right hemisphere capabilities, at a time when aphasia worsened.

Fig. 4 Performance of the left and right damaged groups on the matched pair tests (a) letter search-recognition tests, (b) light sequential-pattern tests.

For other disorders producing abnormal cognitive behaviour, the role of the CLQ has special significance. Preliminary evidence, for example, has shown that demented patients have a large deficiency in performance—a very low CTQ—but a greater deterioration in the right hemisphere relative to the left—a negative CLQ (Bentin *et al.*, 1978). Also Parkinsonism patients have a greater (less negative) CTQ than demented patients but have a larger CLQ, indicating an even greater right hemisphere deterioration relative to the left (Bentin, Silverberg, and Gordon, in preparation).

Developmental dyslexia is yet another example of a disorder in which more patients have a CLQ different from zero, but in this case highly positive. In other words, left hemisphere performance (not specifically verbal) is considerably underdeveloped relative to normal or above normal right hemisphere development (Carmon *et al.*, 1978). The CLQ was also positive in the male siblings of dyslexic children, implying that the genetic role in congenital dyslexia may be a predisposition to a particular cognitive profile of which dyslexia is a part (Gordon and Melamed, 1978).

The validity of these test batteries in the measurement of right and left hemisphere functions is clear from the results. This does not mean, however, that these are the only tests or that the best have been found. Indeed, other cognitive subdivisions have been distinguished (Luria, 1966) which should be incorporated as the current model is developed and extended. Furthermore, even the tests of the present battery are not likely to be equivalent measures of right and left function. Accordingly a more proper formulation of A and P would be:

$$A = \frac{1}{n_R} \sum k_{iR} \cdot Z_{Ri}; P = \frac{1}{n_L} \sum k_{iL} \cdot Z_{Li}$$

where k is a constant weighting factor that has to be established empirically for each test. The only claim for the present series is that each battery is a good measure of functions for its respective hemisphere and that the relative measurement will give an accurate profile.

Other problems such as time of presentation and instrumentation need to be overcome. It was encouraging that one paired test was a good predictor of side of lesion, implying that the length of the battery may be considerably reduced. Also, the technology is available to produce small, inexpensive audiovisual units for individual neuropsychological testing.

A more serious problem is that some subtests require motor skills—for example, arranging blocks, producing words (fluency), and so on—where others do not. Patients with motor symptoms like those with

Parkinson's disease might be handicapped, thereby biasing their CLQ. Although studies suggest that rigidity, tremor, and akinesia do not significantly influence the performance on the Performance Scale of WAIS in patients with Parkinsonism patients (Loranger *et al.*, 1972), the left and right batteries should be balanced with respect to this problem. Again, the use of paired tests will provide a partial solution.

A clinical diagnosis of aetiology, size, location, etc of cerebral pathology is best made by the appropriate neurological or surgical techniques. A neuropsychological test battery can only contribute in a confirmative capacity but it cannot be used in isolation for these purposes. On the other hand, the usefulness of neuropsychological testing is well known for assessing the cognitive function of patients, either to establish a degree of overall performance (or deterioration) or to define a type of intellectual loss. The test battery suggested here is designed to measure the cognitive function of the right and left cerebral hemispheres. The dichotomy was chosen as a first step because it reflects the relative behavioural output of two distinct anatomical structures. The Cognitive Laterality Quotient provides a profile of hemispheric function emphasising a *kind* of thinking rather than an amount.

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