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COGNITION AND COMMISSUROTOMY

by JOSEPH E. LEDOUX, GAIL L. RISSE, SALLY P. SPRINGER, DONALD H. WILSON *and* M. S. GAZZANIGA

(*From the Department of Psychology, State University of New York at Stony Brook and Dartmouth Medical School, USA*)

THE evaluation of cognitive functioning in patients with sectioned forebrain commissures has previously been confined largely to descriptions of the breakdown in the interhemispheric transfer of information. While early reports have emphasized the apparent lack of intellectual impairment and personality disruption following commissurotomy (Gazzaniga, 1965, 1967, 1968, 1970) it has recently been suggested that such patients may suffer a lasting and severe memory deficit subsequent to operation (Zaidel and Sperry, 1974). These authors report that short-term memory deficits were found in 8 patients with complete section of the forebrain commissures and 2 patients with partial sections. The deficits were evaluated by comparing the patients' scores on standardized memory tests with published scores on normal and epileptic control subjects. While the poor performance of these patients is striking, the conclusion that the corpus callosum plays an important selective role in mnestic function may be premature, given the absence of pre-operative control data.

In the present report, we describe the extensive evaluation of cognition in a recent callosotomy case. It should be noted that this is the first recorded split-brain case where pre-operative testing of this kind was carried out. Thus, in addition to re-examining the memory issue using standardized tests, we were interested in obtaining a more complete assessment of cognitive functioning by using several special experimental tests that allow for a greater fractionation of the memory process, as well as a complex hypothesis testing task. With these latter tests, we hoped to identify the functional locus in the memory process that might underlie the earlier reported memory deficit, as well as extend the evaluation of cognition following commissurotomy.

CASE REPORT

D. H. is a 15-year-old, right-handed male who suffered an attack of herpes encephalitis at age 10 which required emergency decompression of the right temporal lobe. Following the operation he showed a left hemiparesis which cleared, leaving a left arm drift and a left lower facial weakness. Upon recovery from his illness and operation, he developed intractable seizures which became incapacitating in spite of intensive anticonvulsive therapy. The pneumoencephalogram showed a dilated right ventricular system with atrophy of the right hemisphere. Serial EEGs showed diffuse seizure foci over the whole of the right hemisphere which eventually spread to include the previously normal left hemisphere as well. In July, 1975 he was treated by complete sectioning of the corpus callosum, sparing the anterior commissure. The operation was performed by D. H. Wilson of the Dartmouth Medical School (Wilson, Reeves, Gazzaniga and Culver, 1977). The incidence of seizures has been substantially reduced.

Pre- and post-operative administration of the WAIS provided the following intelligence measures: pre-operative—verbal, 97; performance, 86; full scale, 92; post-operative—verbal, 113; performance, 90; full scale, 103.

MEMORY TESTS

Three standardized tests of memory function as well as several special experimental memory tasks were administered under standardized test conditions four and five days before operation. All tests were then readministered between six to ten weeks post-operatively, using a second form of each test, when available. Presentation of the standardized memory tests closely conformed to the procedure outlined in the instruction manuals and scores were interpreted according to the published norms available for each test.

Standardized Memory Tests

Wechsler Memory Scale (WMS). This brief memory survey is divided into 7 subtests: information, orientation, mental control, logical memory, digit span, visual reproduction and associate learning. Raw scores of individual subtests are combined and corrected for age to yield a memory quotient (MQ). An MQ of 100 is considered average in the normal population (Wechsler, 1945). A second form was administered post-operatively.

Memory For Designs (MFD). In this test of graphic reproduction, the subject is shown a series of 15 geometric figures printed on cards, one at a time, and after viewing the design for 5 seconds is asked to reproduce it on paper from memory. The figures are scored for errors of distortion and orientation, the score reflecting the total number of errors committed. Scores of 0-4 are considered normal, 5-10 borderline and 12 or more indicative of brain damage (Graham and Kendall, 1960). Only one form was used.

Visual Sequential Memory (VSM). This is a subtest of the Illinois Test of Psycholinguistic Abilities (ITPA). The subject is required to rearrange progressively long sequences of plastic chips printed with abstract figures from memory. The score is based on the number of correct sequences reproduced with a second trial offered (for less credit) if the first is failed (Kirk, McCarthy and Kirk, 1968). The same form was used post-operatively.

Experimental Memory Tests

Memory for letters. Slides containing two horizontal rows of four English consonants were tachistoscopically projected at 150 ms to either the right or left cerebral hemisphere while the subject fixated on a dot in the centre of a viewing screen. Immediately after each slide was presented the subject was asked to report all the letters he could remember. Twenty slides containing a total of 160 letters were flashed both pre- and post-operatively. The score is the total number of letters correctly identified. This test is a modification of a task developed by Sperling (1960) for the investigation of the process by which the iconic store is converted into short-term memory.

Digit span memory. Permutations of the digits 1-9 were presented orally at 2 digit/second rate for immediate written recall on a response sheet containing a blank space for each digit. Over-all performance on this task in terms of percentage correct is believed to reflect short-term memory capacity, while a finer-grained analysis of per cent recall at each position in the sequence provides information about the contribution of primacy and recency effects to performance and permits inferences concerning information processing mechanisms.

Selective reminding in free recall. The selective reminding verbal learning task is a modification of a traditional memory paradigm proposed by Buschke (1973) to allow the simultaneous analysis of several components of memory and learning in verbal free recall. In this procedure the subject is asked to learn a list of 20 related words in any order. The entire list is read aloud to the subject once at a 2 second per item rate prior to the subject's first attempt to recall. After attempting to recall the items the subject is then selectively reminded only of those items which were not recalled on the immediately preceding trial. On each trial, however, the subject tries to recall all items. In the present study the procedure was terminated after the trial on which the subject was first able to produce the entire list correctly, or at the end of the eleventh trial, whichever came first.

This procedure assumes that once a subject recalls an item without having been presented with that word immediately prior to recall, the word had been placed in long-term storage (LTS) on the preceding trial. It further assumes that once an item has been placed in LTS it remains there—any failures to recall the item subsequently are considered retrieval failures. The selective reminding paradigm permits the subject to demonstrate retrieval from LTS by recalling an item which was not presented on that trial and hence it differentiates between retrieval from long-term storage (LTS) and recall from short-term storage (STS).

The distinction between short- and long-term memory processes is based upon whether the subject could have recalled the item on the basis of some short-lived trace believed to exist for a brief period of time following presentation of an item, or whether recall is based upon access to a more permanent type of storage established on previous trials. In the case of possible disordered learning and memory, the selective reminding procedure permits an analysis of the functional locus of deficits, rather than a global statement to the effect that performance is poorer. The pre- and post-operative administrations were of different forms of the test.

RESULTS

The performance of D. H. on the three standardized memory tests both pre- and post-operatively is presented in Table 1. With the possible exception of VSM, his pre-operative level is well within the normal range, and in each test a marked increase in performance occurs post-operatively. Scores on the MFD test reflect the number of errors committed when figures were drawn with the preferred right hand. Post-operative performance was also assessed using the nonpreferred and somewhat inco-ordinate left hand. Under these conditions, a much longer time was required to draw the figures which were greatly reduced in size compared to those produced with the right hand. In spite of this, only 2 errors were scored out of a possible 45 for the 15 designs.

TABLE 1. PRE- AND POST-OPERATIVE PERFORMANCE OF D. H. ON 3 STANDARDIZED MEMORY TESTS SHOWING POST-OPERATIVE IMPROVEMENT IN ALL CASES

	Pre	*Post*
Wechsler Memory Scale	93	108
Visual Sequential Memory	19	29
Memory For Designs	3 (RH)	0 (RH) 2 (LH)

Score on MFD indicates number of errors. RH—right hand. LH—left hand.

Although norms for the VSM have only been published for children up to 10 years, it is clear that the post-operative increase of 10 points represents a significant improvement in performance. In spite of the young age of this patient, the post-operative score of 29 is dramatically superior to commissurotomized patients previously tested on this task. A mean post-operative raw score of 16·8 for complete commissurotomy cases and 21 for partial sectioned patients has been reported (Zaidel and Sperry; 1974).

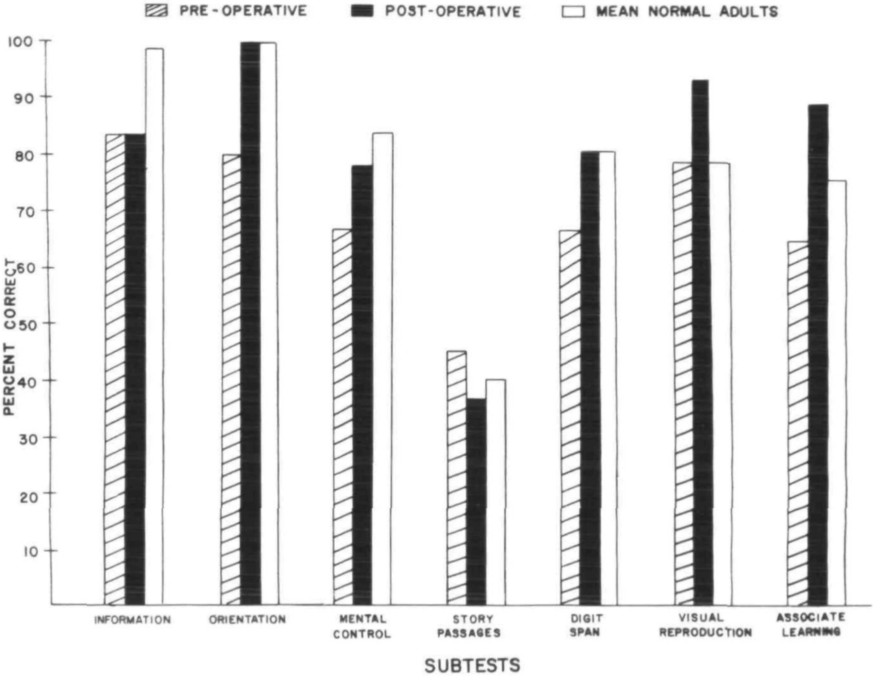

FIG. 1. Pre- and post-operative performance of D. H. on individual subtests of the Wechsler Memory Scale compared to the mean obtained by normal adults according to Wechsler (1945). His outstanding performance on visual reproduction and associate learning post-operatively are particularly noteworthy.

The post-operative improvement on the WMS is presented according to individual subtests in fig. 1. It can be seen that in almost every case, there is an increase in scores post-operatively, in some cases putting the performance of this patient well above the mean for normal adults. The two exceptions are the information subtest on which post-operative performance remained the same, and story passages in which there was a slight decrease in performance post-operatively. It should be noted that population norms for the WMS only apply to adults aged 21 and over and the scores of our patient have been interpreted as those of a young adult although he is only 15 years of age. If norms were available for this age range the memory quotient of this patient would undoubtedly be enhanced.

Verbal recall of the tachistoscopically presented arrays of letters also improved post-operatively. From a pre-operative total score of 48 (an average of 2·4 letters correctly recalled on each trial), performance increased to a total of 62 letters named accurately (average 3·1 per trial) after operation. No significant field differences occurred on the letter naming task either pre- or post-operatively, indicating successful transfer of visual information from the right to the left hemisphere in spite of his complete callosal section. It is believed that this visual function can be attributed to the intact anterior commissure (Risse, LeDoux, Springer, Wilson and Gazzaniga, 1977).

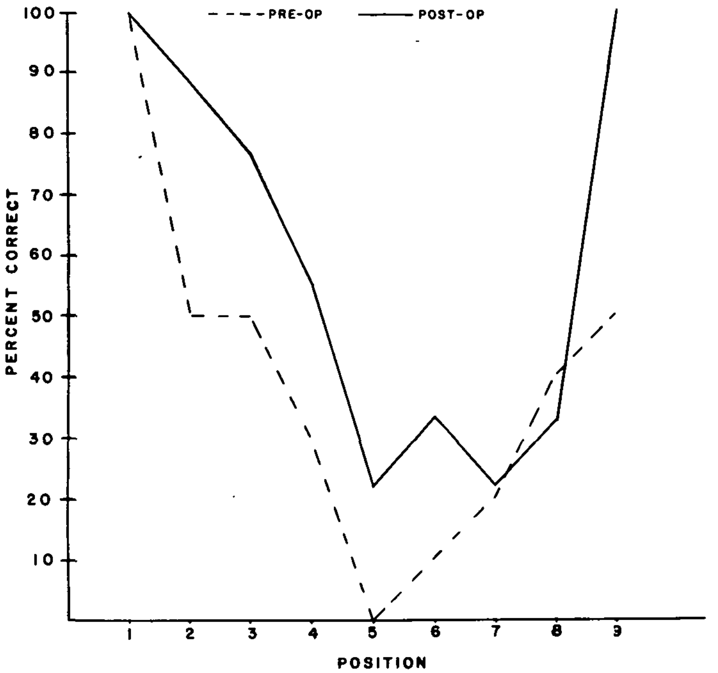

FIG. 2. Percentage correct as a function of serial position in digit span memory task. To be counted as correct, a digit must be placed in the appropriate blank (representing its temporal position in the sequence).

The serial position curves for the digit span memory task are shown in fig. 2. Performance improved post-operatively at almost every position in the sequence. In one contemporary analysis of serial recall of an auditorily presented list, the primacy effect is believed to be due to the advantage conferred upon initial list items by virtue of greater opportunities for rehearsal as compared with items in the middle of the list, with the recency effect the result of a readout of the last few list items held in a very short-term auditory store (Crowder and Morton, 1969). The digit span results provide no evidence whatever for post-operative deficits in either of these two memory processes.

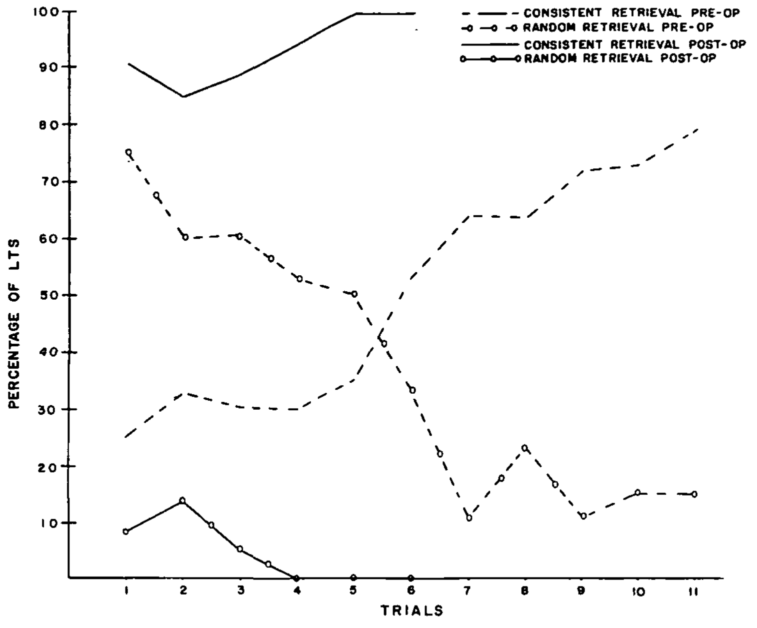

FIG. 3. Percentage correct as a function of trial in selective reminding in free recall task. Consistent retrieval represents percentage of items present in LTS on a given trial which are recalled on that trial and all subsequent trials. Random retrieval represents percentage of items present in LTS on a given trial which are recalled on that trial with a retrieval failure on one or more subsequent trials.

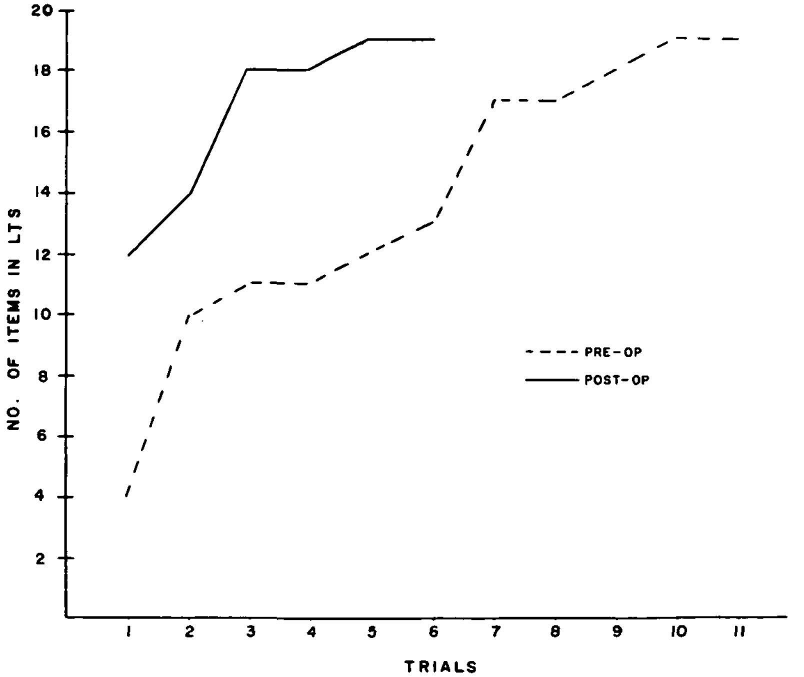

FIG. 4. Number of items entered into LTS on or by a given trial of selective reminding in free recall task.

Figs. 3 and 4 present the selective reminding results. In the Buschke paradigm recall of items in LTS takes two forms; consistent retrieval in which an item is successfully recalled on all subsequent trials without further presentation, and inconsistent or random retrieval. Fig. 3 shows how the percentage of information in LTS that is either consistently or randomly retrieved varies as a function of trial, while fig. 4 shows the number of items in LTS as a function of trial. Post-operatively, the percentage of material in LTS consistently retrieved is higher on every trial and in addition, items are added to the LTS at a much faster rate.

HYPOTHESIS TESTING

Hypothesis (H) theory is a cognitive learning theory whch has recently emerged out of the continuity-noncontinuity debate as the leading formulation concerning human learning. The theory describes learning not as a gradual, continuous process of strengthening of the correct response through reinforcement, but rather as a noncontinuous process of information utilization. That is, prior to grasping the nature of the solution, no learning occurs; but once the organism understands the task, learning is completed in one trial. H-theory is specifically concerned with the manner in which a subject (S) faced with a multidimensional stimulus complex comes to focus in on the correct aspect of the stimulus situation by systematically testing various Hs. Thus, H-theory is an information-processing theory of learning.

Using the procedure to be described, Levine and his associates (Levine, 1963, 1966, 1969, 1970; Levine, Miller and Steinmeyer, 1967; Levine, Yoder, Kleinberg and Rosenberg, 1968; Karpf and Levine, 1971; Gholson, Levine and Phillips, 1972) have made certain assumptions to account for discrimination and concept learning:

1. Subjects approach a novel situation with a hunch or hypothesis, and they respond to the situation on the basis of that hypothesis.

2. Hypotheses are not responses, but rather constitute the cognitive determinants of responses.

3. When a response is followed by positive feedback, S keeps the hypothesis on which the response was based. When a response is followed by negative feedback, S switches hypotheses.

4. The nature and the range of appropriate hypotheses are defined by the instructions of the H-task. Following several preliminary practice problems, normal Ss only test appropriate hypotheses.

5. In each new situation (problem), Ss perform near chance until the point at which the solution (the correct hypothesis) is discovered. Thus, prior to this point, S seldom tests the correct hypothesis, but afterwards, the correct hypothesis dominates performance.

In addition to generating assumptions about the course of learning, H-theory has allowed for the classification of response systems (Gholson *et al.*, 1972). Strategies (focusing, dimension checking, H-checking) are patterns of Hs that allow S to solve the problem, but stereotypes (stimulus preference and position preference) are patterns that produce perseveration of disconfirmed Hs, and thus prevent problem solution. The particular system that a subject uses is correlated with his age and/or educational level. College students tend to use the more efficient strategies (focusing and dimension-checking), young school children use the less efficient strategies (dimension-checking and H-checking), and kindergarten children use stereotypes.

The H-task was selected because its use makes possible a quantitative and a qualitative evaluation of the effects of commissurotomy on cognition. The quantitative evaluation involves pre- and post-operative comparisons of S's capacity for short-term memory, as well as other facets of information processing efficiency. Qualitatively, S's pre- and post-operative performance can be assessed in terms of its conformity to H-theory. If pre-operative performance conforms to the theory, then any post-operative evidence of nonconformity can be attributed to commissurotomy.

METHOD

Materials. A carousel projector was used to rear-project stimulus slides on to a viewing screen in front of S. Each slide contained 2 seven-dimensional stimuli. The 7 dimensions are shown in fig. 5. It should be apparent that the 2 stimuli are complementary. That is, if the border on the right stimulus is a circle, then the border on the left must be a square. Similarly, if the letter A appears on the left, then the letter T must appear on the right. Thus, each of the 7 dimensions is composed of 2 complementary stimulus values, one of which appears in the left stimulus pattern, the other in the right.

A problem consisted of 12 trials. On each trial, S saw one slide containing the complementary seven-dimensional stimuli. The slides were constructed so that when placed in proper sequence, values from either 3 or 4 of the 7 dimensions changed sides on every trial. The values changed sides in accordance

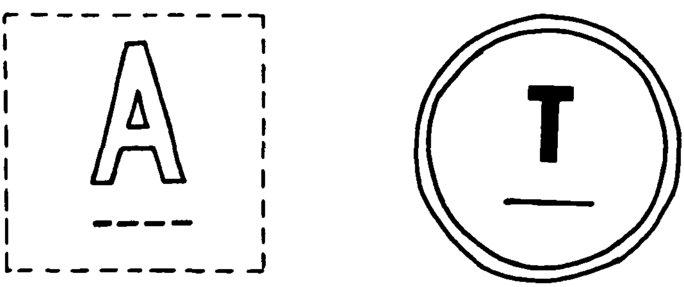

FIG. 5. A sample slide. This figure illustrates the complementary seven-dimensional stimuli. The 7 dimensions are letter name, letter size, letter colour, border shape, border texture, number of borders and underline texture. Thus, the left stimulus contains the following values: A, large, white, square, dashed border, one border and dashed underline. The complementary values of the right stimulus include T, small, black, circle, solid border, two borders and solid underline.

with the rules of internal orthogonality outlined by Levine (1969). These rules ensured that each successive slide was a logical outcome of the slide preceding it. A problem was terminated after 12 trials, or after S held the correct H (H+) for 4 consecutive trials.

Procedure. S was given the following instructions:

I am going to show you a lot of slides. Each slide contains two patterns, one on the left, and one on the right. Each pattern is made up of 7 elements, so there are 14 elements on a slide. The 7 elements on one side are complemented by the 7 on the other side. By that I mean that while both sides of the slide have letters, one side has an A, the other side has a T. On one side the letter is large, on the other side it is small. The border on one side is single, but it is double on the other side, and so on.

The slides will be shown to you in groups of 12. For each group of 12, only one of the 14 elements is correct. I want you to try to figure out which one it is.

Before each slide comes on, you pick the element you think is right and tell me what your choice is. I will then show you the slide and you will say left or right, depending on which side the element you picked is on. I will then tell you if your choice of left or right is correct, but not whether your choice of element is, and then you tell me what your next choice of element is.

After receiving the above instructions, S studied a card similar to fig. 5. He was then presented with 4 practice problems and 128 test problems. The test problems were distributed over 4 sessions.

The post-operative procedure was similar to the pre-operative procedure in all respects, except that only one practice problem was given before 2 blocks of 32 test problems.

Measures. Using the H-task we can extract several quantitative measures for S's performance. Short-term memory (STM) can be analysed by examining the size of the set from which S resamples, given that an H has been disconfirmed. The conditional is added because H-theory predicts that S only resamples following negative feedback. All of the information needed to solve any of the problems is contained in the first 3 trials (the information trials) of the problem. Thus, a hypothetical perfect processor starts out with a set of 14 Hs at the beginning of a 12-trial problem; after the first outcome trial (T_1), on the average, he reduces his set to 7, to 3·5 after T_2, to 1·75 after T_3 and to H+ after T_4. Fig. 6 depicts a hypothetical perfect processor during the information trials of a problem. Collapsing set size over the information trials indicates that a perfect processor resamples following negative feedback from a set size of approximately 3·3. This figure should be compared with two other hypothetical subjects. An S that remembers nothing from previous trials resamples from a set of 14, and an S that remembers only the information of the previous trial resamples from an average set of 7. Thus, short-term memory is measured by the resampling set size and is evaluated by comparison with a hypothetical perfect processor, a processor that has no memory, and a processor that only has memory for the previous trial.

In addition to STM, the H-task enables one to look at learning rate. As used here, learning rate is not to be construed as a measure of learning capacity. Since the task was essentially learned pre-operatively, post-operative data really reflect performance rather than acquisition. Thus, it is more appropriate to treat learning rate as a measure of the efficiency of information utilization.

The nature of the H-task requires two types of learning. Within a problem, S must acquire information specific to the discovery of H+ for that problem. Such information is stimulus dependent, and thus only applies to the problem in question. Acquisition of stimulus-dependent information is referred to as intra-problem learning. Of more importance to efficient H-testing is the abstraction of stimulus-independent information that provides for more efficient performance on later problems. This is inter-problem acquisition.

The H-task also allows a qualitative analysis of performance. That is, it is possible to assess the degree to which performance conforms to H-theory before and after operation. This analysis is of interest because the assumptions of the theory are highly reliable in accounting for the performance of normal adults. Furthermore, patients with Korsakoff's syndrome have been found to violate the theoretical assumptions (Oscar-Berman, 1973). Thus, the theory accounts for normal performance and

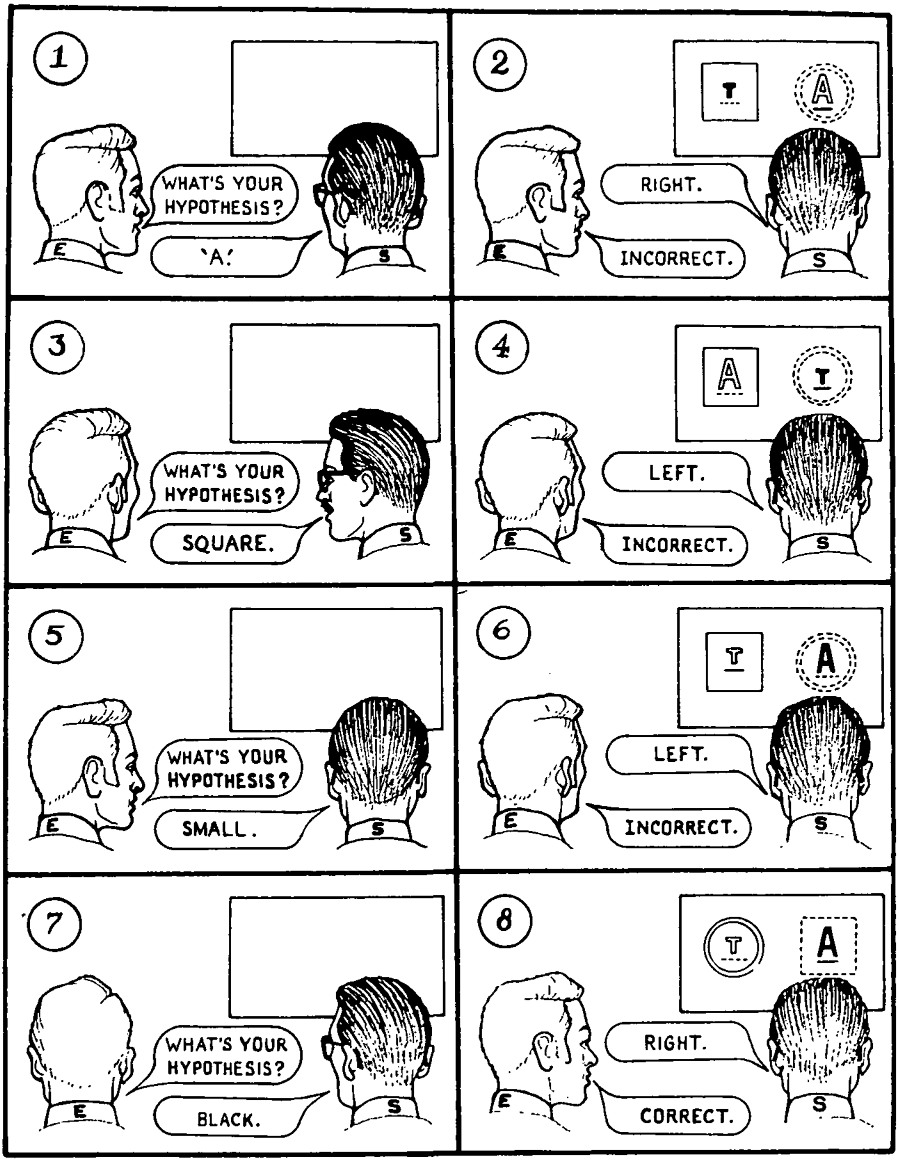

FIG. 6. The information trials. Perfect processing during the information trials of a problem is depicted here. S and E are indicated by letters on their collars. The top caption belongs to the first speaker in the frame. Each row (2 frames) represents one complete trial. S guesses 'blindly' from a set of 14 Hs on trial 1 before seeing the first stimulus of the problem. Feedback on trial 1 allows the perfect processing S to 'focus' in on the 7 values in the left stimulus, as he was told that his choice of the right stimulus was incorrect. Thus, on trial 2 S selects from small, black, T, dashed underline, solid, square and single border. Following feedback on trial 2, S eliminates those values that were on the right on trial 1 and on the left on trial 2, leaving small, black and T as possible solutions. On trial 3, small and T are eliminated, leaving black as H+.

is sensitive to processing deficits resulting from at least one form of brain damage. If pre-operative performance conforms to the theory, then post-operative non-conformity is indicative of processing changes attributable to callosotomy.

Several qualitative analyses are available. It is possible to determine whether S responds on the basis of his stated H, and whether positive feedback results in hypothesis 'keeping' and negative feedback results in hypothesis 'shifting.' In addition, the H-task permits an evaluation of the efficiency of the information processing strategies used in performing the task. Focusing is the most efficient strategy, dimension checking and hypothesis checking are of intermediate efficiency, and stereotypy is the least efficient. Finally, it is possible to examine whether performance is near chance prior to the outcome trial of last error (TLE) and whether the solution H (H+) is ever held prior to TLE. H-theory predicts that when H+ is discovered, performance immediately shifts from chance to asymptotic levels. Errors are no longer committed because H+ dominates the response repertoire. TLE is the point at which these behavioural changes take place. TLE varies from problem to problem, depending on how soon H+ is discovered.

RESULTS

(*STM*) *Short-term memory* is measured by the size of the set from which S resamples, given that an H has been disconfirmed. Pre-operatively, D. H. resampled during the information trials of the problems from an average set of 6·3. Post-operatively, D. H.'s resampling set size was 3·5. Comparing these set sizes with the hypothetical Ss reveals that pre-operatively D. H. performed like the S that had STM only for the previous trial. Post-operatively, D. H.'s performance indicated that he remembered the information of the previous trial, plus some information from earlier trials. In fact, D. H.'s post-operative set size approached that of a perfect processor.

Learning rate. Learning rate is a measure of processing efficiency. D. H.'s H-learning curves are presented in fig. 7. These curves show the proportion of problems that H+ was held on each of the 12 trials of the various problems within each session. The slopes of the curves indicate the rate of intra-problem learning. It can be seen that both pre- and post-operatively, D. H. came to hold H+ with a greater relative frequency with increasing trials. Notice, however, that the post-operative curve rises at a faster rate, indicating that D. H. was discovering H+ sooner within problems.

One way of evaluating inter-problem learning is to examine learning curves for successive blocks of 32 problems. H-learning curves for successive blocks of problems are shown in fig. 7. Notice the small incrementation of the second over the first pre-operative block and the large increase of the post-operative block over the last pre-operative block. This large post-operative increase indicates that commissurotomy did not disrupt D. H.'s processing efficiency, and may have even enhanced it.

A consolidated measure of learning rate is the proportion of problems solved in successive blocks of problems. This is indicated by the proportion of correct Hs (P(H+)) at trial 12 for each block (*see* fig. 7). Pre-operatively, D. H. solved 57 per cent of the problems in block I, and 62 per cent in block II. This contrasts with the post-operative block during which D. H. solved 85 per cent of the problems.

Thus, all measures of learning rate show post-operative increases above the level that would have been predicted by pre-operative data. This suggests a post-operative enhancement of information-processing facility.

H-testing. Both pre- and post-operatively, D. H.'s performance on the H-task was totally in line with the predictions of H-theory. His responses were virtually always consonant with his stated H, and E's instructions and the practice problems were sufficient to restrict his sampling of Hs to single cues. The significance of this is that commissurotomy did not alter his ability to remember his stated H and use it as a basis for responding once the stimulus slide was presented.

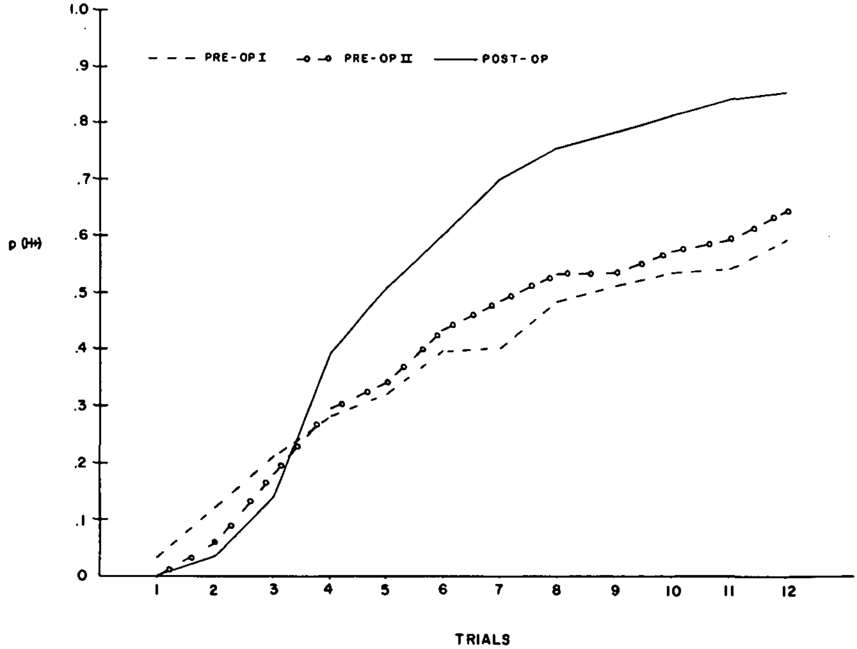

FIG. 7. Hypothesis-learning curve. The hypothesis-learning curve represents the proportion of problems on which H+ was held, plotted by trials. Each curve represents 64 12-trial problems. The dashed curves constitute pre-operative data, and the solid curve is post-operative. It can be seen that the post-operative curve is steeper than the pre-operative curves, indicating a more efficient rate of within-problem learning. In addition, following the first 4 trials, the information trials, post-operative performance is well above the level that would have been predicted by successive pre-operative blocks of problems, indicating a more efficient rate of between-problem learning.

Figs. 8 and 9 compare D. H.'s pre- and post-operative learning and hypothesis curves (these curves are to be distinguished from the H-learning curve of fig. 7). Fig. 8 (H-curve) plots the proportion of trials on which H+ was held before and after the trial of last error (TLE) of each problem. It can be seen that D. H.'s pre- and post-operative H-curves run along the abscissa until the TLE, at which point they rise to the asymptotic level. This shows that prior to TLE, D. H. seldom held H+, and after TLE he always held it. Fig. 9 (learning curve) plots the proportion

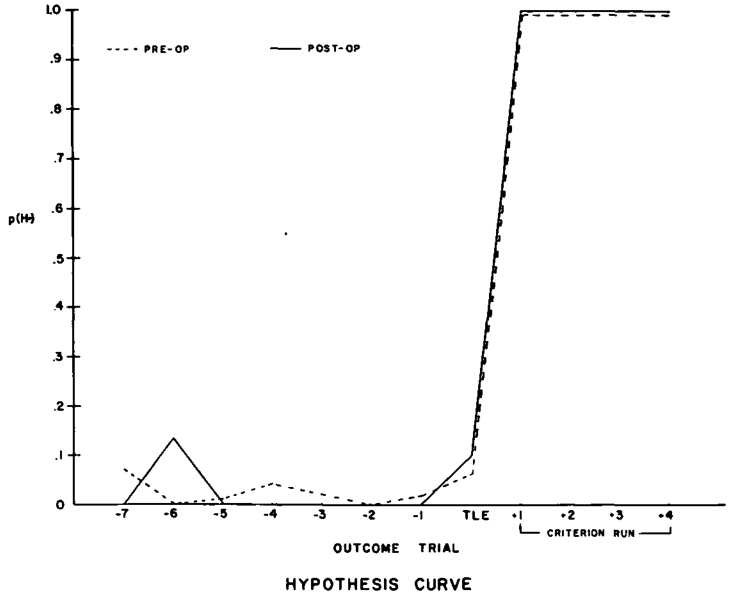

FIG. 8. Hypothesis curve. The hypothesis curve represents the proportion of problems on which the solution hypothesis (H+) was held, plotted by trial around TLE. Both pre- and post-operatively, H+ was seldom held prior to TLE, and furthermore, after TLE, H+ dominates performance.

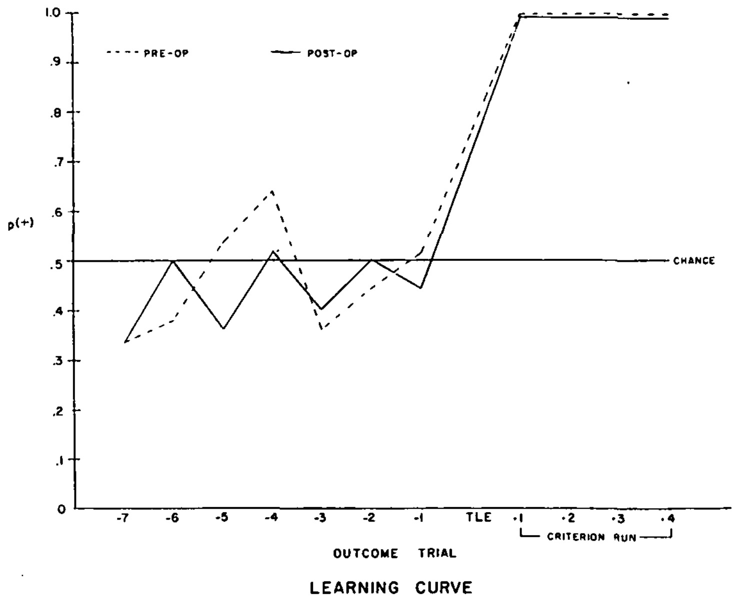

FIG. 9. Learning curve. The learning curve represents the proportion of correct responses on each trial, plotted by trial around TLE. Both pre- and post-operatively, performance was near chance, and following TLE performance rose to asymptotic levels.

of correct responses on each trial before and after TLE. These curves show that prior to TLE, D. H. responded near the chance level (0·5), and after TLE he is, of course, always correct. The curves in both these figures, although based on empirical data from a single subject, mirror Levine's (1969) theoretical curves with remarkable accuracy.

Before operation, D. H. kept a confirmed H 97 per cent of the time; after operation, he kept a confirmed H 99 per cent of the time. Similarly, before operation, he resampled following a disconfirmed H 96 per cent of the time, and after operation he resampled 99 per cent of the time. Thus, he seemed to have been rendered slightly more sensitive to the effects of feedback, and neither his pre- nor his post-operative sensitivities to feedback are out of line with the predictions of H-theory.

Given D. H.'s age and educational level, one would expect him to utilize H-systems that are less efficient than those used by college students and somewhat more efficient than those used by young school students. This is, in fact, exactly how he fared. He primarily manifested dimension-checking and H-checking, but also focused, and never used stereotypes. If there was any noticeable pre- and post-operative difference, it was in the direction of an increase in post-operative usage of more effective strategies. This is implicit in fig. 7, which shows that post-operatively D. H. came to hold H+ on a greater proportion of problems, and within problems, he arrived at H+ in fewer trials.

GENERAL DISCUSSION

A comparison of the pre- and post-operative performance of D. H. on a variety of tasks suggests that sectioning of the largest fibre tract of the human brain, the corpus callosum, fails to disrupt cognitive functioning. This finding is surprising in the light of Zaidel and Sperry's (1974) claim of marked memory deficits following commissurotomy.

The specialized tests employed in the present study allowed for a greater fractionation of the memory process than is provided by standardized tests, and, in addition, provided measures of a number of other processes. In spite of this detailed survey of cognition, including an analysis of short- and long-term memory capacity, primacy and recency effects in memory, information processing efficiency and hypothesis testing performance, we found no evidence of post-operative deficits, frustrating the original hope of pin-pointing the functional locus of the memory deficit reported by Zaidel and Sperry.

In all likelihood, the discrepancy between our results and those previously reported is attributable to methodological considerations. First, it is possible that the discrepancy is reflective of the large individual differences which must surely exist in the brain organization underlying cognition. In addition, the discrepancy may reflect the patients' responses to the differing surgical approaches used (Bogen and Vogel, 1962; Wilson *et al.*, 1977). Most probably, however, it reflects the fact that Zaidel and Sperry were unable to establish pre-operative baselines on their subjects, and thus were forced to rely on control data from subjects matched on certain variables. Their sample size was by necessity small, and this increased the probability that sampling error was responsible for the differences in performance between control and experimental Ss. As such, it is difficult to conclude that their results are attributable to commissurotomy. In contrast, although our results are from a single subject, these controlled observations on D. H. unequivocally argue that commissurotomy does not necessarily produce cognitive deficits.

The dramatic post-operative improvement in cognitive functioning seen in our patient is intriguing. Most simply, it can be explained by postulating a general sense of well being and optimism following operation. Surely, such motivational variables enter into the performance of cognitive tasks of the type used here. On the other hand, given that our tests largely, though not entirely, reflected verbal processing, and that D. H.'s right hemisphere is abnormal, it is possible that commissurotomy enhanced cognitive functioning by isolating the verbal system from the abnormal hemisphere. Support for this notion comes from Milner's (1958) observation that surgical excision of seizure foci from the right hemisphere resulted in improved post-operative verbal memory and IQ scores. Presumably, removing the influence of abnormal tissue, either by ablating it or by functionally isolating it by commissurotomy, allows for more efficient processing in the remaining tissue. This notion, however, seems less plausible in light of the fact that D. H.'s anterior commissure is intact and subserving interhemispheric communication (Risse *et al.*, 1977). This commissure interconnects temporal neocortex (Whitlock and Nauta, 1956), and thus provides a potential source of influence of the abnormalities of the right temporal lobe on the verbal processing system of the left hemisphere.

Another possible explanation of the post-operative improvement is suggested by Schneider's (1976) work on synaptic reorganization. He has demonstrated that unilateral damage to a portion of the hamster's optic tectum evicts retinal fibres from their normal synaptic loci. In the process of reorganizing, the retinal fibres cross the mid-line and terminate on the contralateral tectum. As a result, when the hamster is offered a sunflower seed in the portion of the visual field subserved by the reorganized axons, it turns to the wrong side. Most interestingly, however, mid-line sectioning of the anomalous projection eliminates aberrant turning responses.

Although current understanding of neuronal growth in adult primates does not permit a direct analogy to Schneider's work, the possibility that fibres evicted from the damaged right hemisphere of our patient crossed the mid-line and reorganized in the left hemisphere provides an interesting model. Callosotomy, according to this interpretation, would eliminate the anomalous connections and the interference that they were sustaining. Indirect support for this possibility is provided by Rakic and Yakovlev's (1968) observation that in some human cases, callosal fibres do not cross the mid-line during development, but rather form anomalous connections within the ipsilateral hemisphere. Thus, evidence of the redirection of axons to novel systems is not limited to lower animals (Schneider, 1976).

Regardless of the explanation of the dramatic post-operative improvement, the fact remains that destruction of 200 million cortical axons fails to disrupt the ability to efficiently process, store and retrieve information, and to analyse and react appropriately to a rapidly changing, multidimensional stimulus situation. These data are consistent with Nakamura's (1976) recent finding that split-brain monkeys perform as well as normals when both eyes, and hemispheres, are allowed to process complex information. Taken together with our findings, these data suggest that efficient cognitive functioning is more dependent upon intrahemispheric integrity than on interhemispheric integrity. As such, the role of the great cerebral commissures in the richer aspects of mental life continues to elude specification.

SUMMARY

Cognitive functioning was extensively evaluated in a recent callosum-sectioned patient. A number of standardized and specialized experimental memory tests, as well as a sophisticated hypothesis testing task, were administered both before and after operation. No post-operative deficits were obtained. In fact, this patient showed marked improvement on almost every measure utilized. These results demonstrate that the cognitive processing of complex information is not necessarily dependent on the integrity of the corpus callosum, but rather suggest that cognitive functioning is largely an intrahemispheric process.

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