Neuropsychologia, 1965, Vol. 3, pp. 339 to 351. Pergamon Press Ltd. Printed in England

TACTUALLY-GUIDED MAZE LEARNING IN MAN: EFFECTS OF UNILATERAL CORTICAL EXCISIONS AND BILATERAL HIPPOCAMPAL LESIONS*

SUZANNE CORKIN†

Department of Psychology, McGill University, Montreal, Canada

(*Received* 6 *August* 1965)

Abstract—Fifty-three patients with different cerebral lesions were trained on a tactual stylus maze. Those with lesions of the frontal or temporal lobes in the left (dominant) hemisphere performed normally on this task, but right temporal-lobe patients with the ipsilateral hippocampus excised were impaired, and the right frontal-lobe group had even greater deficits. Scores for patients with unilateral excisions invading parts of the parietal lobe, but not necessarily restricted to it, were correlated with lesion size. Three patients with bilateral hippocampal lesions were inferior to the most impaired patients with unilateral temporal lobectomies. There is a high correlation between performance on this task and on a visually-guided stylus maze.

THIS study will emphasize one aspect of the findings concerning somesthetic function in patients operated upon for focal epilepsy. These data on tactually-guided learning are more meaningful, however, when contrasted with the results for quantitative measures of sensory discrimination on the hand obtained in the same patients. CORKIN, MILNER and RASMUSSEN [6] reported that residual defects in pressure sensitivity, two-point discrimination and point localization were clearly related to excisions invading either Rolandic region, and did not follow removal of posterior parietal cortex, an observation at variance with EVANS' [7] conclusion that the inferior parietal lobule is the critical area for sensory function. In the cases of sensory defect studied by CORKIN *et al.* [6] the incidence of contralateral impairment was not the same for the three tests, with lesions of the postcentral gyrus producing fewer defects in pressure sensitivity than in two-point discrimination or point localization. There was a high incidence of ipsilateral defects as well, although in all instances of ipsilateral sensory loss there was a more severe defect of the contralateral hand. The detection of ipsilateral involvement (more frequent on point localization than on the other two measures) is a cross-validation of the findings of SEMMES, WEINSTEIN, GHENT and TEUBER [30], and illustrates the importance of evaluating scores in terms of a quantitative normative standard, and not merely comparing the sensitivity of homologous body parts.

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* These data were reported at the 1964 meeting of the Eastern Psychological Association and are part of the author's unpublished doctoral thesis submitted to McGill University.

† Present address: Department of Psychology, Massachusetts Institute of Technology, Cambridge, Mass. 02139, U.S.A.

With several tactual learning and problem-solving tasks the breakdown of results was quite different, showing a greater vulnerability of such functions to right-hemisphere excision than to left (CORKIN [5]). The group differences were most clear-cut for a tactual stylus maze, and the results for this test will, therefore, be described in detail.

It was decided to include this task in a study of somesthetic function in order to test the generality of MILNER's [20] findings for a visual stylus maze of the stepping-stone variety. Thus, all patients in the present study had previously been brought to criterion on the visual maze, both tasks being given post-operatively only. MILNER [20] found that patients with memory disorders attributable to bilateral hippocampal damage were more impaired in learning this task than were patients with various unilateral cortical excisions. Patients with left temporal-lobe lesions required fewer trials to criterion and made fewer errors than did patients with right temporal-lobe lesions, and the frontal-lobe subjects made more intra-trial repetitive errors than did other patients. The administration of a tactual maze to these patients permitted a cross-modal correlation of error scores.

Such a correlation is also of interest in view of SEMMES, WEINSTEIN, GHENT and TEUBER's [29] finding for a locomotor route-finding task that performance guided by visual maps was positively correlated with that guided by tactual maps, the tactual maps being translated into a visual context. There is clearly a need for more data on this problem using spatial tasks in which visual guidance is completely excluded.

METHOD

Subjects

All 53 patients in this study were included in MILNER's [20] report of 79 cases tested on a visual maze task. The 11 normal control subjects in that study were the same as those in the present one.

Table 1. Age and I.Q. rating at time of testing

Locus of excision	N	Time since operation		Age		Wechsler I.Q.	
		2–3 wk	1–14 yr	Mean	Range	Mean	Range
Right frontal	5	3	2	21.0	15–33	95.0	82–112
Left frontal	3	1	2	23.7	17–28	104.7	90–124
Right temporal	11	11	0	23.4	13–51	107.3	94–124
Left temporal	18	9	9	24.2	15–51	103.4	79–128
Parietal (4R, 4L, 3LND)	11	0	11	25.3	16–40	104.0	89–116

Table 1 gives the mean ages and Wechsler I.Q. ratings for 48 subjects operated upon for the relief of focal cerebral seizures. Two other patients, well-matched for age, I.Q. and locus of excision, were also included in the results. One was a 20-year-old woman with an I.Q. of 90, who had undergone a right frontotemporal removal, and the other was a 23-year-old man with an I.Q. of 92, who had a comparable lesion in the left hemisphere (Fig. 1, Cases L. P. and J. Eu.). Speech was represented in the left hemisphere in all cases except the three parietal-lobe patients referred to as left non-dominant (LND). Patients who manifested subcortical or diffuse cortical electrographic abnormality were excluded,

as were those with neoplasms or bilateral speech representation as determined by the Sodium Amytal test (BRANCH, MILNER and RASMUSSEN [4]). In addition to the main series of subjects, three patients with bilateral hippocampal damage and marked recent-memory disturbance to clinical observation were tested in follow-up. The mean I.Q. of these patients was 117.7 (range: 109–123) and their mean age 43.0 years (range: 36–55).

There was considerable overlap between the extent of removal in the right and left temporal lobectomies. The average left temporal-lobe excision measured 5.3 cm from the end of the middle fossa along the first temporal convolution (range: 4.5–9 cm) and 5.9 cm along the third (range: 4.5–10.5 cm). The corresponding measurements for the right temporal-lobe patients were 5.6 cm (range: 5–7 cm) and 6.4 cm (range: 5–9.5 cm), along

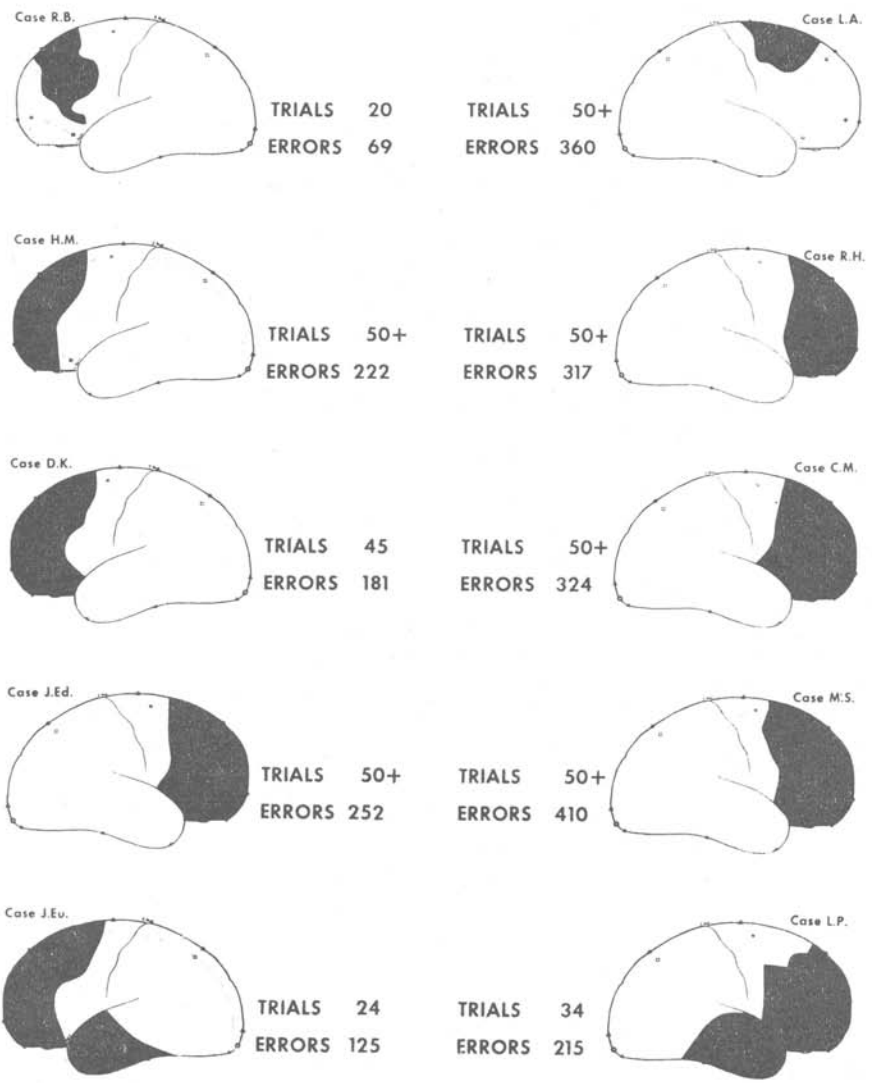

FIG. 1. Lateral extent of excision, and maze scores for patients with frontal or frontotemporal lobectomies.

the first and third temporal convolutions respectively. In all cases of temporal lobectomy, the amygdala was removed either completely, or almost completely. In seven cases of left temporal lobectomy and five cases of right, the hippocampus and hippocampal gyrus were said to have been completely excised, but these structures were spared in four left temporal-lobe removals. In the remaining excisions, seven left-sided and six right-sided, either the pes hippocampi alone or the pes and part of the body were removed.

The ten frontal lobectomies are shown in Fig. 1. All frontal lobectomies but one (Case R. B.) extended onto the mesial surface, including either the anterior cingulate gyrus, the subcallosal gyrus, or both. The precentral gyrus was spared in all cases, as was Broca's area in the left frontal lobe.

In contrast to the other groups, where the ablation was restricted to the lobe specified, the parietal-lobe patients had excisions invading parts of the parietal lobe but not necessarily restricted to it. The removals ranged from a massive right posterior cortical excision to a partial excision of left Rolandic cortex (MILNER [20], Fig. 2, p. 321, Case G. G., Fig. 3, p.322, (Case J. St. M.). Thus the parietal-lobe group in this study included patients from both the parietal and the right parieto-temporo-occipital groups in Milner's study.

In the early postoperative period, most patients were receiving Dilantin (100 mg t.i.d.) and Phenobarbital (60 mg b.i.d.). The follow-up patients were either on these doses of Dilantin and Phenobarbital, on reduced doses, or off medication completely. There were no systematic differences among groups in type or dose of anticonvulsant medication.

The 11 normal control subjects consisted of 8 women and 3 men, having a mean age of 22.2 years (range: 18–45). All were high school graduates, and their occupations included secretary, EEG technician, key-punch operator and bank clerk.

Apparatus and procedure

Figure 2 shows the apparatus used, an aluminium stylus maze ($12\frac{3}{4}$ in. $\times$ 10 in.), which was placed inside a wooden frame (30 in. wide $\times$ $11\frac{1}{2}$ in. high $\times$ 12 in. deep). The frame was open on the experimenter's side, but was covered on the subject's side by a black cloth curtain which concealed the maze from view. The subject was first allowed to feel the perimeter of the apparatus with both hands. Then, his preferred hand (holding the stylus) was guided by the experimenter to the starting area, to the finish, and back to the start, thus providing a general orientation in the maze. The instructions were to find the correct path from start to finish. Each time the subject entered a blind alley, a bell was rung which signalled him to move back. He was prevented mechanically from retracing the correct path and was warned against making repetitive errors within a single trial, that is, retracing the incorrect path. Training took place on two consecutive days, proceeding in blocks of 10 trials to a criterion of 3 consecutive errorless runs or until 50 trials had been completed. No more than 30 and no less than 20 trials were given in one day.

RESULTS

Unilateral cortical excisions

A simple analysis of variance on the mean error scores for all unilateral lesion groups and for the normal control group yielded an F ratio of 7.72, significant beyond the 0.01 level of probability. Figure 3 gives the data for all except the parietal-lobe patients, who will be treated separately because of the heterogeneity of their removals. It is clear that the

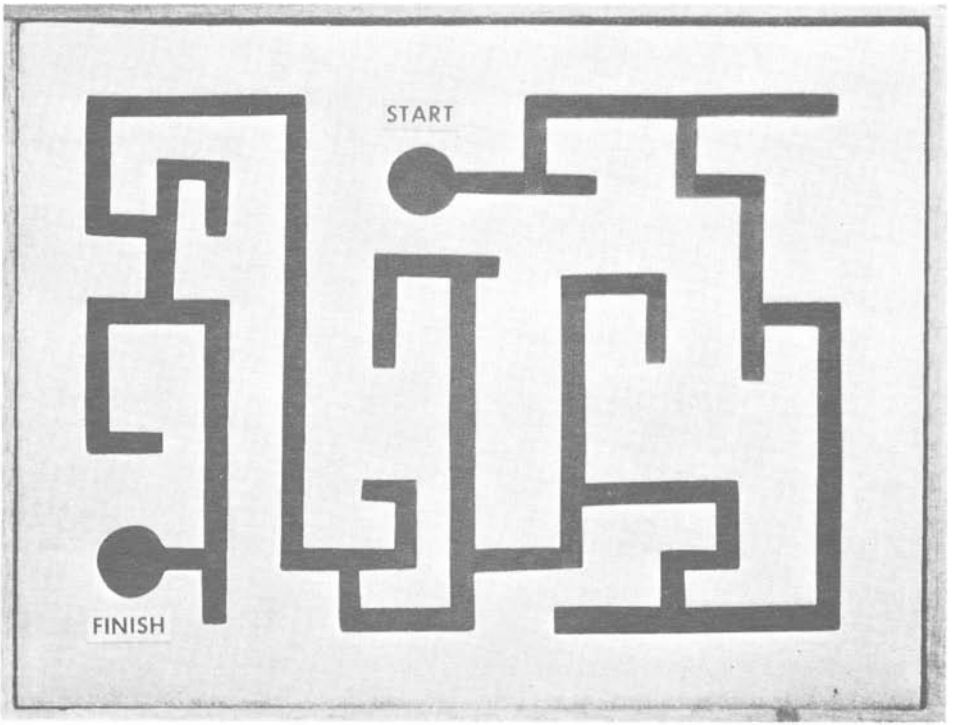

FIG. 2. Tactual stylus maze (distributed by Lafayette Instrument Company).

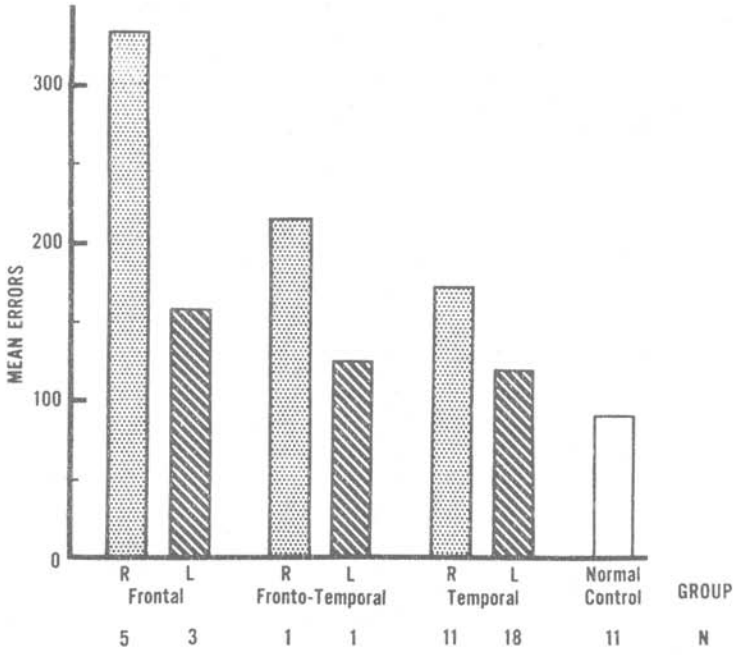

FIG. 3. Mean error scores as related to side and locus of cortical excision.

patients with right-hemisphere lesions were inferior to those with left-hemisphere lesions. The right frontal-lobe group made significantly more errors than the left frontal-lobe group ($t=3.19$ $P<0.05$); in fact, the two distributions did not overlap. None of the five right frontal-lobe patients reached criterion in 50 trials, whereas two of the three left frontal-lobe patients did. Similarly, the one patient with a right frontal- plus temporal-lobe excision made considerably more errors than the patient with a corresponding left-hemisphere excision, although they both reached criterion in less than 50 trials (Fig. 1). Although four of the five right frontal-lobe removals were larger than the four on the left (Fig. 1), Case L. A., with a small right-sided excision did not reach criterion in 50 trials and made 360 errors, suggesting that side rather than extent of removal is the critical variable in the poor performance of the right frontal-lobe group. Moreover, the impairment seen in these patients cannot be explained by their having a lower mean I.Q. than the left frontal-lobe patients (Table 1), since the product-moment correlation between error scores and I.Q. ratings for 49 patients was -0.14, the correlations within individual groups being equally low.

For the temporal-lobe groups also, patients with right-sided removals were inferior to those with left, the t-value just missing significance ($t=2.03$, $P<0.06$). This difference was artificially reduced by the arbitrary termination of training after 50 trials, for, had all subjects been brought to criterion, the mean for the right temporal-lobe patients would have been much higher, but the left temporal-lobe mean only slightly so. Moreover, the performance of the left temporal-lobe patients closely approximated that of the normal control subjects, whereas the mean of the right temporal-lobe group was significantly

different from that of the normal control group ($t=2.78$, $P<0.02$). The greater efficiency of the left temporal-lobe group was not due to the fact that half of the patients were tested in follow-up, since these follow-up patients were slightly, though not significantly, inferior to those tested in the early postoperative period.

Another way of considering the maze data is in terms of the number of patients reaching criterion in 50 trials or less (Fig. 4). Fifteen of the 18 patients in the left temporal-lobe

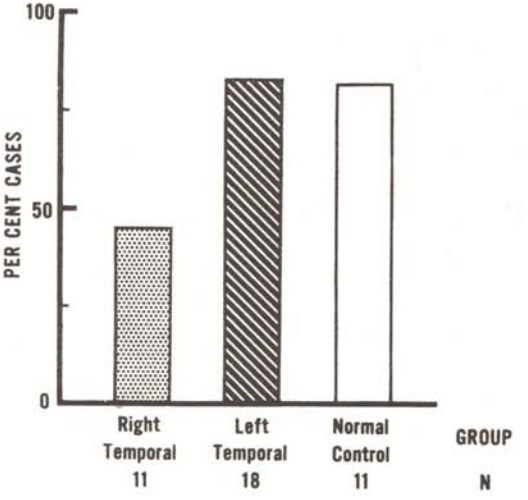

FIG. 4. Tactually-guided maze learning after unilateral temporal lobectomy: percentage of subjects reaching criterion in 50 trials or less.

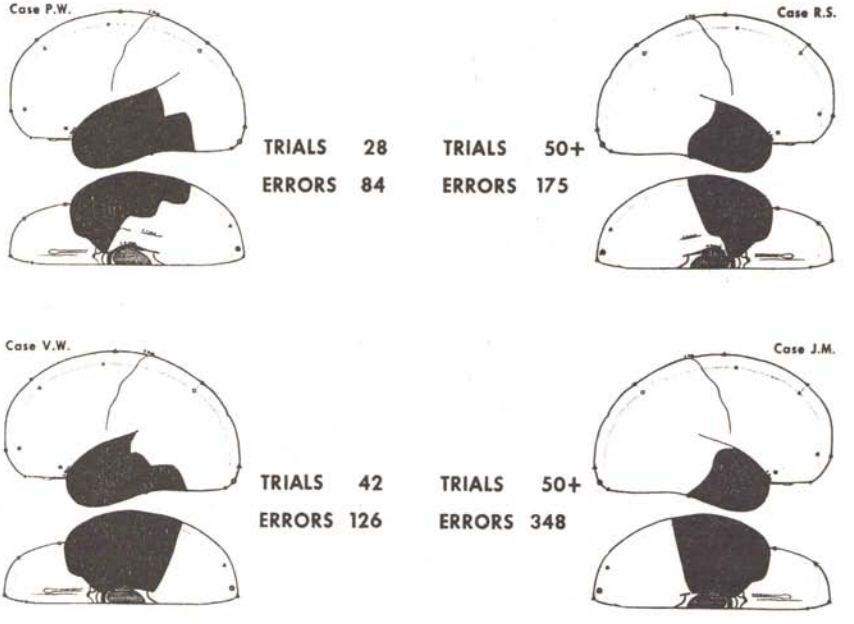

FIG. 5. Unilateral temporal lobectomies (lateral and inferior views): maze scores for illustrative cases.

group succeeded, but only 5 of the 11 patients in the right temporal-lobe group did. The proportion of right temporal-lobe patients who learned the maze was significantly less than the combined proportion of left temporal-lobe patients and normal control subjects who achieved this end ($X^2=3.86$, $P<0.05$).

The difference between the results for left and right temporal-lobe patients is not attributable to differences in amount of temporal-lobe tissue excised on the lateral surface. This point is illustrated in Fig. 5, which shows two large excisions in the left temporal lobe compatible with good performance on the maze, in contrast to two small right temporal lobectomies in patients failing to reach criterion.

An attempt was made to delineate the region of the right temporal lobe which is critical for tactual maze learning. This was done by comparing right and left temporal-lobe cases, contrasting patients whose excision included the bulk of the hippocampus unilaterally with those in whom the hippocampus was spared or only partially removed.

Table 2. Differential effects of right and left hippocampal excision in temporal-lobe patients

Group	Mean errors	Per cent subjects reaching criterion in 50 trials
Right temporal with hippocampus radically excised (N=5)	231.8	20.0
Right temporal with hippocampus essentially spared (N=6)	123.0	66.7
Left temporal with hippocampus radically excised (N=7)	117.6	85.7
Left temporal with hippocampus essentially spared (N=11)	119.2	81.8

(Table 2). There was no difference in error scores for the two left temporal-lobe groups, suggesting that inclusion of the hippocampus in a left temporal lobectomy does not alter performance on the maze. The right temporal-lobe group with the hippocampus partially excised was similarly unimpaired, in contrast to the right temporal-lobe group with the hippocampus radically excised. These patients made nearly twice as many errors as the other three temporal-lobe groups, the difference between the two right-sided groups just missing significance because of the small number of cases ($U=6$, $P=0.063$). This finding was reflected in the number of patients reaching criterion in 50 trials or less, only one out of five succeeding in the right temporal-lobe group with the hippocampus excised, as opposed to two-thirds or more of the patients in the other three groups (Table 2.).

Further analysis showed that the right frontal-lobe group made significantly more errors than the right temporal-lobe group ($t=3.80$, $P<0.001$). This finding may be due to the larger excisions in the right frontal-lobe patients. Another possible explanation is the high incidence of repetitive errors included in the total error scores for the right frontal-lobe group. The need for taking account of such errors first became apparent in the performance of Case M. S. (Fig. 1), who frequently retraced the incorrect path within a given trial.

The number of trials in which repetitive errors occurred was subsequently recorded for Cases L. A., J. Ed. and C. M. (Table 3.). There were numerous instances of this behavior and no overlap between the repetitive error scores for right frontal patients and those for

Table 3. Incidence of repetitive errors in the first 20 trials

Group	N	No. of trials with repetitive errors	
		Mean	Range
Right frontal	3	14.3	13–15
Left frontal	2	7.0	2, 12
Right temporal	9	5.4	1–11
Left temporal	17	4.0	0–8
Parietal	8	5.2	1–10
Normal control	11	4.0	0–9

other groups. This observation is similar to MILNER's [19, 20] findings for a larger frontal-lobe group, but the point certainly requires further investigation in view of the smallness of the present sample.

For the group with unilateral excisions which invaded parts of the parietal lobe (but were not necessarily restricted to it), the mean error score of 138.9 falls within the range of results for the right and left temporal-lobe groups. Since the removals varied considerably in locus and extent, the 11 subjects were ranked according to mass of tissue excised, and a Spearman rank-correlation coefficient of $+0.85$ ($P<0.01$) was found between lesion size and total errors. There was nothing to suggest that small parietal-lobe removals in either hemisphere are damaging to maze performance, or that severe unilateral sensory defects are related to impairment on this task. These findings are clearly demonstrated in Case G. G. (MILNER [20], Fig. 2, p. 321). This patient, with a relatively small excision limited to parts of the pre- and postcentral gyri, had severe and lasting sensory defects of the hand as well as persistent dysphasia, but reached criterion in 13 trials with 48 errors, a performance superior to that of most normal control subjects. Furthermore, the difference between error scores for the right and left parietal-lobe groups (excluding the three left non-dominant cases) nearly attained significance, the mean for those with left-sided excisions being 87.8 and for those with right-sided excisions (which were larger) being 138.5.

The results are in general strikingly consistent with those obtained by MILNER [20] and, since all patients with unilateral cortical excisions studied here had previously learned the visual maze, as had the 11 normal control subjects, it was possible to correlate the two sets of error scores. The resulting Pearson product–moment correlation for 60 subjects was $+0.77$ ($P<0.001$).

Bilateral hippocampal lesions

The three hippocampal patients were even more impaired on the maze task than were the patients with right-sided cortical excisions. The error curves are shown in Fig. 6, the trials for two of the patients having been carried beyond the usual 50 in an attempt to

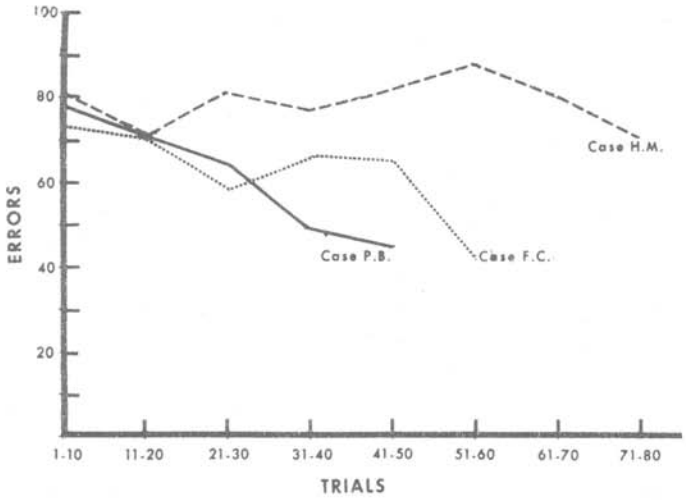

FIG. 6. Learning curves for patients with bilateral hippocampal damage: total errors for consecutive blocks of 10 trials.

demonstrate some progress. Case H. M., with a bilateral medial temporal-lobe resection, manifested a severe memory disturbance clinically (SCOVILLE and MILNER [28]), and his error scores suggest that no learning was taking place. The recent-memory deficit was milder in Cases F. C. and P. B., who had both undergone left temporal lobectomies, but in addition manifested right-temporal electrographic abnormality (PENFIELD and MILNER [22]). Both

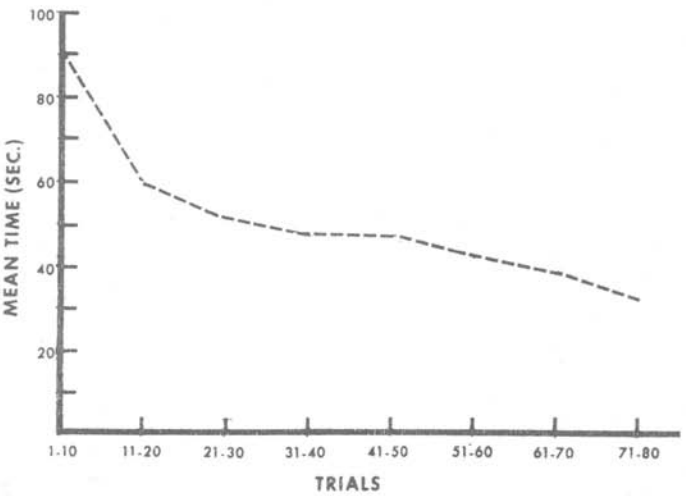

FIG. 7. Case H. M.: mean time scores for consecutive blocks of 10 trials.

subjects improved significantly with practice and presumably would have reached criterion had training been continued. Their error scores for trials 41–50 were, however, significantly higher than those of the other subjects with unilateral temporal-lobe excisions who did not reach criterion ($U=1$, $P=0.05$, one-tailed).

Figure 7 gives the mean time scores for Case H. M., whose error scores did not decrease significantly over 80 trials. The steady slope of the curve suggests that the patient acquired the proprioceptive-motor skills involved in the task despite being unable to retain the correct sequence of turns. The decrease in time scores is consistent with MILNER's [18] finding that this same subject's time and error scores on mirror drawing, a visuo-motor task, improved steadily over a three-day period.

DISCUSSION

The high positive correlation between the results of the present study and those for MILNERS's [20] visual maze supports the idea that spatial abilities are not organized along modality–specific lines (SEMMES, WEINSTEIN, GHENT and TEUBER [29]). The data for the frontal-lobe groups do, however, suggest that the tactual test differentiates between right- and left-sided cases, whereas the visual maze data are less clear, showing only a tendency for the left frontal-lobe group to be more efficient than the right.

It will be recalled that the right frontal group had higher repetitive error scores than the other subjects tested, but, for technical reasons, the number of repetitive errors committed during each trial could not be counted independently of non-repetitive ones. Thus it was not possible to determine the exact contribution of repetitive errors to the total error scores. Whether or not this contribution was a significant one in the right frontal group, the fact remains that the prepotency of such behavior excluded an efficient approach to learning the correct sequence of turns. This difficulty does not bear any obvious relationship to spatial disorientation but may reflect the same underlying disturbance as the impairment seen on the Porteus Mazes in the early stages after frontal lobotomy (LANDIS and ERLICK [11]). Nevertheless, there is some evidence of spatial disorientation with anterior brain lesions. MARIE and BÉHAGUE [12] observed patients with deep gunshot wounds of the frontal lobes, who lost their way in the light and were even more disorientated in the dark, not being able to tell right from left. Similarly, MARIE, BOUTTIER and VAN BOGAERT [13] studied a patient with a right prefrontal tumor who, despite being able to perform visual construction tests, complained of losing his way. The authors considered that this difficulty in "directional orientation" differed in kind from that seen in patients with parietal-lobe damage. Other evidence of spatial deficits resulting from anterior lesions was provided by TEUBER and MISHKIN [32], who tested cases with penetrating lesions on the Aubert task, and by SEMMES, WEINSTEIN, GHENT and TEUBER [31], who investigated right–left orientation with respect to body parts.

Turning now to the parietal region, it is apparent that large non-dominant posterior excisions (which destroyed the bulk of the parietal lobe) altered tactually-guided maze learning, but that smaller parietal-lobe excisions in either hemisphere had no such effect, even in patients with severe sensory loss. These findings are in marked contrast to earlier reports that, on both tactual and visual forms of the route-finding task, the group with parietal-lobe lesions was the only one impaired (SEMMES *et al.* [29]), and the deficits were associated with elevated two-point discrimination thresholds (WEINSTEIN, SEMMES, GHENT and TEUBER [35]). One way of explaining these discrepancies between locomotor- and stylus-maze data is to suppose that the parietal-lobe patients tested on the locomotor mazes had large lesions, and that had patients with small lesions been tested, they would have been unimpaired.

Both the tactual and visual stylus mazes differ from the route-following tasks of SEMMES *et al.* [29] in testing learning and not merely orientation. The learning aspect is strikingly demonstrated by the poor performance, on both stylus mazes, of the patients with bilateral hippocampal lesions. The fact that the subject not only has to discover the correct path but has to remember it as well perhaps accounts for the finding that a right temporal lobectomy, including the hippocampus, produces a deficit in visually- and tactually-guided maze learning. The results of the present study strengthen the existing evidence for the inferiority of patients with right temporal lesions on certain non-verbal tasks (KIMURA [10]; MILNER [16, 17, 20]; MILNER and KIMURA [21]; PRISKO [26]), extending the visual and auditory findings to somesthesis, where previous data were relatively scant (MILNER [14, 15]; TEUBER and WEINSTEIN [33]).

The finding that a right temporal lobectomy must include a radical removal of the hippocampus in order to produce an impairment in tactually-guided maze learning is in agreement with MILNER's [20] data for a visual maze. Whether a right hippocampectomy is sufficient to alter performance cannot be said, however, since no excision in the present study or in MILNER's [20] was restricted to the right hippocampus with temporal neocortex spared. Nevertheless, the fact that no deficits were seen after a right temporal lobectomy essentially sparing the hippocampus suggests that lateral temporal tissue is not making a crucial contribution to tactual maze learning. In this connection, studies with lower primates have shown that somesthetic discrimination learning, unlike visual, is unaffected by inferotemporal resection (BATES and ETTLINGER [1]; PRIBRAM and BARRY [25]; WILSON [36]).

The general finding of the inferiority of patients with right-sided cortical excisions on the tactual maze is consistent with evidence from visuo-spatial tasks in patients with miscellaneous cerebral lesions. This asymmetry of function has been repeatedly observed on two- and three-dimensional construction tests (BENTON and FOGEL [3]; HÉCAEN [8]; PIERCY, HÉCAEN and AJURIAGUERRA [23]; PIERCY and SMYTH [24]); on a visual multiple choice problem (BENTON, ELITHORN, FOGEL and KERR [2]); and on a variety of other spatial tasks (HÉCAEN, PENFIELD, BERTRAND and MALMO [9]). The importance of the right hemisphere for the utilization of complex somesthetic cues has also been demonstrated by REITAN [27] and by WEINSTEIN [34].

The differential effects of right- and left-hemisphere excisions on tactually-guided behavior shown in the present study suggest a diffuse representation of complex tactual functions in the right hemisphere, although an alternative possibility is that lesions in different right-hemisphere regions produce qualitatively different disturbances in behavior. It is possible that left posterior parietal excisions (which were not sampled, since such an excision is damaging to speech) would produce impairment, but, on the basis of the lesions sampled here, all one can conclude is that right-hemisphere lesions impair performance on this task, and that left-hemisphere lesions do not.

Acknowledgements—This research was supported by Canadian Defence Research Board Grant 27-274 to Dr. D. O. HEBB, and by United States Public Health Grant 28960 from the National Institute of Mental Health also to Dr. HEBB. Study of the bilateral hippocampal patients and some of the parietal-lobe patients was made possible by United States Public Health Small Grant M5774A to Dr. BRENDA MILNER. Preparation of this article was supported by a grant to Dr. H.-L. TEUBER from the John A. Hartford Foundation. I am indebted to Dr. BRENDA MILNER for stimulation and guidance during the course of the experimentation and writing, and to Drs. WILDER PENFIELD, THEODORE RASMUSSEN, CHARLES BRANCH and WILLIAM FEINDEL for permission to study their patients at the Montreal Neurological Institute. I also wish to thank Dr. W. B. SCOVILLE of the Hartford Hospital for allowing his patient, Case H. M., to be tested in Montreal.

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Résumé—L'apprentissage d'un labyrinthe tactile a été étudié chez 53 malades ayant différentes lésions cérébrales. Les malades avec une lésion du lobe frontal ou temporal de l'hémisphère gauche dominant donnent des résultats semblables à ceux des sujets normaux. Par contre, on observe un déficit après une lobectomie temporale droite accompagnée de l'ablation ipsilatérale de l'hippocampe, et le déficit est encore plus marqué après une lobectomie frontale droite. Le nombre d'erreurs est en relation directe avec l'étendue de la lésion après des ablations envahissant le lobe pariétal sans être limitées à cette région. Chez trois malades une lésion bilatérale de l'hippocampe a produit des résultats inférieurs aux plus mauvais qu'a entrainé l'ablation d'un lobe temporal. Il existe une corrélation élévée entre les résultats obtenus à cette tâche et l'apprentissage d'un labyrinthe sous controle visuel.

Zusammenfassung—Das Erlernen eines taktilen Labyrinthes wurde bei 53 Patienten mit verschiedenen Hirnläsionen untersucht. Die Resultate der Patienten mit einer frontalen oder temporalen Läsion der linken, dominanten Grosshirnhemisphäre sind denen der normalen Versuchsperson ähnlich. Hingegen weisen Patienten mit einer rechten temporalen Lobektomie und einer zusätzlichen Abtragung des gleichseitigen Hippocampus ein Defizit auf, und eine rechte Frontallappenabtragung bewirkt eine noch stärkere Herabsetzung der Leistung. Nach Abtragungen, die den Partietallappen betreffen, ohne auf diese Region begrenzt zu sein, steht die Fehlerzahl im direkten Verhältnis zu der Ausdehnung der Läsion. Drei Patienten mit einer beidseitigen Hippocampusläsion erzielten niedrigere Resultate als die schlechtesten Patienten mit einseitiger Temporallappenabtragung. Es besteht eine hohe Korrelation zwischen den Resultaten an diesem Labyrinth und an einem solchen mit visueller Darbietung.