Ogden, J. A., & Corkin, S. (1991). Memories of H.M. In W. C Abraham, M. Corballis, and K. G. White (Eds), Memory Mechanisms: A tribute to G.V. Goddard. Hillsdale, NJ: Lawrence Erlbaum Associates.

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Memories of H.M.

Jenni A. Ogden & Suzanne Corkin
University of Auckland, New Zealand and Massachusetts Institute of Technology

In 1968 an issue of *Neuropsychologia* (Volume 6, Number 3) was produced under the special editorship of Dr. Brenda Milner. This issue was entitled "Disorders of memory after brain lesions in man," and five of the nine papers in it were devoted to a single subject, known as H.M. At that time H.M. was 42 years old; 14 years previously he had undergone a bilateral medial temporal-lobe resection for the relief of intractable epilepsy. As a result, although his seizures were reduced to manageable levels, he was left with a dense global amnesia. Today he is 62 years old, and neuropsychologists and cognitive psychologists continue to study his memory disorders and publish their findings. Indeed, he has probably had more words written about him than any other case in neurological or psychological history.

Since the 1950s, when Doctors William Scoville and Brenda Milner first published their finding that bilateral removal of the mesial temporal lobes results in a profound global amnesia (Scoville, 1954; Scoville & Milner, 1957), there have been substantial advances in the procedures and techniques used to tease apart memory processes. The study of H.M. not only tells us a great deal about memory, but also provides a striking illustration of the evolution and growth of cognitive psychology and neuropsychology. The theories of memory resulting from early studies of H.M. and the various dichotomies of memory suggested by H.M.'s defisome of the questions posed by H.M.'s pattern of memory loss and sparing remain unanswered. However, the numerous experiments over the past 20 years with H.M. as the subject, and related work on normal subjects and on other humans with memory disorders, have contributed substantially to our knowledge about memory systems of the human brain.

The paradox of H.M. is that because of him we have learned a great deal about human memory, but because of the unexpected tragic results of his surgery, the sample size of one will never increase. Although there have been and will continue to be valuable studies carried out on amnesic subjects with pathological, rather than surgical, bilateral lesions of the mesial temporal lobes and midline structures of the brain, these subjects do not appear to manifest the same severity of amnesia as H.M. and are much more likely to have other cognitive disorders that confound the study of their amnesia.

Like many other single case studies, research articles on H.M., while systematically exploring the parameters of his memory, usually do not describe in detail the rich qualitative data gathered by the experimenters during their extended interactions with H.M. Two exceptions to this are the review papers published on H.M. in 1968 and 1984 (Corkin, 1984; Milner, Corkin, & Teuber, 1968). These papers comment on H.M.'s gentle, passive nature and describe some of the problems H.M.'s amnesia causes in his day-to-day life.

In clinical neuropsychology generally, qualitative data and anecdotal evidence not only serve to lighten the tedium that often accompanies long sessions of testing in an experimental situation but, more importantly, may also enrich our understanding of the neuropsychological functions we are attempting to measure experimentally. This contribution certainly holds true for the study of H.M. While hours, days, weeks, and years of watching the same stimuli on a computer monitor and pressing buttons in response may not be tedious for him because he has no conscious awareness of ever having done the experiment (or any other experiment) before, it would certainly become tedious for the experimenters, but for the delightful personality of their subject and the conversations and interactions that occur during the testing session.

At the Clinical Research Center at MIT where H.M. has undergone most of his assessments over the last 20 years, he is a great favourite with researchers and clinical staff alike, not because of his now famous initials and the intensively studied amnesia associated with them, but because of his endearing nature, his sense of humor, and his willingness to be helpful. Perhaps if his personality were less agreeable, there would be fewer researchers willing to spend numerous hours with him, and we would know considerably less about his memory and memory functions in general.

HISTORY

H.M. was born in 1926, and his development was apparently normal until, at the age of 7 years, he was knocked down by a bicycle and was unconcious for about 5 minutes (Corkin, 1984). He began having petit mal seizures three years later, and grand mal seizures began on his sixteenth birthday. Over the next 11 years he was having about 10 petit mal seizures a day and one grand mal seizure a week, and these could not be controlled by large doses of anticonvulsant medications. Electroencephalography (EEG) did not show any localized epileptogenic area but did indicate diffuse slow activity. During a minor seizure, bilateral generalized EEG abnormalities were recorded, with a predominance in the centro-temporal areas of both hemispheres.

In 1953, when H.M. was 27 years old, a bilateral medial temporal-lobe resection was performed by Scoville. An EEG recorded at the time of the operation gave no clear-cut evidence of an epileptogenic focus. The resection was carried out through bilateral supra-orbital 1.5-inch trephine holes. The medial half of the tip of each temporal lobe was resected, and the gray and white matter mesial to the temporal horns of the lateral ventricles and extending 8 cm back from the tips of the temporal lobes was removed by suction. Included were the prepyriform gyrus, uncus, amygdala, hippocampus, and parahippocampal gyrus. The temporal neocortex was left almost intact. H.M. was awake and talking during the procedure (Corkin, 1984; Scoville, 1968).

The frequency of seizures was reduced substantially as a result of the operation. His major seizures have since occurred less than once a year, and he has about five petit mal seizures a month. He remains on anticonvulsant medication. Since his operation H.M. has had a profound anterograde amnesia and a retrograde amnesia for the 11 years preceding his surgery, but his other cognitive functions remain largely unaffected. The tragic results of this procedure motivated Dr. Scoville to campaign widely against its use (Scoville, 1968).

After his operation, H.M. lived with his parents. Following the death of his father in 1967, he attended a rehabilitation workshop daily for 10 years. He lived with his mother until 1977, and she died in a nursing home in 1981, at the age of 94. H.M. has lived in a nursing home since 1980. In 1986, when asked where he lived, he said in a house with his mother. When asked whether his father was alive, he looked very sad and answered that he wasn't sure, but thought that he may have died because he had been quite ill with TB. At other times H.M. remembers that both his parents are dead and that he is all alone.

GENERAL INTELLECTUAL ABILITIES

On the day before his operation H.M. was assessed on the Wechsler–Bellevue Scale, and on this test his Verbal IQ was 101 and his Performance IQ was 106. It is interesting to note that he was not given any memory tests at this time, presumably because there was no reason to believe that his memory would be affected by the operation. Since his operation, he has been assessed on the Wechsler Intelligence Scales and the Wechsler Memory Scale six times. He falls in the average range for Verbal IQ and in the average-to-superior ranges for Performance IQ. His Memory Quotient consistently falls 35 points or more below his Full Scale IQ, and his delayed recall scores on the Logical Memory and Paired Associate (verbal) and Visual Reproduction (nonverbal) tests are always zero.

In 1983, when H.M. was 57, his IQ scores were 10 to 11 points lower than they had been 10 years previously. This change may reflect premature aging related to his long-term seizure disorder and medication with anticonvulsants, in addition to the substantial amount of brain tissue removed at his operation (Corkin, 1984).

MEMORY FUNCTIONS

H.M.'s pattern of sparing and loss of memory functions can be conceptualized in a number of different ways. His memory disorder generally fits all of the following dichotomies; the first process being largely spared and the second being severely impaired:

1. immediate memory versus long-term memory (new learning);
2. Remote memory versus anterograde memory;
3. Implicit memory versus explicit memory.

In addition, HM has demonstrated impairments since his operation on both processes of the following dichotomies:

4. Verbal memory versus nonverbal memory.
5. Semantic memory versus episodic memory.

Experimental and anecdotal evidence for each of these aspects of H.M.'s memory will be reviewed.

Immediate versus Long-term Memory

H.M.'s immediate memory span for digits and block patterns has bee borderline normal since 1955 (Corkin, 1982), although in recent years h digit span has dropped from 6 to 5. This is probably due to the norm aging process. Decay of immediate or short-term memory (STM) measured by recognition (Wickelgren, 1968) or recall (Corkin, 1982) normal. As soon as H.M.'s span is exceeded by one item, or he is di tracted, or he is unable to rehearse the material verbally, he forgets (Corsi, 1972; Drachman & Arbit, 1966; Milner, 1968; Prisko, 1963).

One day, H.M. was given five digits to repeat and remember, and the the experimenter was called away. An hour or more later she returned H.M.'s room, and on seeing her H.M. accurately repeated the five digit As he had not been distracted, he had been rehearsing the numbers th entire time, thus containing them in immediate or working memory Because time is measured by the memories that are laid down as passes, H.M. was presumably unaware of the time that had elapsed sinc the experimenter had left the room.

One of us (JAO) decided to assess H.M.'s ability to measure time an told him that he would be left alone for a period, and then asked estimate the time that had elapsed. JAO left the room at 2.05 pm an returned at 2.17 pm. When H.M. was asked how many minutes ha passed, he replied, without hesitation, "12 minutes; got you there' There was a large clock on the wall and H.M. had noted the time whe JAO left, and continued to rehearse it while looking at the clock. Whe asked how many minutes had passed he simply subtracted the time h was rehearsing from the time shown on the clock. This anecdote illu trates more about H.M.'s sense of humor, his willingness to cooperat with anything experimenters may come up with, and his intact intellec than about his ability to estimate time without memories!

His long-term memory (new learning) for both verbal and nonverb material in all modalities is severely impaired. He demonstrates a inability to learn stories, verbal and nonverbal paired associates, bloc patterns, songs and drawings, new vocabulary words (Gabrieli, Cohen, Corkin, 1988), visual and tactual stylus mazes (Corkin, 1965; Milne 1965), digit strings (Drachman & Arbit, 1966), object names (Smith Milner, 1981), and object locations (Smith, 1988). He also perform poorly on forced-choice recognition tasks using faces, houses, words, an tonal sequences.

Evidence exists, however, that H.M. has some ability to store and us new information. This conclusion comes from experiments using prin ing—that is, the influence of prior processing of material upon later pu poseful performance with that material. For example, if H.M. is shown word such as "DEFINE," and is later given the stem "DEF" and asked to complete it with the first word that comes to mind, then he usually responds with the previously experienced word. He is unable, however, to pick out the words he has just seen from a list of words (Keane, Gabrieli, & Corkin, 1987). Similarly, if he is asked to draw a figure by connecting five dots in a matrix of nine dots, and is later asked to draw the first pattern that comes to mind using a matrix of nine dots, he responds by drawing the previously drawn figure as often as control subjects (Gabrieli, 1986). If shown the patterns amongst other patterns, however, he cannot recognize the ones he drew earlier. He also gets faster at recognizing incomplete line drawings of objects with repeated exposure, although he cannot recognize which drawings he has previously seen (Milner et al., 1968).

Remote versus Anterograde Memory

Milner et al. (1968) reported that H.M.'s retrograde amnesia extended back two years before his operation. This estimate came from the neurosurgeon's notes and postoperative interviews with H.M. Since that time, a number of objective tests of remote memory given to H.M. support an 11-year period of retrograde amnesia. These tests involve the recall or recognition of famous tunes, public events, and famous scenes taken from the 1920s to the 1960s (Corkin, 1984). H.M.'s personal memories are also nearly all from the age of 16 years or earlier, thus also suggesting a loss of memories or inability to retrieve them for an 11-year period prior to his surgery (Sagar, Cohen, Corkin, & Growdon, 1985). It may be that H.M.'s seizures and high doses of anticonvulsant medications could have resulted in an inability to store new memories prior to his operation, and there may be an increasing loss of remote memories because of impoverished rehearsal of them. However, H.M. does report some memories from the 11-year period prior to his surgery, such as the name of the surgeon who had carried out the operation and people he had known in the years immediately preceding the operation. He also occasionally remembers information he must have stored after the operation. For example, he knows that as a result of the surgery he has memory problems, and that the operation has not been done on anyone else since.

The remote memories that are intact seem detailed and clear, presumably because to H.M. they are relatively recent memories and have not been subject to interference from new memories. When asked about various actors and singers famous in his childhood, he can often describe them, what films they were in, and who their costars were. He knows the names of the friends he had in second grade and can talk about being

knocked down by a bicycle when he was a small boy (aged 7 years). He remembers his first major seizure, which, he said, happened on his fifteenth birthday when he was riding in a car with his parents (this was in fact on his sixteenth birthday). He talks about his gun collection, relates pleasurable memories of hunting with his father, and remembers that he used to enjoy roller skating. At the age of 60, when asked about roller skating, he said that he gave it up about 13 years ago! He also relates stories about his parents' families, presumably told to him by his parents when he was young. He talks about his mother's trip to Ireland as a girl to be confirmed, and an aunt who emigrated to Australia. This latter story was often cued when JAO told him she came from New Zealand.

Constant retelling of old memories, whether they are factual or not, does not change them significantly for H.M., because unlike most of us he is unable to update his memories and recall the slightly changed version. As a result, the many researchers who have assessed H.M. over 30 years can all repeat stories told by H.M., with very similar words and intonations. When H.M. is distracted while telling one of his stories, he can be cued into retelling it a few minutes later, and will repeat it not only using the same verbal expressions, but using the same facial expressions and gestures. Occasionally, however, he appears to lose the thread of the story, and inserts a different line, but then quickly returns to the old story. For example, when asked about his operation he will usually launch into a story about wanting to be a brain surgeon. The following transcript of a conversation one of us (JAO) had with H.M. illustrates these points.

In this particular conversation, the first time he told the story he changed it slightly (indicated by the words in italics). Near the end of the story he forgot he had just been telling it but cued himself into telling it again, this time using the phrases he usually uses. This conversation also gives some insight into the way in which H.M. thinks about his operation and its results.

JAO: Do you know why you are here at MIT?
H.M.: I wonder at times, but I know one thing. What is learned about me will help other people.
JAO: Yes, it has helped other people.
H.M.: And that is the important thing. Because at one time that's what I wanted to be, a brain surgeon.
JAO: Really? A brain surgeon?
H.M.: And I said "no" to myself, before I had any kind of epilepsy.
JAO: Did you. Why is that?
H.M.: Because I wore glasses. I said, suppose you are making an incision in someone—[pause]—*and you could get blood on your glasses*, or an attendant could be mopping your brow and go too low and move your glasses over. You could make the wrong movement then.

JAO: And then what would happen?
H.M.: And that person could be dead, or paralyzed.
JAO: So it's a good job you decided not to be a brain surgeon.
H.M.: Yeah. I thought mostly dead, but could be paralyzed in a way. You could make the incision just right, and then a little deviation, might be a leg or an arm, or maybe an eye too; on one side in fact.
JAO: Do you remember when you had your operation?
H.M.: No, I don't.
JAO: What do you think happened there?
H.M.: Well I think I was ah —well, I'm having an argument with myself right away. I'm the third or fourth person who had it, and I think that they, well, possibly didn't make the right movement at the right time, themselves then. But they learned something.
JAO: They did indeed.
H.M.: That would help other people around the world too.
JAO: They never did it again.
H.M.: They never did it again because by knowing it—[pause]—and a funny part, I always thought of being a brain surgeon myself.
JAO: Did you?
H.M.: Yeah. And I said "no" to myself.
JAO: Why was that?
H.M.: Because I said an attendant might mop your brow and might move your glasses over a little bit, and you would make the wrong movement.
JAO: What would happen if you made the wrong movement?
H.M.: And that would affect all the other operations you had then.
JAO: Would it? How?
H.M.: Because if that person was paralyzed on one side, or you made the wrong movement, in a way, and they possibly couldn't hear on one side, or one eye, you would wonder to yourself and that would make you nervous.
JAO: Yes, it would.
H.M.: Because every time you did you would try and be extra careful and you might be detrimental to that person; to perform that operation right on that time because you'd have that thought and that might slow you up, then, because you were making a movement and you should have continued right on.
JAO: Do you remember who the surgeon was who did your operation?
H.M.: No, I don't.
JAO: I'll give you a hint. Sc–.
H.M.: Scoville.
JAO: That's right. You got that fast.
H.M.: Well, because I couldn't remember fully, but the little hint.

The most memorable aspect of H.M.'s memory impairment is his dense anterograde amnesia for nearly all episodic information since his operation. He cannot say what he was doing 5 minutes ago, nor can he say where he lives, whom he lives with, what day, month, year, or season

it is, or what his age is. The following conversation illustrates his co fusion about his age.

JAO: How old do you think you are now?
H.M.: Round about 34. I think of that right off.
JAO: How old do you think I am?
H.M.: Well, I'm thinking of 27 right off.
JAO: Aren't you kind! I'm really 37.
H.M.: 37? So I must be more than that.
JAO: Why? Do you think you're older than me?
H.M.: Yeah.
JAO: How old do you think you are?
H.M.: Well, I always think too much ahead in a way. Well nearer, well 38.
JAO: 38? You act 38! You know you are really 60. You had your 60th birthd the other day. You had a big cake.
H.M.: See, I don't remember.

H.M. does not recognize anyone he has met or seen since 1953, a even after 20 years of returning to MIT and being assessed every year one of us (SC) he still demonstrates no recognition. When given a t designed to assess his ability to recall or recognize personal events, th was an absence of personal memories after the age of 16 years (Cork 1984; Sagar, Cohen, Corkin, & Growdon, 1985). As mentioned p viously, however, he does have islands of memory, related to how of and how recently he has heard or seen the information. For examp during his regular visits to the MIT Clinical Research Center, he is a to state that he is at MIT. This response suggests that the frequency of visits to MIT over many years has enabled him to store and recall "MI when cued by the surroundings and perhaps the change of daily rout he encounters there. This learning may be a type of semantic learni because he cannot recall any particular visit to MIT. Indeed, when t about an event such as his 60th birthday party that had taken place MIT, he shows no recognition of it only hours later.

On a test designed to assess the content and the temporal context public events over five decades, H.M. demonstrated normal performa for events from the 1940s, but impaired performance for the 1950s 1980s (Corkin, 1984; Corkin, Cohen, & Sagar, 1983; Gabrieli, Cohen Corkin, 1988). His occasional recall of famous people and episodes t were publicized after his operation in 1953 is spasmodic at best, and tends to confuse these memories with other episodic memories, or confuses them in time. The following conversation, where he confu Elvis Presley's death with the assassinations of President John Kenn and Robert Kennedy, illustrates this point. An Elvis Presley record was first played on radio in 1954, one year after H.M.'s operation.

JAO: Do you know who Elvis Presley is?
H.M.: He was a recording star, and he used to sing a lot.
JAO: What sort of things did he sing?
H.M.: Jive.
JAO: Do you like to jive, or did you like to jive?
H.M.: No.
JAO: Why not?
H.M.: I liked to listen, that was all.
JAO: Do you think he is still alive, Elvis Presley?
H.M.: No, I don't think so.
JAO: Have you any idea what might have happened to him?
H.M.: Well I believe he got the first bullet I think that was for Kennedy, I think it was.
JAO: You remember Kennedy?
H.M.: Yes, Robert.
JAO: What was he?
H.M.: Well, he was the President. I think about three times. He was appointed to President too.
JAO: He got a bullet. What was that all about?
H.M.: Well, they were trying to assassinate him.
JAO: And did they? Did they kill him or not?
H.M.: No they didn't.
JAO: So is he still alive?
H.M.: Yes, he is still alive, but he got out of politics in a way.
JAO: I don't blame him.
H.M.: No, guess not.
JAO: How long ago was he the President do you think?
H.M.: He became the President after Roosevelt. 'Course there was Teddy Roosevelt. That was a long time before that.
JAO: What is Franklin Roosevelt's wife's name?
H.M.: I can't think of it.
JAO: It starts with "E" I think.—Eleanor. You were going to say that?
H.M.: No I wasn't. I was going to say "Ethel."

H.M. spends much of his day watching television and reading the newspapers, and therefore hears, sees, and reads reports of major news items many times over. It appears that many repetitions of significant events make it more likely that HM will recall them in part, at least over a period of days. Two weeks before the following conversation, the American space shuttle "Challenger" exploded shortly after it was launched, and this, and stories about the woman teacher who was on board, dominated the news media for weeks after.

JAO: What is a space shuttle?
H.M.: Well, I think it is a space ship they shot up and after it is shot up then it turns itself on. And also there is another part to it that can be sent back.

After they've shot off, and shot off the second one, they can return. use part of it again.
JAO: Something happened when they sent up a space shuttle a couple of w ago. Do you remember anything about that?
H.M.: The one which was flung back at the moon, and they were trying to r it but they couldn't. And they wondered doubly themselves if one of clouds or something had deflected the sound; the sound that was sent t control it, and deflected it.
JAO: So what happened?
H.M.: They don't know.
JAO: It just disappeared?
H.M.: It went back of the moon and they couldn't get it to go around like wanted it to, and it didn't return or anything.
JAO: Just a couple of weeks ago, one blew up, exploded just after it had t off. How many people do you think were on it?
H.M.: I think of eight right off.
JAO: Pretty close. There were seven in fact. Were they all men do you think
H.M.: I think there were two women on it. And supposed to be about the no the second ones that had gone up in space. Of course it was goin return and everything, and all the data and everything blew up on laun
JAO: It was the first space ship to have a civilian on board; not an astronaut. a civilian and that was one of the women. Do you know what she did job?
H.M.: I think of working for the army.
JAO: No, she was a teacher.

This illustrates the dense nature of H.M.'s amnesia. Although H had some knowledge of the space shuttle program generally, and poss of the 'Challenger' explosion specifically, his memory for that ev remained fragmented and incomplete, in spite of current, repeated matic exposure to it in pictures and in words.

Implicit Memory versus Explicit Memory

This dichotomy perhaps fits H.M.'s memory disorder better than other. It is purely descriptive, and may not apply to all learning memory phenomena. Explicit memory describes traditional tests recognition and recall, and implicit memory describes a range of mem abilities that do not require the explicit conscious recollection of previ experiences (Schacter, 1987). In 1962, Milner reported that H decreased his error rate and time scores on a mirror-drawing task o three days of training. He never recognized the apparatus or that he done the task before. This achievement could be classified as m learning and learning a new procedure. Certainly it could be describe implicit learning without explicit knowledge. Since then, his ability learn new procedural skills (knowing how to do something), without explicit knowledge that he has performed the task before, has been demonstrated many times (Corkin, 1968; Mickel, Gabrieli, Rosen, Corkin, & Growdon, 1986; Nissen, Cohen, & Corkin, 1981). He improves on mirror reading and reading words presented briefly on a tachistoscope (Nissen et al., 1981), which are both perceptual skills. H.M. has also demonstrated an improvement on a task that involves cognitive skills, the Tower of Hanoi puzzle (Cohen & Corkin, 1981). More recently, Gabrieli, Keane, and Corkin (1987) found that H.M. did not improve on the Tower of Hanoi puzzle when the examiner did not pose prescribed questions throughout the procedure that were designed to encourage the adoption of a particular strategy. On another test of problem solving, however, the Missionaries-and-Cannibals problem, H.M. demonstrated increased efficiency across days. The implicit learning of problem-solving skills thus appears to be shaped in some way by appropriate examiner–subject interactions.

H.M.'s normal ability to learn how to perform new tasks is evident in his daily routine. For example, at the age of 60, he broke his ankle and was obliged to use a fold-up wheelchair to get around. He learned how to open it, and was also able to explain to others how to do so, and he learned the most effective way to position himself so that he could get into it from another chair. Later, when he advanced to a walking frame, he acquired the procedure for dealing with that equipment as well. He still uses the walker with considerable skill but does not remember why he uses it.

More recently he has been tested on his ability to learn a mental rotation task. On this task, he is shown a letter such as an *R*, *F*, or *L*, presented either in its normal or mirror-reversed form in one of eight orientations in the picture plane. For most normal subjects, the time to rotate the letter mentally to its upright position in order to decide whether it is normal or mirror reversed is a monotonically increasing function of the angle of orientation (Corballis, 1982). Under some conditions, with practice, the slope of this reaction time/orientation function gradually flattens out (Kaushall & Parsons, 1981). Parsons, Gabrieli, and Corkin (1987) found that although H.M. made fewer errors with practice on the mental rotation of *R*, he did not improve his mean reaction time, nor did he show a decrease in the slope of the reaction time/orientation function. However in 1988, Parsons, Gabrieli, Yucaitis, and Corkin reported a different result. This time H.M. showed a gradual, strong, normal decrease in the slope of his reaction time/orientation function and in his overall mean reaction time and error rate. They put this down to the different types of responses required in the two experiments. In the 1987 experiment the task required a forced-choice buttonpress response, and in the 1988 experiment H.M. made verbal responses that were detected by a voice key.

This explanation, however, may not be the correct one for the different results of Parsons et al. (1987, 1988). In a similar mental rotation experiment carried out by the first author in 1986, H.M. was given blocks of trials over a period of 28 days. On Days 1, 2, and 3 he was given 160 trials each day of the letter *F* presented in either the normal or backward position at each of eight orientations around 360 degrees; on Days 3, 4, and 5 he was given 160 trials each day of *L*; and on Days 5, 9, and 10 he was given 160 trials each day of *R*. On each of Days 15, 23, and 28 he was retested on all three letters (160 presentations of each letter over the three days). The letters were viewed on a computer monitor, and the response was a forced-choice button press; the two buttons being labeled NORMAL and BACK. On the first day, and when it appeared necessary thereafter, H.M. was instructed to turn the letter around in his mind until it was upright, then decide whether it was normal or backward, and push the appropriate button.

He had a typical reaction time/orientation function on the first day for the letter *F*, but from Day 2 onward the mental rotation function flattened out and became irregular. H.M. may have learned to recognize normal and backward letters without having to rotate them, or he may have started to use a different strategy. For each letter, however, his mean reaction time improved significantly across sessions within days and across days, and there was substantial generalization from one letter to another in terms of faster reaction times (Fig. 10.1) and error rates. The first day on the third letter *R* was an exception, in that the mean reaction time was longer than for the other letters. By the second day, however, it had decreased significantly. On the first day of the first letter *F*, H.M. made 26 errors over 160 trials, dropping to 8 errors on the second day. On the first day of the second letter *L*, he made 9 errors, and no errors on the second day; on the first day of the third letter, *R*, he made 14 errors, and 5 errors on the second day. Two and three weeks later when he was retested, his reaction times for all three letters remained at their shortest times, and he made no more than 2 errors on any of the letters.

This improving ability to carry out this task, whether or not mental rotation is the strategy used, would seem to fit most comfortably within the category of implicit learning. As always with H.M., there was a dissociation between this "knowing how" ability and an explicit knowledge that he had performed the task previously. This dissociation became apparent when H.M. was taken into the room where he was tested every day. When asked what the computer was and what he was to do with it, he would say he didn't know. However, after having the mental rotation task explained to him many times on Day 1, on Day 2 he was shown a

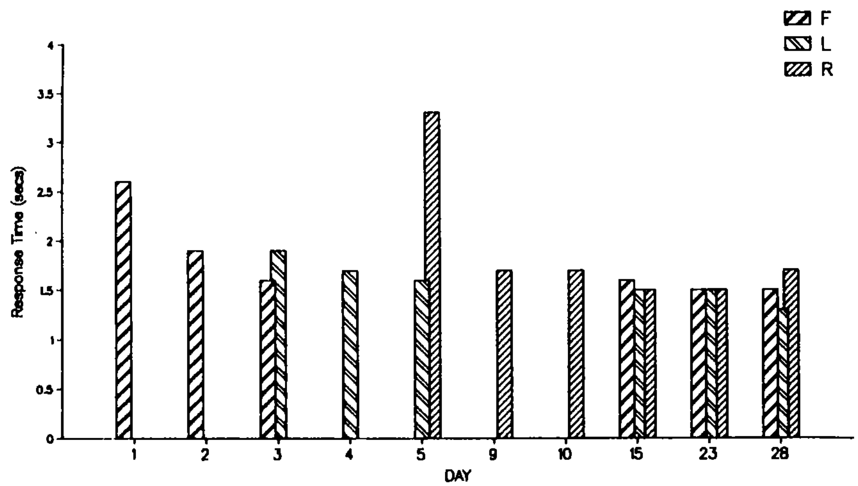

FIG. 10.1. H.M.'s response times in seconds on a mental rotation task using the letters *F*, *L*, and *R*.

card with an upside-down, mirror-reversed *F* drawn on it and asked whether he remembered what to do if a letter like that came up on the computer screen in front of him. He replied, "I don't remember, but I suppose I could turn it around in my mind until it was upright, and then I would press this button that says 'Back' on it because the 'F' is backwards."

Occasionally he still said he couldn't remember what to do when shown the card with the *F*. The test was sometimes then started without further explanation, and as soon as the first letter came up on the screen, H.M. would say, "Well, that would be backwards (or normal) so I press this button." This ability to perform a well-practiced task without conscious knowledge of having done it before, and sometimes even to make correct verbal "guesses" about how to do it is another example of preserved implicit memory and impaired explicit memory.

Verbal versus Nonverbal Memory

As a result of his operation, H.M. has been unable to recall or recognize verbal or nonverbal material, whether it is presented in the visual, auditory, or tactile modality (Corkin, 1965; Drachman & Arbit, 1966; Jones, 1974; Milner, 1965; Scoville & Milner, 1957). Since the consequences of his bilateral medial temporal lobectomy have become known, it has been demonstrated in many studies of the memory impairments of patients

with damage to one temporal lobe that essential processes involved verbal long-term memory are mediated predominantly by the tempor lobe structures, and especially the hippocampus/amygdala of the hen sphere dominant for speech (usually the left) (Meyer & Yates, 19: Milner, 1966), and that essential processes involved in nonverbal lon term memory are mediated by the temporal-lobe structures of the "n verbal" hemisphere (usually the right) (Milner, 1968). It seems clear th there is no dissociation between verbal and nonverbal memory in H.M because he has lost most of the mesial temporal-lobe structures of b hemispheres.

Because of the amnesia H.M. suffered following his surgery, patie with intractable temporal-lobe epilepsy who are being considered for s gical resection of one temporal lobe are carefully assessed for evidence verbal and nonverbal memory impairment, as impairments of both wo indicate bilateral dysfunction of the mesial temporal-lobe structu (Milner, 1975; Jones-Gotman, 1987). If this were the case, then resecti the epileptogenic temporal lobe might result in a global amnesia. Follo ing unilateral temporal lobectomy (typically involving a 5- to 8-cm res tion from the tip of the temporal lobe and including the amygdala and anterior part of the hippocampus), patients whose other temporal lob functioning normally do not become amnesic, nor do they suffer p found material-specific (i.e., verbal or nonverbal) memory impairmen They do suffer some degree of impairment in learning new material (v bal after left temporal lobectomy, and nonverbal after right temporal l ectomy), but it is something of a paradox that in circumstances wh there is only one intact temporal lobe, the remaining temporal lo whether left or right, can cope reasonably well with verbal and nonver memory (Jones-Gotman, 1987).

Semantic versus Episodic Memory

Tulving (1972, 1983) proposed a dissociation between context-f generic knowledge of the world (semantic memory), and autobiograp cal records of personal experience associated with a particular time a place (episodic memory). Within the framework of the implicit/expl memory dichotomy, semantic and episodic memory can be seen as co ponents of explicit memory, and therefore should both be impaired global amnesias (Cermak, Talbot, Chandler, & Wolbarst, 1985; Coh 1984; Squire, 1986; Zola-Morgan, Cohen, & Squire, 1983). Most studi however, have addressed the episodic components of explicit mem and neglected the ability of amnesics to learn new facts. Studies that h assessed semantic knowledge in amnesics have tested explicit knowle about public events and figures (Cohen & Squire, 1980; Marsel-Wilson

Teuber, 1975), and such studies have demonstrated that semantic learning is impaired in amnesia.

Gabrieli, Cohen, and Corkin (1988) argued that these findings may be a result of the recognition or recall procedures used to assess new semantic knowledge. It has been shown that amnesic patients, including H.M., demonstrate preserved learning only when it is assessed without the subjects' explicit knowledge, and Gabrieli et al. (1988) devised a way to assess new semantic learning in H.M. using implicit measures of performance. They carried out a series of experiments using uncommon words and words that were new to the English language since H.M.'s operation in 1953. In one experiment H.M. and control subjects were taught definitions of eight uncommon English words, and learning was assessed by improved performance over trials with the same words. Subjects were never asked whether they had seen the words before. H.M. was unable to learn the meaning of any word he did not already know.

A second experiment looked at the possibility that H.M. would learn new words better if they were presented in a real-life "ecological" rather than laboratory context, as predicted by Kinsbourne and Wood (1975). He was tested on the recall and recognition of words that had entered a standard English dictionary between 1954 and 1981. All the words were commonly known to high-school students. H.M. was also asked to make a lexical decision about each word and similar, pronounceable nonwords. H.M. demonstrated normal recall of definitions of words entering the English language prior to 1950, borderline recall for 1950s words, and severely impaired recall for post-1950s words. These results were paralleled on the recognition and lexical decision tasks. H.M. was also asked to pronounce words and nonwords presented visually in a perceptually difficult condition. A control subject was 17% faster at reading new words than nonwords, but H.M.'s reading of post-1950s words was no faster than his reading of nonwords.

Another experiment examined whether H.M. could recognize names of famous people when they were interspersed among names of nonfamous people. He scored normally on names that had been famous prior to the 1950s, 1 *SD* below normal on names that had become famous in the 1950s, and 2 *SD* below normal on names that had become famous in the 1960s to 1980s. This series of experiments provides good evidence that H.M. has suffered a markedly impaired ability to encode and store semantic information since his operation. Even so, H.M.'s ability occasionally to recall or recognize a famous name or face demonstrates that he has stored some semantic information since 1953. Because he has some posterior hippocampus remaining bilaterally, this tissue may be sufficient to mediate some new memories. Alternatively or in addition, memory circuits that bypass the hippocampus and amygdala may be able to mediate new memories, albeit in an impoverished way.

CONCLUSIONS

The many studies carried out with H.M. continue to confirm the importance of the hippocampus and amygdala for the encoding and storage of new explicit "knowing that" information, whether it is episodic or semantic. Studies of H.M.'s memory abilities have also shown that, with the exception of lexical decision tasks, most tasks requiring implicit learning do not require the amygdala and anterior hippocampus, whether the learning involves motor, perceptual, or cognitive skills.

H.M.'s impoverished retrieval of explicit information presumably encoded and stored in the 11 years immediately preceding his operation cannot be so clearly related to the removal of the mesial temporal-lobe structures. There is some evidence that semantic information presented immediately before his operation is better recalled than episodic events that occurred during the same time span. For example, H.M.'s personal (episodic) memories are drawn almost entirely from the period when he was less than 17 years old (Sagar et al., 1985), but he demonstrates only moderately impaired recall (1 *SD* below the mean) for definitions of English words (semantic information) that entered the dictionary in the 1950s, yet severely impaired recall (more than 2 *SD*s below the mean) for 1960s and later words (Gabrieli et al., 1988). Possibly semantic information encoded and stored in the years immediately preceding his operation remains more salient than episodic information stored during the same period, because semantic facts (e.g., 1950s words) continue to be presented in H.M.'s day-to-day environment, whereas rehearsal of his personal memories relies primarily on his own initiative and the reminders of others who have been told of the specific episodes. His good recall of episodes prior to the age of 17 may in part be a consequence of his frequent rehearsal of these childhood memories with his parents and other relatives when they were alive.

The most parsimonious explanation for H.M.'s 11 years of somewhat patchy retrograde amnesia may be that his encoding and storage of new information was impoverished, but not totally absent, as a result of the ongoing seizure activity he suffered during that period and high doses of anticonvulsant medication. In support of this view, his first grand mal seizure occurred on his sixteenth birthday. The weak memory traces laid down in the 11-year period prior to H.M.'s operation may have faded if H.M. was not frequently reminded of them, and are therefore less likely to be recalled or recognized. Thus, world facts from the 1940s and 1950s that are still commonly used will be better recalled than personal episodes from that time period.

H.M. is 63 in 1989, and the effects of age on his general health and on his cognitive functioning, mean that he may soon be retired from his work as a research subject. For more than 30 years he has put enormous amounts of effort and time into memory research, and the fact that he has no conscious memory of this work does not in any way detract from the debt we owe him. For all our "explicit" knowledge about memory processes, H.M. can still keep some of us on our toes. As the following episodic memory[1] of one of us illustrates, H.M. always has the last word.

At 9.30am on 14 February 1986, JAO went to collect H.M. from his room at the MIT Clinical Research Center. He was eating a large chocolate heart that had been given to him by the staff to celebrate St. Valentine's Day. He finished the heart, crinkled up the red, shiny paper it had been wrapped in, and put it in his shirt pocket. He then came with me to the testing room, and for the next 2 hours we concentrated on mentally rotating letters, and other tasks. About 11.30 am, H.M. put his hand into his shirt pocket to get out his handkerchief, and pulled out the red, shiny paper at the same time. He held it at arms length, and looked at it quizzically, so I asked him why he had the paper in his pocket. "Well," replied H.M., "It could have been wrapped around a big chocolate heart. It must be Valentine's Day!" I tried to contain my excitement over this evidence of recall of a personal episode that had occurred 2 hours earlier, and told H.M. to replace the red paper in his pocket. I then took him to the lunch room and went to tell my story to John Gabrieli, an experienced tester of H.M. John said with certitude that H.M., being a true American, had been eating large chocolate hearts wrapped in red shiny paper every Valentine's Day since he was a year old. This episode was just a well-learned old association, and certainly not evidence of new learning. I insisted that this was not so and took John to the lunch room, where I asked H.M. to look in his shirt pocket. He pulled out the red, shiny paper, held it at arms length, and looked at it quizzically. I asked him why he had the paper in his pocket, and he replied, "Well, it might have been wrapped around a big chocolate rabbit. It must be Easter!"

ACKNOWLEDGMENTS

We thank Dr. Brenda Milner for permission to examine H.M. on numerous occasions, and the many neuroscientists whose research findings on H.M. have been reviewed here. In particular, we thank the staff of the MIT Clinical Research Center who care for H.M. on his visits there, and who have provided the facilities and necessary environment for most of these studies. JAO was partially su[pported] by a N.Z. Medical Research Council Overseas Research Fellowship wh[ile] at MIT, and much of the research reviewed here was supported by USPHS gra[nts] MH24433, MH32724, MH06410, MH08280, NS19698, and RR00088.

[1]This H.M. story was first told by JAO during the presentation of a paper entitled "HM at age 60 years: A neuropsychological profile" in a symposium on memory organized and chaired by Professor Graham Goddard at the annual conference of the New Zealand Psychological Society in Dunedin, N.Z., August, 1986. Graham was very amused by this story and asked if he could use it in a paper he was planning to write. Because of his tragic death five months later, that paper was never written, and we record it here in his memory.

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