H.M. Revisits the Tower of Hanoi Puzzle

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To address the controversy of whether an intact procedural memory system alone can support the learning of the recursive strategy for solving the Tower of Hanoi Puzzle, the authors tested 2 amnesic patients, H.M. and P.N. Contrary to the report of N. J. Cohen, H. Eichenbaum, B. S. Deacedo, and S. Corkin (1985), both patients failed to master the recursive strategy under the active-interaction condition. In contrast, normal control participants were able to master the strategy under identical testing conditions. The failure of H.M. and P.N. could not be attributed to the differences between the original and current testing conditions. In addition, neither patient showed frontal lobe dysfunction or impairment in procedural memory. Together with evidence provided by theoretical analyses of this puzzle as well as studies on normal participants, the authors conclude that declarative memory plays a vital role in the acquisition of the recursive strategy for solving the Tower of Hanoi Puzzle.

It is well established in the field of cognitive neuroscience that there are two functionally and anatomically separable long-term memory systems in humans (e.g., Corkin, 1984; Squire, 1992; Schacter & Tulving, 1994). Declarative or explicit memory refers to the conscious recollection of facts and events, that is, learning with awareness (e.g., Graf & Schacter, 1985; Squire, 1986). In contrast, nondeclarative or implicit memory refers to the influence of previous experience on task performance without conscious referral to stored information, that is, learning without awareness. Evidence supporting the declarative–nondeclarative memory distinction comes from studies of patients, normal participants, and experimental animals. For example, many studies have found that amnesic patients are able to acquire new skills, such as mirror tracing, rotary pursuit, and mirror-reversed text reading, despite their inability to recall the experience of doing so (e.g., Brooks & Baddeley, 1976; Cermak, Lewis, Butters, & Goodglass, 1973; Cohen, 1981; Cohen & Squire, 1980; Corkin, 1968; Gabrieli, Keane, & Corkin, 1987; Martone, Butters, Payne, Becker, & Sax, 1984; Milner, 1962; Weiskrantz & Warrington, 1979). In contrast, patients with Parkinson’s disease (PD) or Huntington’s disease (HD) show the reverse dissociation, with their ability to learn rule-based tasks impaired and their semantic and episodic memory preserved (e.g., Brandt & Butters, 1986; Heindel, Salmon, Shults, Walicke, & Butters, 1989; Heindel, Salmon, & Butters, 1991). The declarative memory system is supported by medial temporal lobe and diencephalic structures, whereas the nondeclarative memory system is supported by the striatum, neocortex, cerebellum, or reflex pathways, depending on the nature of the procedural learning (Gabrieli, 1998; Keane, Gabrieli, Mapstone, Johnson, & Corkin, 1995; Squire & Knowlton, 1995; Verfaellie & Keane, 1997).

In an attempt to explore the range of tasks that could be supported by the nondeclarative memory system alone, research in the last two decades has documented amnesic patients’ ability to acquire information that was not exclusively perceptual or motor. In one study, amnesic patients were able to learn a specific sequence of keypresses without being able to generate consciously the sequence in subsequent tests and without awareness that a sequence had been presented (Nissen & Buller, 1987; Willingham, Nissen, & Buller, 1989). On another task, the Sugar Production Task (Berry & Broadbent, 1988), amnesic patients were able to learn to control the level of an output variable by manipulating an input variable that related to the output variable (by a simple formula) without ever being aware of these variables (Squire & Graf, 1990). Similar learning abilities were also observed in other abstract cognitive tasks such as probabilistic classification (Knowlton, Squire, & Gluck, 1994) and artificial grammar learning (Knowlton, Ramus, & Squire, 1992; Knowlton & Squire, 1994). Despite amnesic patients’ learning ability for these complex and abstract tasks, there remains a controversy as to whether such participants could also master the recursive strategy for solving the Tower of Hanoi Puzzle (Tower puzzle) without the support of an intact declarative memory system.

The Tower puzzle consists of three vertical pegs and a few blocks in increasing size (Figure 1). In the initial configuration, all of the blocks are on the leftmost peg with the largest block on the bottom and the smallest one on the top. The goal of the puzzle is to move all the blocks from the leftmost peg to the rightmost peg, so that all the blocks are
on the rightmost peg in the same order as they were on the leftmost peg in the initial configuration. To solve the puzzle, participants can move only one block at a time, and they can never place a larger block on top of a smaller one.

The Tower puzzle belongs to a class of problems called transformation problems, which entail reaching a goal state through the execution of a series of moves. This puzzle is particularly interesting because participants seem to be able to develop some idea of good solution strategies with minimal experience (Karat, 1982); yet, if the puzzle consists of more than three blocks, participants do not generally solve the task in the minimum number of moves during the first few trials. As participants become more experienced with the puzzle, they begin to adopt more efficient strategies. The most effective strategy, the subgoal recursive strategy, consists of solving a series of subproblems of the same kind (Simon, 1975). That is, the solution to the 5-block version of the puzzle requires solving two 4-block problems, each of which in turn, requires solving two 3-block problems, and each of which requires solving two 2-block problems (Cohen & Eichenbaum, 1993). In other words, as Cohen and Eichenbaum (1993) put it,

Given (1) the rules of the task, (2) the overall goal of rebuilding the five-disc tower onto the rightmost peg, and (3) the recursive subgoal strategy of building smaller “sub-towers” on the way to building the full five-disc tower, subjects can engage their problem-solving abilities to compute the best next move on a move-by-move basis, without having to remember particular puzzle configurations or moves, and without having to remember the previous moves that led to the current configuration of the puzzle. (p. 200)

Although the application of the recursive strategy could be carried out without the necessary engagement of the declarative memory system, it is unclear whether the initial learning of this recursive strategy could also be achieved without any contribution from the declarative memory system. In other words, could amnesic patients master the recursive strategy for solving the Tower puzzle?

Cohen and colleagues (Cohen, 1981; Cohen, Eichenbaum, Deacedo, & Corkin, 1985) studied the learning of the Tower puzzle in H.M. and other amnesic patients as well as in normal control participants (NCPs). While participants were working on the puzzle, the experimenter (Cohen) systematically probed the participants with questions. After several days of testing, all the amnesic participants, including H.M., were reported to be able to learn the recursive strategy and to solve the puzzle consistently in the near minimum number of moves, like the NCPs. In particular, H.M. learned the recursive strategy to solve the puzzle across eight testing sessions, and the number of moves he used decreased from session to session. The mean number of moves he needed to finish a trial in the first testing session was 53 (the minimum being 31); by the last testing session, he needed only 32 moves on average.

When H.M. was retested by a different experimenter in 1987, with minimal experimenter–participant interaction (Gabrieli et al., 1987), he failed to learn the strategy and did not show a systematic reduction in the number of moves needed to solve the puzzle. His performance varied tremendously: Sometimes he finished a trial in 32 moves, and other times he required as many as 625 moves. Gabrieli et al. (1987) and Cohen and Eichenbaum (1993) attributed this inconsistency in the results to the absence of frequent experimenter–participant interactions in the second study. According to Cohen and Eichenbaum (1993), the purpose of the probe questions posed by the experimenter was to encourage NCPs and amnesic participants to adopt the recursive strategy to solve the puzzle. When there was not this control over the use of strategies, NCPs might have used declarative remembering in guiding their performance, and, therefore, the performance of NCPs and amnesic patients differed.

Two other studies also tested amnesic patients’ ability to solve the Tower puzzle. Saint-Cyr, Taylor, and Lang (1988) found normal learning and improvement in amnesic patients with the four-block version of the puzzle. In contrast, the amnesic patients studied by Butters, Wolfe, Martone, Granholm, and Cernak (1985) failed to improve compared to NCPs with the five-block version of the puzzle (however, see Cohen & Eichenbaum, 1993, for possible accounts of this negative result).

The purpose of the present study was, therefore, to test systematically Cohen and Eichenbaum’s (1993) hypothesis that active experimenter–participant interaction plays a key role in amnesic patients’ acquisition of the recursive strategy for solving the Tower puzzle. Xu tested H.M. twice, first with passive experimenter–participant interaction as Gabrieli et al. (1987) had done and then with active interaction as Cohen (1981) and Cohen et al. (1985) had done. H.M. was then tested by Cohen once more under the active-interaction condition, in an effort to replicate the original 1981 study as much as possible. Another amnesic patient,
P.N., was also tested by Xu under the active-interaction condition to clarify several additional issues. It is possible for amnesic patients to acquire some nonrecursive strategies and to improve in solving the Tower of Hanoi puzzle especially when the puzzle has fewer blocks. Only the acquisition of the recursive strategy, however, will enable a participant to consistently solve the puzzle in the minimum number of moves regardless of the number of blocks the puzzle may have.

Experiment 1

The goal of Experiment 1 was to replicate H.M.’s performance in solving the Tower puzzle as obtained by Gabrieli et al. (1987) and by Cohen et al. (1985) with the method used in each experiment. H.M. performed the Tower puzzle twice, once with passive experimenter-participant interaction and, 4 months later, with active experimenter-participant interaction. Three NCPs were also tested under the active-interaction condition.

Method

Participants

Amnesic patient H.M. H.M., who had 12 years of education, was 69 years old at the time of this study. H.M. had a profound and pervasive amnesia due to bilateral resection of medial temporal lobe structures in 1953 for the relief of chronic epilepsy. The resection eliminated the medial temporal polar cortex, virtually the entire amygdaloid complex, all of the entorhinal cortex, and at least half of the intraventricular portion of the hippocampal formation (for a more detailed account of H.M.’s case history and a detailed description of his lesion based on magnetic resonance imaging [MRI], see Corkin, 1984; Corkin, Amaral, Gonzalez, Johnson, & Hyman, 1997). Some relevant standardized test results for H.M. are shown in Table 1. In everyday life, H.M. does crossword puzzles and other word puzzles regularly.

NCPs. Two men and 1 woman also participated in the study. Their mean age was 68.0 years (SD = 1.0), and mean years of education was 12.0 (SD = 0). All NCPs had some experience doing puzzles.

Experimenter

The experimenter was Yaoda Xu.

Materials and Design

A five-block computerized version of the puzzle was used (see Figure 1). All the blocks were blue and were lettered from A to E. The blocks could be moved either with the mouse or with specific keys on the keyboard.

Procedure

Passive test. H.M. was tested on 4 consecutive days, with four trials per day. The four trials were administered within a 2-hr testing period, with a break after the second trial. H.M. received the instructions orally from the experimenter and in written form on a card placed in front of the computer monitor. The card had the goal (move all the blocks on the leftmost peg to the rightmost peg using as few moves as possible) and the rules of the task (only one block may be moved at a time and a larger block may never be placed on top of a smaller one) written on it. The instruction card remained visible to H.M. throughout the experiment. On each testing day, H.M. practiced on a three-block version of the puzzle once before starting on the five-block experimental trials. During the experiment, H.M. verbalized his intended moves, and the blocks were moved by the experimenter. Minimal experimenter-participant interaction occurred.

Although the three-block practice trial was not used in the original testing by Cohen (1981), Cohen et al. (1985), and Gabrieli et al. (1987), pilot testing on NCPs showed that the instructions and rules were much easier to follow if participants had practiced beforehand on the three-block puzzle. Moreover, Saint-Cyr et al. (1988), who observed normal performance by their amnesic participants in solving this puzzle, included the three-block practice trial in their testing as well. We included the three-block practice trial in all of the experiments reported in this article.

Active test. Four months later, H.M. was tested again using this procedure. All of the NCPs were tested in this condition as well. The procedure was identical to that of the passive test, except that when the participants were working on the puzzle, they were probed with questions to encourage them to adopt the recursive strategy for solving the puzzle as Cohen et al. (1985) had done. The probing procedure was carried out as follows (Cohen, 1981):

<table>
<thead>
<tr>
<th>Table 1</th>
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<tbody>
<tr>
<td>Participant Characteristics and Standardized Behavioral Test Results</td>
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<tr>
<td>---------------------------------</td>
</tr>
<tr>
<td>Variable</td>
</tr>
<tr>
<td>---------------------------------</td>
</tr>
<tr>
<td>Handedness</td>
</tr>
<tr>
<td>Age at testing</td>
</tr>
<tr>
<td>Year of testing</td>
</tr>
<tr>
<td>Age at onset of amnesia</td>
</tr>
<tr>
<td>Years of education</td>
</tr>
<tr>
<td>WAIS-R: Full Scale IQ</td>
</tr>
<tr>
<td>WAIS-R: Verbal IQ</td>
</tr>
<tr>
<td>WAIS-R: Performance IQ</td>
</tr>
<tr>
<td>WMS-R: General Memory</td>
</tr>
<tr>
<td>WMS-R: Verbal Memory</td>
</tr>
<tr>
<td>WMS-R: Visual Memory</td>
</tr>
<tr>
<td>WMS-R: Attention-Concentration</td>
</tr>
<tr>
<td>WMS-R: Delayed Recall</td>
</tr>
</tbody>
</table>

Note. H.M. and P.N. refer to patients’ initials. WAIS-R = Wechsler Adult Intelligence Scale—Revised (Wechsler, 1981); WMS-R = Wechsler Memory Scale—Revised (Wechsler, 1987).

(1) Whenever subjects paused for a time before making a move, they were asked, “What are you trying to do now?”; (2) whenever subjects responded to the first question by stating that they were trying to get a particular block or group of blocks onto a particular peg, they were asked, “How are you going to accomplish that?”; (3) whenever the subjects’ stated goal was complicated by the presence of blocks that prevented them from implementing the desired move directly, they were asked, “Where will they [the obstructing blocks] have to go?”; (4) after each successful solution, and at the start of each new session, subjects were asked one or more questions of the form “How did you solve the problem?” or “What rules or strategies did you use in solving the problem?” or “What sort of order did you impose on this task to tell you where to move a particular block?” (p. 125)
Results

Passive Tests

H.M. failed to improve in solving the Tower puzzle either within or across the 4 testing days, \( F(3, 9) = 0.93, p = .46 \), and \( F(3, 9) = 0.59, p = .64 \), respectively (see Figure 2). He never solved the puzzle consistently with a near minimum number of moves (31 moves), even on the last day of testing. The average number of moves on each testing day was greater than twice the minimum number of moves required to solve the puzzle. This result replicated the findings of Gabrieli et al. (1987). During testing, H.M. always tried to build a tower with the three smallest blocks whenever he could, even when doing so reversed his progress in solving the puzzle.

Active Tests

Amnesic patient H.M. Under active experimenter–participant interaction, H.M. failed again to improve in solving the puzzle either within or across the 4 days of testing (see Figure 3), \( F(3, 6) = 1.04, p = .42 \), and \( F(3, 9) = 0.30, p = .83 \), respectively. Close inspection of the data, however, indicated that on Days 2, 3, and 4, he always began with a high number of moves, and then on subsequent trials the number of moves decreased. An analysis of variance (ANOVA) for Days 2, 3, and 4 showed a significant difference across trials, \( F(3, 6) = 10.14, p = .009 \), but not across days, \( F(2, 6) = 1.55, p = .29 \). On Day 4, H.M. did not succeed in solving the puzzle consistently in the near minimum number of moves, contrary to his performance in the original testing. Overall, the number of moves H.M. took to complete the puzzle ranged between 38 and 165, unlike his original performance in 1981 in which the number of moves ranged only between 31 and 53. We, therefore, failed to replicate Cohen’s (1981) original finding.

NCPs. Under the active experimenter–participant interaction condition, all NCPs were able to improve substantially in solving the Tower puzzle (see Figure 3) and were able to consistently solve the puzzle with a near minimum number of moves on Day 4 of testing. NCPs improved significantly across days and across the four trials within each day, \( F(3, 6) = 5.87, p = .032 \), and \( F(3, 6) = 5.56, p = .036 \), respectively. The interaction between the improvement across and within days was not significant, \( F(9, 18) = 1.54, p = .21 \).

Discussion

Contrary to Cohen and Eichenbaum’s (1993) hypothesis, we found that H.M.’s performance on the Tower puzzle failed to improve across days under passive and under active experimenter–participant interaction conditions. In contrast, under the active interaction condition, all three NCPs were able to improve consistently within as well as across the testing days and to master the recursive strategy for solving the Tower puzzle by Day 4. Although H.M. did show improvement under the active testing condition on Days 2, 3, and 4, the learning was not carried across days. Before any conclusions can be drawn, however, we need to consider several differences between our study and that of Cohen et al. (1985).

First, the active experimenter–participant interaction might have depended on the skill, style, and personality of the experimenter. Thus, Xu may not have been able to guide H.M. to adopt the recursive strategy as effectively as Cohen did. Second, in the original study, H.M. was given a wooden version of the puzzle, and he was able to move the blocks freely with his own hands. With the computerized version of the puzzle used in the current studies, H.M. might have been limited in his interactions with the puzzle, which possibly restricted his procedural learning.

Third, H.M.’s poor performance may be evidence of cerebellar dysfunction related to the marked and diffuse atrophy of the cerebellar vermis and hemispheres (Corkin et al., 1997). He manifested cerebellar signs due to phenytoin toxicity as far back as 1962 and discontinued this medication in 1984. Thus, cerebellar atrophy was likely present when Cohen first tested H.M. in 1981. It is possible, however, that this preexisting cerebellar degeneration left him...
with a smaller margin of safety to withstand the consequences of age-related cell loss and degeneration in cerebellar Purkinje’s cells (Ellis, 1920; Hall, Miller, & Corsellis, 1975; Scheibel, 1996). Because the cerebellum is extensively connected with association areas of the frontal and parietal cortex, researchers have found cognitive deficits extending beyond impaired motor control in patients with cerebellar pathology (e.g., Botez, Gravel, Attig, & Vezina, 1985; Bracke-Tolkmitt et al., 1989; Fehrenbach, Wallesch, & Claus, 1984; Fiez, Petersen, Cheney, & Raichle, 1992; Leiner, Leiner, & Dow, 1986; Sasaki, 1979; Schmahmann & Sherman, 1998; Wallesch & Horn, 1990). In particular, Grafman, Litvan, Massaquoi, and Stewart (1992) found that participants with cerebellar lesions “solved significantly fewer Tower of Hanoi problems than normal controls” (p. 1495). In a single case study with a patient who had an extensive right-sided cerebellar infarct, Fiez et al. (1992) found that the patient used significantly more moves to solve the Tower of Toronto puzzle (the four-block version of the Tower puzzle) compared to NCPs. A recent study by Daum, Ackermann, Schugens, and Reimold (1993), however, argued that patients with damage to the cerebellum alone did not actually use more moves to solve the Tower puzzle than did NCPs. Thus, the evidence linking cerebellar abnormality to impaired performance in solving the Tower puzzle is not particularly strong. Moreover, in all these studies, patients varied in the locus and extent of the cerebellar lesion, and most patients had more severe damage than H.M. Most important of all, none of these studies used active experimenter–participant interactions in administering the Tower puzzle. Instead, participants solved the puzzle using any strategy they wished. These studies did not address the issue that was relevant to the present studies, which was whether patients with cerebellar lesions could successfully acquire the recursive strategy for solving the Tower puzzle under active experimenter–participant interactions. Thus, previous studies do not support the view that H.M.’s failure was due to his cerebellar atrophy.

Experiment 2

To address the first two possible accounts of our failure to replicate the results of Cohen et al. (1985) in Experiment 1, Cohen tested H.M. again with the wooden version of the puzzle. To determine whether H.M.’s poor performance on the Tower puzzle was due to his amnesia or to his cerebellar degeneration, we tested another amnesic patient, P.N., who had neither clinical nor radiological signs of cerebellar degeneration. P.N. was tested by Xu under the active experimenter–participant interaction condition.

Method

Participants

Amnesic patient H.M. and amnesic patient P.N. were the participants in Experiment 2. P.N. was a 62-year-old woman who had 16 years of education. She was diagnosed with herpes simplex encephalitis and a seizure disorder in 1992. In 1994, she experienced a hypoxic episode. Since then, she has had a profound anterograde amnesia. Some relevant standardized test results for P.N. are shown in Table 1.

Experimenters

The experimenters in Experiment 2 were N. J. Cohen and Yaoda Xu.

Materials

A wooden version of the Tower of Hanoi puzzle was used. The blocks were numbered from 1 to 5.

Design and Procedure

The design and procedure were similar to those used in Experiment 1 but with two differences. The first difference is that a stopwatch was used, and whenever the participants paused for more than 10 s between moves, questions were posed. This timing procedure had been used in the 1981 testing but was omitted from the original report (Cohen, 1981). The second difference is that participants were instructed to move the blocks with their own hands. The testing sessions were video recorded. H.M. was tested by Cohen, as in the original study. P.N. was tested by Xu because Cohen was not available.

Results

Amnesic Patient H.M.

Under testing conditions that replicated those in the original study, H.M. again failed to improve in solving the Tower puzzle (see Figure 4), F(3, 9) = 1.00, p = .44, within days, and F(3, 9) = 0.73, p = .56, across days. As in the previous two testings by Xu, H.M. was never able to consistently solve the puzzle with a near minimum number of moves, even on the last day of testing. In many places, the probe questions posed by the experimenter forced H.M. to have a clear subgoal. H.M., however, quickly lost track of his moves and returned to his original moving style as observed in Experiment 1 (i.e., he always tried to build a tower with the three smallest blocks whenever he could.

![Figure 4](image_url). The performance of the amnesic patient H.M. in Experiment 2 when tested by the original experimenter, N. J. Cohen, under active experimenter–participant interaction.
even when doing so reversed his progress in solving the puzzle). Unlike his 1981 performance, as Cohen commented, H.M. was much faster in his moves, and when he got stuck, he usually paused for less than 10 s. Therefore, Cohen was able to probe him only a few times during testing.

**Amnesic Patient P.N.**

P.N.’s performance on Days 1 and 2 was good in that she solved the puzzle with a near minimum number of moves on Trials 2–7, 10, and 13 (see Figure 5). From Trial 8 on, however, her performance became more variable and resembled that of H.M. Overall, P.N. did not consistently solve the puzzle either within or across the 5 testing days, $F(3, 12) = 0.25$, $p = .86$, and $F(4, 12) = 0.24$, $p = .91$, respectively. We concluded, therefore, that patient P.N. did not acquire the recursive strategy for solving the Tower puzzle.

**Discussion**

H.M.’s poor performance when tested by Cohen, the original experimenter, showed that his failure to master the recursive strategy for solving the Tower puzzle could not be attributed to differences between experimenters or between puzzle versions. The lack of improvement in solving the Tower puzzle that was observed in another amnesic patient with an intact cerebellum under identical testing conditions further demonstrated that H.M.’s failure was likely related to his amnesic syndrome and not to his cerebellar abnormality.

**General Discussion**

In the present study, we tried to resolve the controversy surrounding H.M.’s ability or inability to learn the recursive strategy for solving the Tower puzzle. Whereas all three NCPs tested were able to master the recursive strategy for solving the puzzle with active experimenter–participant interactions, H.M. was not. Thus, we failed to replicate previous results obtained by Cohen et al. (1985) and found that H.M. was unable to learn to solve the puzzle recursively with either passive or active experimenter–participant interactions. This result was obtained regardless of whether the experimenter was the same as in the original study or different and regardless of whether the puzzle was administered in the computerized version or the wooden version. Moreover, another severely amnesic participant, P.N., also failed to master the recursive strategy for solving the puzzle under the condition of active experimenter–participant interaction, which suggests that H.M.’s failure was unlikely to be the result of his cerebellar degeneration.

Goel and Graffman (1995) showed that participants with frontal lobe lesions had poorer performance than NCPs, and they attributed this difference to the frontal lobe participants’ inability to inhibit inappropriate spontaneous responses in favor of alternative appropriate responses (see also Daum et al., 1995; Morris, Mirotto, Feigenbaum, Bullock, & Polkey, 1997). That explanation does not apply to H.M. and P.N., however, because both patients performed normally in the Wisconsin Card Sorting Test (see Table 2), a test sensitive to frontal lobe dysfunction (Milner, 1963). MRI scans also revealed a normal appearance of H.M.’s and P.N.’s frontal lobes (Corkin et al., 1997; Hood, Postle, & Corkin, 1999). Moreover, in Goel and Graffman’s (1995) study, participants did not receive the kind of active experimenter–participant interactions that were used in our studies. The active testing condition that we used favored the suppression of inappropriate responses and facilitated the use of the appropriate ones in the acquisition of the recursive strategy in our participants. In short, frontal lobe abnormality is unlikely to have been the cause of H.M.’s and P.N.’s failure to master the recursive strategy.

Damage to the basal ganglia has been shown to disrupt procedure learning. Saint-Cyr et al. (1988) observed that early-stage PD patients and advanced HD patients were severely impaired in learning to solve the Tower puzzle. Daum et al. (1995) observed similar deficits in advanced PD patients. We think it is unlikely, however, that H.M.’s procedural memory has declined since 1981. In a recent MRI study (Corkin et al., 1997), H.M.’s basal ganglia appeared to be normal. Further, he showed normal procedural learning in performing the mirror tracing test in 1986 (Gabrieli, Corkin, Mickel, & Growdon, 1993), as well as in a recent testing in 1995 (see Table 3). In another series of tests conducted between 1995 and 1996, H.M. showed normal word-stem completion priming and perceptual identification priming with words he acquired before the onset of his amnesia (Postle & Corkin, 1998), further indicating that his nondeclarative memory was intact. Similarly, P.N. appeared to have normal basal ganglia as revealed by MRI, and she acquired and retained the mirror tracing skill as well as NCPs, even though she had poor recall of the test on the 2nd day of testing. In summary, no impairment in procedure memory was found in either patient, and thus their failure to acquire the recursive strategy for solving the Tower puzzle cannot be attributed to dysfunction of the procedure memory system.

Saint-Cyr et al. (1988), using the four-block version of the Tower puzzle and passive experimenter–participant in-
Table 2

Wisconsin Card Sorting Test Results

<table>
<thead>
<tr>
<th>Test result</th>
<th>H.M.</th>
<th>P.N.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year of testing</td>
<td>1996</td>
<td>1996</td>
</tr>
<tr>
<td>Total number of errors</td>
<td>36</td>
<td>31</td>
</tr>
<tr>
<td>Number of preservative errors</td>
<td>14</td>
<td>20</td>
</tr>
<tr>
<td>Number of nonpreservative errors</td>
<td>21</td>
<td>11</td>
</tr>
<tr>
<td>Unique errors</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Number of categories completed</td>
<td>5</td>
<td>6</td>
</tr>
</tbody>
</table>

Note. H.M. and P.N. refer to patients’ initials.

Methodological Weaknesses

Controlling the Amount of Interaction

We noticed that H.M. was much faster between moves in our recent study than he was in the original study in 1981, and one could argue that his interaction with the original experimenter in the current study may not have been sufficient to generate any sustainable learning. It is unclear, however, exactly how many times, how often, and to what extent each participant must be guided before he or she can master the recursive strategy. Participants differ in how long they pause when they are stuck, and they may proceed at different speeds on different days. If the probe questions are posed whenever a participant pauses for more than 10 s, then it is inevitable that the amount of interaction will depend on each participant’s moving speed, with the slower participants getting more guidance from the experimenter. As a result, the procedure itself does not guarantee the learning of the recursive strategy for solving the Tower puzzle by each participant or even by the same participant on different occasions. Our failure to replicate the original result is therefore not surprising.

One could argue that the procedure could be modified to avoid the aforementioned uncertainty by posing the probe questions only after a specific number of moves. For example, all participants would be probed after every five moves. This procedure, however, would be very distracting for the participants, because on many occasions participants would be forced to stop in the middle of a sequence of moves that they had planned in order to answer the probe questions.

The procedure could also be modified so that the experimenter takes into account the participant’s moving speed and probes him or her accordingly. In other words, the experimenter would probe only when the participant pauses relative to his or her own moving speed. This modification, however, would rely entirely on the experimenter’s own judgment as to when to pose questions. It would therefore be impossible to quantify the interaction between different experimenters and different participants. Even the same experimenter may interact differently with different participants or differently with the same participant on different days. Moreover, the experimenter may unconsciously probe the participant more often when the participant is doing something wrong, in which case probing the participant

Table 3

Patient H.M.’s 1995 Mirror Tracing Results

<table>
<thead>
<tr>
<th>Variable</th>
<th>Day 1</th>
<th>Day 2</th>
<th>Day 3</th>
<th>ANOVA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Completion time (s)(^a)</td>
<td>149 (16)</td>
<td>137 (10)</td>
<td>101 (8)</td>
<td>F(2, 33) = 4.59, p = .017</td>
</tr>
<tr>
<td>Number of contacts(^b)</td>
<td>22 (7)</td>
<td>13 (3)</td>
<td>7 (2)</td>
<td>F(2, 33) = 5.16, p = .011</td>
</tr>
<tr>
<td>Time off pattern (s)(^c)</td>
<td>17 (5)</td>
<td>8 (1)</td>
<td>3 (1)</td>
<td>F(2, 33) = 6.00, p = .006</td>
</tr>
</tbody>
</table>


\(^a\) For completion time, H.M. used significantly less time on each day of testing than he did in 1986, presumably because of some retention of the mirror tracing skills he acquired in 1986. 
\(^b\) For the number of contacts, performance on Day 1 was much better than that of the 1986 testing. Performances on Day 2 and Day 3 were comparable with those of 1986. 
\(^c\) For the time off pattern, performance was almost identical to that of 1986.
does not differ much from cuing the participant. In summary, there does not seem to be a way of efficiently carrying out the active experiencer-participant interaction without any drawbacks. As a result, an exact replication of an earlier testing can never be achieved. When a procedure and a result are not easily replicable, even with the same experimenter and participant, their validity and generality should be questioned.

Guiding Versus Cuing

Although the failure in learning the recursive strategy for solving the Tower puzzle could always be attributed to the lack of enough interaction with or guidance from the experimenter, it can be argued that successful learning may have been the result of cuing (too much interaction). The boundary between guiding and cuing is blurry. For example, during testing, when the participant incorrectly answered the questions, he or she would be asked again until the correct answer was provided. In many cases, the correct answer to the question led directly to the correct next move. It is therefore unclear in the 1981 testing whether participants were encouraged to adopt the recursive strategy, as Cohen and Eichenbaum (1993) put it, or whether they were actually given the recursive strategy to solve the puzzle.

Perceptual Strategy

Close examination of the active experiencer-participant interaction procedure revealed that the way probe questions were formed and posed could have led to the acquisition of a less efficient strategy called the perceptual strategy (Simon, 1975). Compare the probe questions used in our study with the following description of the simple perceptual strategy (Simon, 1975):

To rebuild the pyramid on Peg C, the largest disk must be placed on C first, then the next largest, and so on. But a disk can only be moved when two conditions are satisfied: (a) there are no small disks on its peg (the source peg), and (b) there are no smaller disks on the target peg. Therefore, the move of a particular disk, say k, to a target peg, say X, can be accomplished by: (a) moving any movable disk smaller than k off the source peg; (b) repeating step (a) until there are no disks smaller than k on the source peg; (c) moving any disk smaller than k off the target peg; (d) repeating (c) until all the disks smaller than k are off the target peg; (e) moving disk k to the target peg. (p. 271)

Also compare the probe questions used in our study with the following more sophisticated version of the perceptual strategy (Simon, 1975):

(a) Identifying, as previously, the largest disk—call it k—that is not yet on the target peg; (b) by examining both the source peg and the target peg of k, identifying the largest disk that is obstructing its move to the target peg; (c) if there is no obstructor, making the indicated move; (d) if there is such a largest obstructor, establishing the goal of moving the obstructor to the other peg (neither source nor target of k), then recursing, for the obstructor, through steps (b) and (c). (p. 272)

It is easy to see the striking similarity between the probe questions used in our study and the procedures for carrying out the perceptual strategy. In fact, given our set of probe questions, it is not clear why participants should acquire the recursive strategy but not the perceptual strategy. The perceptual strategy is not the most efficient strategy because there is no guarantee that clearing the target peg will not again obstruct the previously cleared source peg (Simon, 1975). Because the perceptual strategy determines the next move by perceiving features of the actual current problem situation rather than the goal state as in the recursive strategy, the perceptual strategy in the simple form and in the more sophisticated form could produce nonterminating cycles of moves. Thus, H.M.'s and P.N.'s failure to master the recursive strategy in solving the Tower puzzle could also be due to the fact that they actually acquired the perceptual strategy. Indeed, the repeated cycles of moves produced by H.M. and P.N. during their performance were consistent with the application of the perceptual strategy.

Alternatively, this account may suggest that the nonrecursive strategy for solving the Tower puzzle is acquired by the procedural memory system. The more blocks a Tower puzzle has, the less likely that application of the perceptual strategy would yield a minimum number of moves to solve the puzzle. Thus, H.M., perhaps using the perceptual strategy, was able to solve the three-block or sometimes the four-block (unpublished observations, Gabrieli et al., 1987) but never the five-block version of the Tower puzzle with a minimum number of moves. This explanation may also account for the findings by Saint-Cyr et al. (1988) that amnesic patients and control participants improved in solving the four-block Tower puzzle but that early-stage PD patients and advanced HD patients failed to do so.

Theoretical Weakness:
The Role of Declarative Memory

If none of the aforementioned methodological weaknesses existed, could H.M. and P.N. have learned the recursive strategy in solving the Tower puzzle? The application of the recursive strategy enables one to solve the Tower puzzle in the minimum number of moves without having to remember each previous move declaratively. It does not logically follow, however, that learning of the recursive strategy could also be achieved without a declarative memory system. Exactly how normal participants acquire this recursive strategy is still a topic of current research (Anderson, 1989; Anzai & Simon, 1979; Karat, 1982; Kotovsky, Hayes, & Simon, 1985; Langley, 1985; Simon, 1975; Sweller, 1983; VanLehn, 1991; Welsh, Cicerello, Cuneo, & Brennan, 1995; Zhang & Norman, 1994).

Anzai and Simon (1979) analyzed in detail the learning of the Tower puzzle by one normal participant. They observed at least four kinds of processes during each episode of the learning: (a) applying the current strategy; (b) gathering information that would be used later to modify the strategy; (c) using information gathered in previous episodes; and (d) deciding to terminate the solution attempt. They noticed that information stored in
long-term memory in the previous trial appeared to be crucial and to provide the basic cues for strategy transformation. Moreover, the acquisition of essential subgoals was not at all trivial for the participant. In particular, the participant had to remember declaratively not to repeat her moves, which required conscious remembering of the most recent moves and the next-to-most-recent moves. VanLehn (1991) analyzed the performance of the same participant and made the additional observation that the participant appeared to have declaratively rejected old strategies to force the development of new ones.

Karat (1982) developed a model of problem solving with incomplete constraint knowledge to explain the learning observed in solving the Tower puzzle. The model discriminated between problem-solving behavior based on constraint knowledge and behavior based on nonspecific general search strategies. Karat (1982) proposed that the following four items must be remembered by the participant to solve the puzzle successfully: (a) the name of the last disk moved; (b) the name of the current subgoal disk; (c) a representation of the goal state; and (d) a list of moves currently under consideration. This information would be retained in working memory and long-term memory.

The studies described previously suggest that declarative memory plays a vital role in the acquisition of the recursive strategy for solving the Tower puzzle. NCPs can use declarative memory to remember the configurations that they have visited before and thus know to repeat certain sets of moves but not others. Without declarative memory and the ability to choose the correct set of moves, however, amnesic participants would either repeat a previous set of moves and get stuck or choose the correct next move by luck. In other words, even if none of the methodological weaknesses existed in the present paradigm, H.M. and P.N. would still be at a great disadvantage in acquiring the recursive strategy for solving the Tower puzzle compared to NCPs.

It is, however, possible that there are ways of acquiring the recursive strategy for solving the Tower puzzle without the use of declarative memory and that these strategies simply did not emerge from the analyses provided earlier. It is also possible that H.M. hit on one of these strategies that ultimately led to his success in 1981. It remains to be seen, however, whether any evidence can be collected to support this argument. In any case, the claim that learning the recursive strategy for solving the Tower puzzle can be achieved without the support of the declarative memory system is questionable.

To summarize, we found that two amnesic patients were unable to acquire the recursive strategy for solving the Tower of Hanoi Puzzle under the active experimenter–participant interaction condition. We were not able to attribute this failure to the differences in the testing condition or to cerebellar or frontal lobe dysfunction. Instead, we found several methodological weaknesses in the original design. Furthermore, contrary to what Cohen et al. (1985) and Cohen and Eichenbaum (1993) proposed, with evidence provided by theoretical analyses of the Tower of Hanoi Puzzle in the cognitive literature as well as studies on normal participants, we conclude that declarative memory played a vital role in the acquisition of the recursive strategy. We believe, therefore, that any one or a combination of these factors contributed to our failure to replicate the previous results. In our view, the Tower of Hanoi Puzzle does not qualify as a measure of nondeclarative memory.

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