PERGAMON

Neuropsychologia 40 (2002) 1324–1334

NEUROPSYCHOLOGIA

www.elsevier.com/locate/neuropsychologia

Dissociating habit and recollection: evidence from Parkinson's disease, amnesia and focal lesion patients

Janine F. Hay [a,*], Morris Moscovitch [a,b], Brian Levine [a,b]

[a] *Rotman Research Institute, Baycrest Centre for Geriatric Care, Toronto, Canada*
[b] *Department of Psychology, University of Toronto, Toronto, Canada*

Received 1 May 2001; accepted 2 November 2001

Abstract

We investigated the role played by the striatum and the medial temporal lobes (MTL) in memory performance by testing patients with Parkinson's disease (PD) and amnesia with Hay and Jacoby's habit-learning task [Journal of Experimental Psychology: Learning, Memory and Cognition 22 (1996) 1323]. Using equations from Jacoby's process-dissociation procedure [Journal of Memory and Language 30 (1991) 513], we were able to separate out the contribution of habit (automatic memory) and recollection (intentional memory) to performance within a single probability-learning paradigm. Amnesics showed the expected dissociation of impaired recollection and intact habit, highlighting the important role of the MTL in recollective processing. Mild PD patients did not perform differently than matched controls for habit or recollection, however, moderate PD patients were impaired in their ability to rely on habit and in their ability to recollect specific information. The performance of focal lesion patients further supported the interpretation that PD patients have a significant deficit in automatic, habit-learning due to striatal dysfunction while their deficit in recollection may arise from impoverished frontal lobe contributions.

Keywords: Nondeclarative memory; Declarative memory; Process-dissociation procedure; Probability-matching; Neurological populations

1. Introduction

In recent years, there has been great interest in dissociating different types of memory and the brain areas that may mediate different memory processes or systems. Converging research has supported the distinction between two qualitatively different types of memory based on evidence from cognitive psychology [21,33,59], patient populations [7,35] and animal learning [34]. Declarative, or explicit, memory has been characterized as a conscious, intentional and effortful ability to recollect a previous episode. This type of memory has consistently been shown to be impaired following damage to medial temporal lobe (MTL) structures [56] and also after frontal structures if more strategic processing is implicated at encoding or retrieval [35]. In contrast, nondeclarative, or implicit, memory has been characterized as an unconscious, automatic basis of responding that does not rely on the ability to recollect. This type of memory is typically preserved in amnesia (for reviews see [37,57]) and is unaffected by other experimental manipulations that impair conscious remembering (e.g. [65]). As we describe findings from the neuropsychological patient literature, we will generally refer to these two types of memory as declarative and nondeclarative, respectively, although the terms 'explicit' and 'implicit' could be interchanged with these. In this study, we more specifically examine declarative and nondeclarative memory by investigating recollection and habit. The terms 'recollection' and 'habit' are more precise terms that are defined within the context of Jacoby's process-dissociation framework [21], as described later. By using a test of memory in which the contribution of recollection and habit could be determined, we hoped to assess the role of different brain structures in mediating recollection and habit.

There have been numerous conceptualizations of nondeclarative memory and it has been measured using a variety of techniques. Nondeclarative memory has been expressed as procedural learning or skill acquisition, measured on motor tasks such mirror reading, maze learning or rotary pursuit [18]. It has also included more cognitive skills such as artificial grammar learning, category learning and probability-matching [27]. Priming has also been subsumed under the broad label of nondeclarative memory. While these different tasks may initially appear dissimilar, it is believed that the cognitive processes that underlie

* Corresponding author. Present address: Credit Valley Hospital, 2200 Eglinton Ave. West, Mississauga, ON, L5M 2N1, Canada.
E-mail address: jhay@rotman-baycrest.on.ca (J.F. Hay).

0028-3932/02/$ – see front matter
PII: S0028-3932(01)00214-7

them are all automatic, unintentional processes that operate independently of a conscious effort to learn or remember. Consequently, it is assumed that the neural mechanisms that give rise to this type of automatic responding are different from the neural mechanisms involved in declarative memory. Nondeclarative memory does not appear to involve the hippocampus and associated MTL structures, or the frontal lobes if the tests are perceptual and data-driven [63,64]. However, our understanding of the brain structures that may mediate nondeclarative memory is limited. The difficulty of localizing nondeclarative memory in the brain may stem from its context-specific nature, as it has been shown to be task-dependent and sensitive to subtle changes in presentation and form (e.g. [22]). Nondeclarative memory has also been assessed with a wide range of different measures, and therefore, it is unlikely to be a single entity consistent across all tasks.

Different forms of nondeclarative memory may be dependent upon distinct neuroanatomic regions [18,35,36,37]. Brain imaging studies that have investigated nondeclarative memory in normal adults have revealed that it is mediated by different brain regions compared to declarative memory [5]. Functional dissociations have also been demonstrated with scalp recordings of event-related brain potentials (ERPs) for declarative and nondeclarative memory [51], as well as recollection and habit [16]. Using positron emission tomography (PET), researchers have shown that visual perceptual priming is mediated by occipital brain areas [56] while others have demonstrated the involvement of left frontal regions in conceptual priming [6,9,45,61]. There is evidence that motor learning tasks recruit subcortical structures such as the basal ganglia (e.g. [12,26,46]) and recently, there has been a demonstration of striatal activation in cognitive habit-learning, using functional magnetic resonance imaging (fMRI) [44].

While it has been established that amnesics, who have sustained damage to the hippocampus and related MTL structures, demonstrate striking deficits in declarative memory in the presence of intact priming (e.g. [7,53]), the opposite dissociation has also been found. That is, patients with Parkinson's disease (PD) have shown impaired nondeclarative memory in the presence of intact recollection (e.g. [27,52]). PD is a neurological disorder that causes a degeneration of neurons in the substantia nigra, resulting in a loss of dopaminergic input to the striatum, which includes the caudate nucleus and putamen in the basal ganglia. Individuals with PD without dementia serve as a useful model of striatal dysfunction in the presence of an otherwise intact neurological system. Studies of skill learning in PD patients have revealed nondeclarative memory deficits on motor tasks [1,18,62], as well as nonmotor tasks [29,32,49,52]. However, when cognitive measures that do not rely on a motor output are used, PD patients do not always reveal deficits in cognitive skill learning [13]. On tests of implicit memory, PD patients have demonstrated intact word stem repetition priming abilities [2,18,20,30], and artificial grammar learning and category learning have also been preserved in PD patients [48].

One factor that may account for the inconsistent findings of the effects of PD on nondeclarative memory is the role of conscious strategic processes. That is, on nondeclarative tasks that do not have a motor component, such as category learning, artificial grammar learning or priming, participants are not instructed to use any intentional or conscious strategies to complete the task. Sometimes, however, participants become aware of task relationships and start to use intentional strategies to assist them with the task. If PD patients have relatively preserved recollective abilities, then it seems possible that they could also use conscious strategies to assist them on many nondeclarative tasks. This might especially be likely an easy tasks that do not exhaust cognitive resources. The extent to which conscious strategies have contaminated performance on nondeclarative tasks has not been measured and may account for inconsistencies in the literature. Indeed, Knowlton et al. [27] showed that PD patients were initially impaired on a probabilistic habit-learning task over the first 50 trials but the same patients did not perform any differently from controls on later trials. Knowlton et al. argued that conscious strategies affected performance on this nondeclarative task, but only on later trials. They suggested that the PD patients started to use their intact conscious strategies to assist their performance later in the task, ameliorating earlier differences that were apparent when performance was based primarily on habit-learning. These findings suggest that the striatum is involved in the initial stages of habit-learning but that the hippocampus and related MTL structures, and possibly the frontal lobes, may become involved in later stages of task performance. Further evidence to support this interpretation comes from a study by Knowlton et al. [28] in which they tested amnesics and controls on the same probabilistic habit-learning task described above. They found that amnesics did not differ from controls on the first 50 trials but that over time they performed more poorly and a difference emerged. These researchers interpreted this finding by arguing that control patients used conscious strategies to assist them later in the task but that the amnesics lacked such abilities and, therefore, could not assist their performance to the same extent.

The purpose of the current study was to further investigate the role of the striatum and the MTL in memory by examining habit-learning and recollection in patients with PD and amnesia, respectively. Rather than rely on different types of tasks to measure declarative and nondeclarative memory processes, we made use of Hay and Jacoby's [14] extension of Jacoby's [21] process-dissociation procedure to investigate the contribution of habit and recollection to performance within a single task. The advantage of our procedure is that it allows us to avoid the contamination concerns associated with previous methods by measuring habit and recollection within a single probability-learning paradigm. We were interested in determining whether PD patients

would reveal a deficit in cognitive habit-learning when measured without the influence of conscious strategies. Another issue we wanted to address with our procedure was the extent to which declarative memory is affected by PD. PD patients have demonstrated intact declarative memory (e.g. [3,27,52]) however, other researchers have found PD patients to be impaired on declarative memory tasks, especially when they involve more strategic, effortful processing [60]. As PD also affects fronto–striatal connections in the brain, we more closely examined the frontal contribution to habit and recollection in Experiment 2, by examining memory performance in patients with focal frontal lesions, as well as in a patient with focal striatal lesions with no frontal involvement.

The results of Knowlton et al.'s studies [27,28] suggested that PD patients failed to establish habits but were able to use conscious strategies to assist them in later stages of the task. In contrast, amnesics formed habits initially, but had difficulty using conscious strategies to assist their performance as the task progressed. Based on the Knowlton et al. findings, the following predictions were made in the current study. We predicted that PD patients would be impaired at habit-learning but demonstrate intact recollective abilities. In contrast, we expected the amnesics to demonstrate intact habit estimates but have deficits in recollection.

The first phase of the experiment was a training session designed to create habits of specific strengths. This part of the paradigm was very similar to a traditional two-choice probability-learning experiment. Participants were exposed to pairs of semantically-related words with the probabilities of the pairings varied. A stimulus word was presented with two related responses such that a "typical" response (e.g. knee-bend) occurred twice as often (67%) as an "atypical" response (e.g. knee-bone, 33%). Once a habit was established, the second phase of the experiment was a series of short memory tests. Participants studied short lists of word pairs they had seen earlier in training and then were tested with the stimulus word and a fragment of the target response that could be completed with either response from training (e.g. knee-b_n_). Estimates of recollection and habit were derived by applying the process-dissociation equations to performance in these study–test sessions.

On congruent trials, participants studied items that were either made typical in training and, therefore, participants could respond correctly by either recollecting (R) the item from the short study list, or by relying on their habit (H) of giving the typical response when recollection failed ($1-R$). Recollection was congruent with the typical habit formed in training. The probability of responding correctly with a typical item on congruent trials can be written as

$$\text{Congruent}: \text{ probability (typical)} = R + H(1-R)$$

On incongruent trials participants studied atypical items and, therefore, habit was now a source of error. Incorrectly responding with a typical item occurred if participants failed to recollect the response they had just studied in the preceding list ($1-R$) and instead relied on their habit of giving the typical response (H). The probability of incorrectly responding with a typical item on incongruent trials can be written as

$$\text{Incongruent}: \text{ probability (typical)} = H(1-R)$$

An estimate of recollection can be calculated by subtracting the probability of responding with a typical response on congruent and incongruent trials

$$R = \text{Congruent} - \text{Incongruent}$$

Given an estimate of recollection, an estimate of habit for the typical response can be derived by algebra

$$H = \frac{\text{Incongruent}}{(1-R)}$$

By using the process-dissociation equations outlined above, we were able to eliminate contamination concerns typically associated with declarative and nondeclarative tests. As such, we could examine the effects of PD and amnesia on pure estimates of habit and recollection.

2. Experiment 1

2.1. Method

2.1.1. Participants

Patients: Twenty-four PD patients participated in the study. The diagnosis of PD without dementia was confirmed by a senior neurologist at the Movement Disorders Centre at the Toronto Hospital in Toronto, Ontario. Based on the Hoehn and Yahr rating scale [19], 12 patients (6 men/6 women) were in the early stages of PD and had ratings of 2.5 or less. The remaining 12 patients (8 men/4 women) were in the moderate to severe range of PD and had ratings of at least 3.0. The mild PD group averaged 63.2 years of age and had 17.0 years of education. Their mean score on the Mini-Mental State Examination (MMSE) [11] was 29.1 and they scored 76% on the Mill Hill Vocabulary Test (MHVT) [47]. The moderate PD group averaged 72.8 years of age and 15.8 years of education. Their mean score on the MMSE was 27.9 and they averaged 67% on the MHVT. There were no significant demographic differences between the mild and moderate groups with respect to age, education or MMSE scores (FS < 1) although Mill Hill scores were lower for the moderate group ($F = 4.61$, MSE $= 4.38$, $P = 0.043$). Patients were excluded if they received a score of 25 or lower on the MMSE, suggestive of impaired cognitive functioning. Only patients with minor fluctuations in their motor status were tested. Exclusion criteria also included any history of neurological or psychiatric disturbances (including depression), alcoholism, or other serious medical problems. All patients were under the care of a neurologist and were optimally medicated on various treatments. They were tested at the Toronto Hospital Movement

Disorder Clinic, Toronto, Canada and were reinbursed for parking expenses.

The amnesics were selected from a pool compiled at Baycrest Hospital in Toronto. They were included in the study if they had sustained damage to MTL regions without damage to frontal regions of the brain. The amnesics (two women, two men) had a mean age of 53.0 and 17.5 years of education. Their mean score on the MMSE was 24.5 and they averaged 81% on the MHVT. One patient had viral herpes encephalitis causing bilateral hippocampal damage that was more extensive on the right side. A second patient had undergone a resection of an arteriovenous malformation in the right temporal area. Another amnesic had a low grade astrocytoma in the third ventricle, resulting in obstructive hydrocephalus. The final patient had bilateral MTL damage arising from complications following cosmetic surgery.

Controls: The controls were matched to PD patients for age, sex and years of education and were excluded using the same criteria as outlined for the PD patients. Controls matched to the mild PD patients averaged 63.8 years of age, 16.8 years of education and had MMSE and MHVT scores of 28.3 and 79%, respectively. The controls matched to the moderate PD group had a mean age of 70.8 years, 13.6 years of education and they received a mean score of 28.8 on the MMSE and 78% on the MHVT. There were no significant differences in age, education, MMSE or MHVT between the mild and moderate PD-matched control groups (FS < 1). Participants were reinbursed for parking expenses and/or were paid a nominal fee for their participation. Testing sites included either the Rotman Research Institute at Baycrest Centre or Erindale College, University of Toronto.

2.2. Materials and procedure

All participants were tested individually on an IBM compatible PC using Schneider's [54] Micro-Experimental Laboratory software. Words were presented in the middle of the computer screen in lowercase letters. The character size of the stimuli was approximately 5 mm × 7 mm, and participants were seated approximately 70–75 cm from the screen.

A pool of 18 stimulus words paired with two associatively related responses (e.g. knee-bend, knee-bone) was selected (see [14] for details). Both responses contained the same number of letters and could be used to complete the same word fragment (e.g. knee-b_n_). The pre-experimental probability of completing fragments with the various responses was equated across counterbalancing conditions. It was also insured that all responses occurred equally often as typical and atypical responses.

The study consisted of two phases: training and study–test sessions. In the training phase, participants were presented with an intact stimulus word and a semantically-related incomplete response word on the computer screen (e.g. knee-b_n_). Participants were instructed to predict, based on previous trials, a semantically-related word that would complete the fragment. The word and fragment remained on the screen for 2 s, during which time participants were encouraged to respond. The correct completion word was then presented for 1 s. Although there were always two possible completions for each fragment (e.g. "bend" and "bone" for knee-b_n_), only one was considered to be correct on any trial. Participants were told that more than one response would appear with each stimulus word and that some responses could appear more often than others. Two pairs of words that did not appear elsewhere in the experiment were used to illustrate the procedure and then participants engaged in three successive blocks of training. The experimenter recorded all responses.

Training consisted of three blocks of 108 presentations each. Participants were presented with typical items on 67% of trials. Within each block, each stimulus was presented six times: four times with its typical response and two times with its atypical response. The order of the items within each block was random with the restriction that the same stimulus word could not be presented more than three times consecutively.

Following training, participants received 18 successive study–test lists, divided into two blocks of nine lists. Each study list contained nine of the word pairs that had been presented during training (e.g. knee-bend), presented at a rate of one pair/s with a 500 ms inter-stimulus interval. Participants were instructed to read the word pairs aloud and to remember them for the memory test that would follow presentation of the study list. After each study list, participants received a cued recall test of memory for the word pairs just seen. For that cued recall test, stimulus words were presented with a fragmented version of the response with which they were paired in the study list (e.g. knee-b_n_). Word pairs remained on the screen for 1.5 s followed by a blank screen which lasted until a response was entered by the experimenter.

The same cues presented during the training session were used in phase 2. Participants were instructed to complete fragments by recalling aloud the response word that was presented in the immediately preceding list. They were told that if they could not remember the studied item, they were to guess with the first response that came to mind. Further, participants were warned that some pairs from training would be tested although they did not appear in the study list just presented. For those "guessing" items, participants were told to complete the fragment with the first word that came to mind.

The study lists maintained the earlier proportion of typical and atypical responses from training. Each list contained nine word pairs, six of which had responses made typical by training and three that were made atypical by training. Each of the 18 typical items was presented six times across the 18 study lists. Each of the 18 atypical items was presented three times. The presentation order for all items in the study and test lists was randomly determined and remained fixed across participants, with the constraint that no item was repeated within a list.

Participants performed a short distractor task between study and test. A number between 30–100 was presented

on the computer screen immediately after each study list. Each number appeared for 1 s followed by a blank screen for 6.5 s. During that time, participants were required to count backwards by threes aloud, as quickly as possible, starting with the number that appeared on the screen. It was emphasized that the backwards counting should continue until a message appeared that instructed them to begin the test. The purpose of the distractor task was to prevent participants from rehearsing items in short-term memory. Following each test, the entire study–test procedure started again with a new study list until all 18 lists had been studied and tested. Different numbers were presented for the distractor task between each study and test session.

2.3. Results and discussion

The results indicated that amnesic patients had a severe deficit in recollection but had normal habit-learning whereas patients with moderate PD were at chance at habit-learning and somewhat impaired at recollection. Mild PD patients performed normally on both habit and recollection. These impressions were confirmed by statistical analyses.

Statistical analyses performed on all dependent variables did not reveal differences between the mild and moderate PD-matched control groups and consequently, these groups were collapsed for all comparisons.

The mean probabilities of responding with a typical item on congruent and incongruent trials for each patient group, has been reported in Table 1. Analysis of correct performance on congruent trials across groups (controls, moderate PD, mild PD, amnesics) revealed a significant effect $F(3, 48) = 8.41$, MSE $= 0.005$, $P < 0.000$. Using the control group as the reference, simple contrasts revealed significantly higher congruent scores in the control group over the moderate PD group (means of 0.76 and 0.66, respectively, $P = 0.001$) but not the mild PD group (mean of 0.79, $P = 0.28$). The amnesics also performed below the controls (mean of 0.65, $P = 0.014$). Analysis of erroneous performance on incongruent trials did not reveal an overall effect of group $F(3, 48) = 2.18$, MSE $= 0.02$, $P = 0.10$, as neither the moderate PD patients ($P = 0.68$) nor the mild PD patients ($P = 0.98$) differed from the controls (means of 0.43, 0.41 and 0.41, respectively). However, the amnesics had more errors on incongruent trials than did controls (mean of 0.57, $P = .016$).

Based on the process-dissociation equations described earlier, an estimate of recollection was calculated as the difference between performance on congruent and incongruent trials (congruent − incongruent). Habit was calculated as performance on incongruent trials divided by (1 − recollection). Guessing scores were calculated as the proportion of typical responses on guessing trials divided by the total number of guessing trials. The mean estimates of recollection, habit and guessing have been reported in Table 1.

Analysis of recollection estimates revealed a main effect of group $F(3, 48) = 4.7$, MSE $= 0.03$, $P = 0.01$. Using the control group as the reference, simple contrasts revealed that the moderate PD group was impaired ($P = 0.05$), as were the amnesics ($P = 0.004$) but the mild PD group did not differ significantly from controls ($P = 0.60$).

The different measures of automatic influences of memory, the habit estimates and the guessing scores, were analyzed. We did not find any significant effect for type of automatic measure $F(1, 48) < 1$, and there was no significant interaction $F(3, 48) = 1.6$, MSE $= 0.003$, $P = 0.20$. However, there was an effect of group. Further analyses of the group effect were performed. An ANOVA on habit estimates revealed a significant effect of group $F(3, 48) = 3.43$, MSE $= 0.02$, $P = 0.024$. Simple planned comparisons using the control group as reference revealed that the moderate PD group was significantly impaired in its habit estimates ($P = 0.01$) but habit for the mild PD group did not differ from controls ($P = 0.47$). Amnesics also did not differ in their habit estimates compared to controls ($P = 0.94$). An analysis of guessing estimates revealed a significant effect of group $F(3, 48) = 9.08$, MSE $= 0.005$, $P = 0.000$. Planned simple comparisons using the control group as reference revealed that the moderate PD patients were significantly impaired compared to controls ($P < 0.000$), but the mild PD patients ($P = 0.88$) and the amnesics ($P = 0.36$) did not differ from controls.

Pearson product–moment correlations were performed on habit, guessing and recollection estimates across and within each patient group. Overall, habit and guessing estimates were significantly correlated (Pearson $r = 0.62$, $P < 0.01$) but habit and recollection were not (Pearson $r = 0.04$, ns).

Table 1
Probabilities of responding with a typical item on congruent and incongruent trials and mean estimates of recollection, habit and guessing for controls, mild PD, moderate PD and amnesics

	Trial type		Estimates		
	Congruent	Incongruent	Recollection	Habit	Guessing
Group					
Controls	0.76	0.41	0.35	0.63	0.66
Mild PD	0.79	0.41	0.38	0.65	0.65
Moderate PD	0.66	0.43	0.23	0.55	0.53
Amnesics	0.65	0.57	0.08	0.62	0.62

Within the control group, correlation coefficients revealed a significant relationship between habit and guessing ($r = 0.39$, $P < 0.03$) and no relationship between recollection and habit ($r = -0.01$, ns). For the PD patients, correlations were also significant between habit and guessing ($r = 0.75$, $P < 0.01$) but not between recollection and habit ($r = 0.03$, ns). Of particular importance, there was no significant correlation between habit and recollection for the moderate PD group ($r = 0.02$, ns), suggesting that these abilities were not merely related to global cognitive functioning. The lack of a correlation between recollection and habit for the moderate PD group was not caused by a floor effect in either condition. With respect to variance, recollection estimates were variable, ranging between 0.02 and 0.46 with a standard deviation of 0.19. However, habit estimates were more constrained given that most moderate PD patients had deficits in habit-learning, producing scores close to chance responding on a two choice alternative. Habit estimates ranged from 0.43 to 0.64 with a standard deviation of 0.09. Therefore, while a floor effect was not evident, one could not rule out the possibility that low variance within the habit estimates limited the correlation between recollection and habit for the moderate PD group.

Overall, the results suggested that while mild PD patients did not show any deficits in either habit-learning or recollective abilities, moderate PD patients were impaired at both types of memory. In addition, guessing scores provided a converging measure of automatic influences that were derived independently of our estimates of habit. Habit and guessing scores did not differ within each group and both measures revealed probability-matching in the performance of the controls, amnesics and the mild PD patients. That is, their estimates of habit and guessing closely reflected the 67% probability that participants were trained on in the first phase of the experiment. Such probability-matching has been observed in healthy young and older adults in earlier studies [14,15]. The performance of the amnesics suggested that amnesia impairs recollection but habit-learning can remain preserved despite extensive damage to MTL structures. This finding is consistent with the literature that has demonstrated impaired declarative memory in the presence of intact nondeclarative memory [7,56], or implicit memory (for review see [37]) in amnesia. For PD, it was apparent that mild stages of the disease did not compromise intentional or automatic memory functioning. In contrast, moderate stages of PD had a significant impact on memory performance. That is, patients in the moderate stages of PD had impairments in both habit and recollection.

A possible interpretation of the impaired habit and recollection in moderate PD is that they were caused by a global reduction in cognitive functioning as a result of striatal damage. Our results, however, do not support such a hypothesis. If there was a global deficit in functioning, then one might expect that habit and recollection would be similarly impaired across patients in moderate stages of PD. However, correlational analyses between habit and recollection estimates in the moderate PD group did not approach significance ($r = 0.02$).

An alternative interpretation is that the deficits emerged from dysfunction in different brain areas that mediate habit and recollection. Based on previous literature that has linked the striatum to habit-learning deficits [27], we would argue that the habit deficits in our study emerged as a result of damage to the striatum. However, in addition to the striatal dysfunction, PD also reduces the dopaminergic connections with the dorsal prefrontal regions of the brain, presumably independently from its effects on the striatum. As a result, PD patients can appear very "frontal" in their behaviour and cognition (e.g. [60]), either because of dopamine depletion in the frontal lobes or because fronto–striatal connections are weakened, or both. In our study, the ability to recollect an item correctly involved making a source discrimination—an ability that has been associated with frontal lobe functioning (e.g. [55]). As such, it is possible that frontal lobe dysfunction may underlie the deficit in recollection that was observed in the moderate PD patients.

We hypothesized that the recollection deficits in our study emerged as a consequence of damage to frontal brain regions and were not related to striatal dysfunction per se. To test this hypothesis, we assessed patients with focal frontal lesions on this task, as well as a person with a focal striatal lesion. If patients with focal frontal lesions have recollection deficits but are able to demonstrate preserved habit-learning, then this would support our hypothesis that the frontal lobes are recruited in recollection but not essential to habit-learning. If habit and recollection are impaired in moderate PD due to the interaction between the striatum and the frontal cortex, then the patient with a focal striatal lesion should be impaired on both. Alternatively, if impaired habit-learning and recollection in PD is due to striatal and frontal dysfunction, respectively, then the patient with focal striatal damage should have impaired habit-learning in the presence of normal recollection, as frontal dopaminergic function would be spared.

3. Experiment 2

3.1. Method

Participants: Five patients with focal frontal lesions were recruited for the study from the volunteer pool at the Rotman Research Institute. Four of the patients had undergone brain surgery to have frontal meningiomas removed from anterior portions of their brain (one on the left side, three on the right side). One patient had epilepsy and underwent surgery on her right frontal lobe to help control her seizures. All focal lesions were located in dorsolateral regions of the frontal lobes. The mean age of the focal frontal patients was 51.8 years, with 12.4 years of education. Their mean score on the MMSE was 29.0 and they scored 69% on the MHVT. The patients were screened according to the same criteria as described for the patients earlier. The patients were paid a

Table 2
Probabilities of responding with a typical item on congruent and incongruent trials and mean estimates of recollection, habit and guessing for patient with focal striatal lesion and patients with focal frontal lesions

	Trial type		Estimates		
	Congruent	Incongruent	Recollection	Habit	Guessing
Group					
Striatal lesion	0.76	0.28	0.48	0.54	0.47
Frontal lesions	0.76	0.50	0.27	0.67	0.68

nominal fee for participating in the study. One male patient who had sustained a focal striatal stroke was also tested (30 years old, 19 years of education). His score was 29 on the MMSE and 70% on the MHVT. His stroke was left-sided and included the caudate and putamen, as well as parts of the globus pallidus and internal capsule. He did not have any significant medical or psychiatric history and he was not medicated.

3.2. Materials and procedure

The identical materials and procedure used in Experiment 1 were again used in the current experiment.

3.3. Results and discussion

The probabilities of responding with a typical item on congruent and incongruent trials and the estimates of recollection, habit and guessing for focal frontal patients and the focal striatal patient, are presented in Table 2. The focal frontal patients had mean scores of 0.76 and 0.50 on congruent and incongruent trials, respectively. Estimates of recollection, habit and guessing were derived and are presented in Table 2. A comparison of their performance to the controls revealed no difference in habit and guessing estimates ($z = +0.57$ and $+0.29$, respectively). Recollection estimates for the patients with focal frontal lesions were somewhat below controls ($z = -0.50$), although it is important to note that one patient (left dorsolateral lesion) scored high on recollection (0.49) while the other four did very poorly. If the one high recollecting patient was removed, the mean estimate for recollection falls to 0.21, two points below the mean recollection estimate of the moderate PD patients. The focal striatal patient had scores of 0.76 and 0.28 on congruent and incongruent trials, respectively. His habit and guessing scores were moderately to severely impaired ($z = -1.3$ and -2.7, respectively) but his recollective abilities were intact ($z = +0.81$). His data are also presented in Table 2.

The intact habit estimates that were attained by the focal frontal lesion patients supported the hypothesis that habit-learning does not rely on dorsolateral frontal regions of the brain. Further, the focal striatal patient demonstrated moderate to severely impaired habit-learning but intact recollection. Taken together, these results suggest that habit-learning is mediated by subcortical brain structures in the striatum. From these results, we can conclude that it is likely the dopamine depletion in the substantia nigra that contributed to impaired habit-learning in moderate PD patients, rather than their impoverished fronto–striatal connections. Damage to frontal areas of the brain may be responsible for the recollection deficits that were apparent in the moderate PD patients. That is, there is a suggestion that recollection can be mediated by frontal brain regions, as patients with focal frontal brain lesions were mildly impaired at recollecting on this task. In contrast, recollective abilities remained intact in the patient with a focal striatal lesion. Although there was variability in the recollection performance of this group of frontal focal lesion patients, the finding that 4/5 were significantly impaired at recollecting supports the hypothesis that recollection, as defined in our study, may be mediated in part, by frontal lobe structures.

4. General discussion

Using Hay and Jacoby's [14] extension of the process-dissociation procedure, we examined the effects of PD and amnesia on habit and recollection within a single task. We found that the moderate PD group was significantly impaired at habit-learning while the mild PD group and amnesics were not. In addition, a patient with a focal striatal lesion also demonstrated impoverished habit-learning performance. Both the moderate PD group and the striatal lesion patient failed to reveal probability-matching in their automatic habit estimates (67%), instead performing closer to chance levels on a two-choice alternative. These results suggest that the striatum plays an important role in habit-learning. There was also a deficit in recollection for the moderate PD participants, as well as the amnesics and most of the focal frontal lesion patients. Again, the mild PD participants performed no differently than controls. These results help to disambiguate previous research examining nondeclarative and declarative memory in PD. By separating out the contribution of habit and recollection within a single task, we avoided the problems associated with conscious contamination and consequently, we were able to examine the effects of PD, as well as amnesia and other focal lesions, on each type of memory separately.

4.1. Habit-learning mediated by striatum

Although it is likely that different types of nondeclarative memory rely on different brain structures, there is growing evidence to suggest that the striatum plays a significant role in habit-learning in humans. It has generally been found that PD patients are impaired at habit-learning at least in the initial stages before conscious strategies are assumed to exert their influence [27]. Our current findings with the moderate PD group support the hypothesis that the striatum plays a critical role in acquiring an automatic response, or habit. That is, moderate PD patients were significantly worse at learning habits than matched controls.

One difficulty that emerges in using PD patients as a model of striatal dysfunction is that these patients also have reduced dopaminergic input to frontal regions of the brain as a result of impoverished fronto–striatal connections (e.g. [4]). Some researchers have postulated that the poor performance of PD patients on probabilistic learning tasks reflects a disruption of reward-based learning, mediated by depleted dopaminergic input to frontal brain areas [58]. However, there is evidence to suggest that the role of the striatum and the frontal lobes in cognition can be dissociated. Several studies [42,43,50] have compared PD patients to patients with frontal lesions and have demonstrated different types of difficulties on cognitive tasks such as the Wisconsin Card Sorting Task (WCST), the Tower of London Task and a task-switching paradigm. For example, Owen et al. [42] used a set shifting task modeled after the WCST to assess patients' abilities to shift their attention away from a previously relevant stimulus and shift their attention to an alternative dimension. These researchers found that frontal patients' deficits in set-shifting reflected an increased tendency to perseverate on a previously relevant stimulus dimension. In contrast, medicated patients with PD were worse at shifting their attention to a previously irrelevant dimension but their responding was not perseverative. Owen et al. concluded that the different types of set-shifting deficits demonstrated by frontal patients and PD patients may involve fundamentally different cognitive and neural mechanisms. Other evidence has suggested the frontal lobes are not critical in procedural memory. Researchers have found intact performance by frontal patients on nondeclarative memory tasks, such as Knowlton et al.'s probabilistic habit-learning task [27] or tasks of perceptual skill learning [8] or serial reaction time [10].

We were able to dissociate the roles of the frontal lobes and the striatum in habit-learning by testing focal frontal and striatal lesion patients with our paradigm. The performance of focal frontal lesion patients provided a test of the frontal lobe contribution to habit and recollection, in the absence of striatal damage. We found that focal frontal patients showed preserved habit-learning to the same extent as controls. Indeed, probability-matching was revealed in both their habit and guessing estimates, suggesting that intact dorsolateral prefrontal lobe functioning is not essential to habit-learning. We also tested a young patient who had sustained a focal stroke in his left striatum. The performance of this patient was striking in that his automatic memory (habit) was impaired while his recollection was not, suggesting that it is not fronto–striatal connections that are crucial to habit performance, but rather the striatum itself. The performance of the focal striatal patient further supported the selective role of the striatum in habit-learning and also revealed that recollection can be unimpaired in the presence of left striatal damage. This finding suggested that recollection is not dependent on striatal brain regions.

4.2. Global or specific deficit in Parkinson's disease?

The results of the current study revealed deficits in both habit and recollection in patients who were in moderate stages of PD. One could interpret these results as an indication that moderate PD patients have a global deficit in functioning possibly arising from poor attentional abilities, distractibility, or generalized cognitive slowing. However, there are several reasons why we would argue that this is not likely to be the case. Previous studies using this paradigm have already established that manipulations affecting attention and processing time such as deadlining responses at test, dividing attention at test or increasing the study list presentation rate, can all have detrimental effects on recollection while leaving habit unaffected (see [14,15,23]). Probability-matching has been reflected in the automatic component even when recollection has been significantly impaired. Therefore, it seems unlikely that any reduction in attentional capacity or cognitive slowing would have had an effect on habit estimates, although it is possible that such an explanation could account for the deficit in recollection. Further, if one postulated a global deficit in functioning in the moderate stages of PD, then one might expect that habit and recollection would be similarly impaired across participants. However, there was no significant correlation between habit and recollection estimates in the moderate PD group. We interpret our results as evidence that striatal dysfunction in moderate stages of PD caused a specific impairment in habit-learning and that a frontal dysfunction in PD may underlie the deficit in recollection demonstrated by the moderate PD patients.

We did not find any cognitive deficits in the mild PD group compared to controls. The presence of cognitive deficits in mild PD is inconsistent in the literature. Although Owen has reported cognitive deficits in mild PD [42], this is not always the case. Indeed, results seem to vary depending on the type of task used [40,41]. With respect to other habit-learning tasks, Knowlton et al. [27] reported habit-learning to be most impaired in moderate/severe PD. Their data revealed less impairment in the mild PD group than in the moderate group, but it is unclear if this difference was statistically significant as the mild versus moderate/severe groups were not directly compared. Owen et al. also found that cognitive deficits in mild PD depended on whether mild PD patients were medicated [40,42]. It is possible that differences in task demands,

medication, or patient selection criteria across studies may account for the conflicting results in the literature.

4.3. Frontal versus medial temporal lobe contributions to recollection

Declarative memory has typically been measured in tasks such as free recall, cued recall or recognition. There is an established literature demonstrating that damage to the hippocampus and MTL structures impair this intentional and conscious form of memory (e.g. for a review see [37]). Using the process-dissociation procedure to derive uncontaminated estimates of recollection, we replicated this finding by demonstrating that amnesic patients were significantly impaired at recollection in our task. In PD, it is generally claimed that PD patients have intact declarative memory (e.g. [27,52]), but this conclusion has been disputed. Recognition performance is more likely to be preserved than recall [3] but there are also reports of recognition performance being impaired (e.g. [2]). We found that moderate PD patients were impaired in their ability to recollect. However, it is likely that the nature of their underlying deficit was different than that of the amnesics.

Although deficits in anterograde learning and memory are the hallmarks of amnesia, the frontal lobes are also implicated in many aspects of memory functioning. The frontal lobes play an important role in strategic aspects of memory (e.g. [35,36,53]). Moscovitch and colleagues have referred to the frontal lobes as a 'working-with-memory' structure that mediates the strategic aspects of memorial processing to and from hippocampal structures (e.g. [35,36,38]). Evidence from neuroimaging studies suggest that the frontal lobes play an important role in conscious remembering, including involvement in encoding/retrieval processes [39], and autobiographical re-experiencing [31]. The frontal lobes have also been implicated in source monitoring [24,25].

In the current paradigm, recollection was measured as the difference between performance on the congruent and incongruent trials. To perform well, participants had to determine if a given test item had appeared on the immediately preceding test list rather than on one of the earlier lists, making source memory a component of this task. Consequently, the frontal lobes might be expected to contribute to the strategic aspects of recollection as measured in this task. The performance of the focal frontal patients suggested that the frontal lobes were necessary to help mediate recollective abilities. Due to their frontal dysfunction, it is possible that moderate PD patients had difficulties with the strategic aspects of recollection and, therefore, did poorly in our task. Clearly, the amnesics were also impaired in their ability to recollect in our task, however, their deficit may be due to a more basic impairment in anterograde memory formation and retention. At this time it is not possible to disambiguate the different contributions made by the MTL and the frontal lobes to recollection performance, however, it is apparent that both brain regions played a role in mediating recollection in our task.

4.4. Conscious strategies and habit-learning

One might argue that declarative memory for the training phase could be used to assist performance in the study–test phase of the current study. That is, participants might have remembered the responses they learned in training and intentionally used them in the second phase of the experiment when their memory was being tested. If participants consciously used information from the training session to inflate their automatic responding, then patients with deficits in recollection, such as amnesics and patients with frontal lesions, should have significantly lower habit estimates than participants who were not impaired at recollecting. The results of this study showed that this was not the case. Both of these patient groups had habit and guessing estimates that did not differ from controls. In addition, their automatic estimates closely approximated the probabilities with which typical items were presented in training (probability-matching). Other studies using this paradigm have found variables that affect recollection but do not affect habit estimates, including normal aging [15], list presentation rate, and amount of time to respond at test [14]. Although some authors [28] have reported that amnesics perform more poorly than controls on probability-learning tasks, such claims have been made on tasks that do not separate out the different contributions of automatic and intentional memory to responding. In contrast, our paradigm was able to examine separately the contributions of habit and recollection and in doing so, showed that amnesics and patients with frontal lesions are able to learn habits as well as controls but they are less able to recollect.

A different argument could be that conscious strategies were needed in the training session initially to learn the stimulus–responses pairs. One might expect that amnesics and patients with frontal lobe damage would have difficulty learning such complex pairings, given their deficits in recollection. If this were the case, then learning difficulties should be reflected in lower habit estimates for the amnesics and frontal patients, compared to controls. The results clearly show that this did not occur. One possible explanation for their intact habit-learning may be that they were able to acquire automatic responding after multiple presentations. If the training session had been shorter, then differences might have emerged in their habit estimates, if conscious strategies were needed to help establish habits initially. Our paradigm measures habit after the completion of training and, therefore, it is assumed that participants learned their habits before the study–test session began (although the study lists maintained the probabilities from training in case this did not occur). We did not measure the rate of habit acquisition among the different patient groups. It would be interesting to investigate habit acquisition systematically in different patient populations by measuring habit and recollection at various stages of the acquisition process. Additionally, the idea that conscious strategies may be used in the initial stages of habit acquisition, before

automatic responding takes over, is an interesting concept that has been supported in recent work comparing young and older adults on a modified version of this paradigm [17].

5. Concluding comments

PD is a neurological disorder that primarily affects motor functioning. However, it is becoming more apparent that there are also significant cognitive effects that emerge as the disease progresses that should not be overlooked. The effects of PD on memory have been difficult to discern due to problems arising from contaminated task performance. Separating out memory processes within a single task allowed us to examine the effects of PD on different types of memory. Based on our findings, there appear to be two separate memory deficits in PD that arise from different sources. An impairment in automatic memory, or habit-learning, may emerge due to striatal damage while recollection deficits may emerge due to dysfunction in the frontal regions of the brain, possibly associated with dopamine depletion.

Acknowledgements

This research was supported by the Ben and Hilda Katz Post-Doctoral Fellowship at the Rotman Research Institute of Baycrest Centre to Janine Hay and by a Natural Sciences and Engineering Research Council (NSERC) operating grant to Morris Moscovitch. We are grateful to Dr. Anthony Lang for referring PD patients to us. We thank Eileen Halket and Luisa Del Rizzo for screening PD patients at the Toronto Hospital Movement Disorders Clinic and Heidi Roesler for testing control participants. We also thank Malcolm Binns for his helpful suggestions.

References

[1] Allain H, Lieury A, Quemener V, Thomas V, Reymann J, Gandon J. Procedural memory and Parkinson's disease. Dementia 1995;6:174–8.
[2] Bondi MW, Kaszniak AW. Implicit and explicit memory in Alzheimer's disease and Parkinson's disease. Journal of Clinical and Experimental Neuropsychology 1991;13:339–58.
[3] Breen EK. Recall and recognition memory in Parkinson's disease. Cortex 1993;29:91–102.
[4] Brown RG, Marsden CD. Cognitive function in Parkinson's disease: from description to theory. Trends in Neuroscience 1990;13:21–9.
[5] Buckner RL, Petersen SE, Ojemann JG, Miezin FM, Squire LR, Raichle ME. Functional anatomical studies of explicit and implicit memory retrieval tasks. Journal of Neuroscience 1995;15:12–29.
[6] Buckner RL, Goodman J, Burock M, Rotte M, Koutstaal W, Schacter DL, et al. Functional–anatomic correlates of object priming in humans revealed by rapid presentation event-related fMRI. Neuron 1998;20:285–96.
[7] Cohen NJ, Squire LR. Preserved learning and retention of pattern-analyzing skills in amnesia: dissociations of knowing how and knowing that. Science 1980;210:207–10.
[8] Daum I, Schugens MM, Spieker S, Pser U, Schonle PW, Birbaumer N. Memory and skill acquisition in Parkinson's disease and frontal lobe dysfunction. Cortex 1995;31:413–32.
[9] Demb JB, Desmond JE, Wagner AD, Vaidya CJ, Glouer GH, Gabrielli JDE. Semantic encoding and retrieval in the left inferior prefrontal cortex: a functional MRI study of task difficulty and process specificity. Journal of Neuroscience 1995;15:5870–8.
[10] Doyon J, Gaudreau D, Laforce Jr R, Castonguay M, Bedard PJ, Bedard F, et al. Role of the striatum, cerebellum, and frontal lobes in the learning of a visuomotor sequence. Brain and Cognition 1997;34:218–45.
[11] Folstein MF, Folstein SE, McHugh PR. Mini-mental state: a practical method for grading the cognitive state of patients for the clinician. Journal of Psychiatric Research 1975;12:189–98.
[12] Grafton ST, Hazeltine E, Ivry R. Functional mapping of sequence learning in normal humans. Journal of Cognitive Neuroscience 1995;7:497–510.
[13] Harrington DL, Haaland KY, Yeo RA, Marder E. Procedural memory in Parkinson's disease: impaired motor but not visuoperceptual learning. Journal of Clinical and Experimental Neuropsychology 1990;12:323–39.
[14] Hay JF, Jacoby LL. Separating habit and recollection: memory slips, process-dissociations and probability-matching. Journal of Experimental Psychology: Learning, Memory and Cognition 1996;22:1323–35.
[15] Hay JF, Jacoby LL. Separating habit and recollection in young and older adults: effects of elaborative processing and distinctive context. Psychology and Aging 1999;14:122–34.
[16] Hay JF, Kane KA, West R, Alain C. Event-related neural activity associated with habit and recollection. Neuropsychologia 2002;40:260–70.
[17] Hay JF, Smilek D, Debner JA, Jacoby LL. Effects of aging and context-specificity on habit and recollection. Brain and Cognition 1999;39:33–6.
[18] Heindel WC, Salmon DP, Shults CW, Walicke PA, Butters N. Neuropsychological evidence for multiple implicit memory systems: a comparison of Alzheimer's, Huntington's, and Parkinson's disease patients. The Journal of Neuroscience 1989;9:582–7.
[19] Hoehn MM, Yahr MD. Parkinsonism: onset, progression and mortality. Neurology 1967;17:427–42.
[20] Huberman M, Moscovitch M, Freedman M. Comparison of patients with Alzheimer's and Parkinson's Disease on different explicit and implicit memory tests. Journal of Behavioral Neurology 1994;7:185–93.
[21] Jacoby LL. A process-dissociation framework: separating automatic from intentional uses of memory. Journal of Memory and Language 1991;30:513–41.
[22] Jacoby LL, Dallas M. On the relationship between autobiographical memory and perceptual learning. Journal of Experimental Psychology: General 1981;110:306–40.
[23] Jacoby LL, Debner J, Hay JF. Proactive interference, accessibility bias, and process-dissociations: valid subjective reports of memory. Journal of Experimental Psychology: Learning, Memory and Cognition, in press.
[24] Johnson MK. MEM: mechanisms of recollection. Journal of Cognitive Neuroscience 1991;4:268–80.
[25] Johnson MK, Hashtroudi S, Lindsay DS. Source monitoring. Psychological Bulletin 1993;114:3–28.
[26] Jueptner M, Weiller C. A review of differences between basal ganglia and cerebellar control of movements as revealed by functional imaging studies. Brain 1998;121:1437–49.
[27] Knowlton BJ, Mangels JA, Squire LR. A neostriatal habit-learning system in humans. Science 1996;273:1399–402.
[28] Knowlton BJ, Squire LR, Gluck MA. Probabilistic classification learning in amnesia. Journal of Learning and Memory 1994;1:106–20.

[29] Koenig O, Thomas-Anterion C, Laurent B. Procedural learning in Parkinson's disease: intact and impaired cognitive components. Neuropsychologia 1999;37:1103–9.
[30] Koivisto M, Portin R, Rinne JO. Perceptual priming in Alzheimer's and Parkinson's diseases. Neuropsychologia 1996;34:449–57.
[31] Levine B, Black SE, Cabeza R, Sinden M, McIntosh AR, Toth JP, et al. Episodic memory and the self in a case of isolated retrograde amnesia. Brain 1998;121:1951–73.
[32] Martone M, Butters N, Payne M, Becker JT, Sax D. Dissociations between skill learning and verbal recognition in amnesia and dementia. Archives of Neurology 1984;41:965–70.
[33] Mandler G. Recognizing: the judgement of previous occurrence. Psychological Review 1980;87:252–71.
[34] Mishkin M, Appenzeller T. The anatomy of memory. Scientific American 1987;256:80–9.
[35] Moscovitch M. Memory and working-with-memory: a component process model based on modules and central systems. Journal of Cognitive Neuroscience 1992;4:257–67.
[36] Moscovitch M. Memory and working with memory: evaluation of a component process model and comparisons with other models. In: Schacter DL, Tulving E, editors. Memory systems. Cambridge, MA: MIT Press, 1994. p. 269–310.
[37] Moscovitch M, Vriezen ER, Gottstein J. Implicit tests of memory in patients with focal lesions or degenerative brain disorders. In: Spinnler H, Boller F, editors. Handbook of neuropsychology, vol. 8. Amsterdam: Elsevier, 1993. p. 133–73.
[38] Moscovitch M, Winocur G. The neuropsychology of memory and aging. In: Craik FIM, Salthouse TA, editors. Handbook of aging and cognition. Hillsdale, NJ: Erlbaum, 1992. p. 315–72.
[39] Nyberg L, McIntosh AR, Houle S, Nilsson LG, Tulving E. Activation of medial temporal lobe structures during episodic memory retrieval. Nature 1996;25(380):715–7.
[40] Owen AM, Iddon JL, Hodges JR, Summers BA, Robbins TW. Spatial and nonspatial working memory at different stages of Parkinson's disease. Neuropsychologia 1997;35:519–32.
[41] Owen AM, James M, Leigh PN, Summers BA, Marsden CD, Quinn NP, et al. Fronto–striatal cognitive deficits at different stages of Parkinson's disease. Brain 1992;115:1727–51.
[42] Owen AM, Roberts A, Hodges J, Summers BA, Polkey CE, Robbins TW. Contrasting mechanisms of impaired attentional set-shifting in patients with frontal lobe damage or Parkinson's disease. Brain 1993;116:1159–75.
[43] Owen AM, Sahakian BJ, Hodges J, Summers BA, Polkey CE, Robbins TW. Dopamine-dependent fronto–striatal planning deficits n early Parkinson's disease. Neuropsychology 1995;9: 126–40.
[44] Poldrack RA, Prabhakaran V, Seger CA, Gabrieli JDE. Striatal activation during acquisition of a cognitive skill. Neuropsychology 1999;13:564–74.
[45] Raichle ME, Fiez JA, Videen TO, MacLeod AM, Pardo JV, Fox PT, et al. Practice-related changes in human brain functional anatomy during nonmotor learning. Cerebral Cortex 1994;4:8–26.
[46] Rauch SL, Whalen PJ, Savage CR, Curran T, Kendrick A, Brown HD, et al. Striatal recruitment during an implicit sequence learning task as measured by functional magnetic resonance imaging. Human Brain Mapping 1997;5:124–32.
[47] Raven JC. Mill hill vocabulary scale. London: H.K. Lewis, 1965.
[48] Reber PJ, Squire LR. Intact learning of artificial grammars and intact category learning by patients with Parkinson's disease. Behavioral Neuroscience 1999;113:235–42.
[49] Roncacci S, Troisi E, Carlesimo GA, Nocentini U, Caltagirone C. Implicit memory in Parkinsonian patients: evidence for deficient skill learning. European Journal of Neurology 1996;36:154–9.
[50] Rogers RD, Sahalian BJ, Hodges JR, Polkey CE, Kennard C, Robbins TW. Dissociating executive mechanisms of task control following frontal lobe damage and Parkinson's disease. Brain 1998;121:815–42.
[51] Rugg MD, Mark RE, Walla P, Schloerscheidt AM, Birch CS, Allan K. Dissociation of the neural correlates of implicit and explicit memory. Nature 1988;392:595–8.
[52] Saint-Cyr JA, Taylor AE, Lang AE. Procedural learning and neostriatal dysfunction in man. Brain 1988;111:941–59.
[53] Schacter D. Implicit expressions of memory in organic amnesia: learning of new facts and associations. Human Neurobiology 1987;6:107–18.
[54] Schneider W. Micro-experimental laboratory: an integrated system for IBM PC compatibles. Behavior Research Methods, Instruments, and Computers 1990;20:206–17.
[55] Shimamura AP, Squire LR. A neuropsychological study of fact memory and source amnesia. Journal of Experimental Psychology: Learning Memory, and Cognition 1987;13:464–73.
[56] Squire LR. Declarative and nondeclarative memory: multiple brain systems supporting learning and memory. Journal of Cognitive Neuroscience 1992;4:232–43.
[57] Squire LR, Knowlton BJ, Musen G. The structure and organization of memory. Annual Review of Psychology 1993;44:453–95.
[58] Swainson R, Rogers RD, Sahakian BJ, Summers BA, Polkey CE, Robbins TW. Probabilistic learning and reversal deficits in patients with Parkinson's disease or frontal or temporal lobe lesions: possible adverse effects of dopaminergic medication. Neuropsychologia 2000;38:596–612.
[59] Tulving E, Schacter DL. Priming and human memory systems. Science 1990;247:301–6.
[60] Vriezen ER, Moscovitch M. Memory for temporal order and conditional associative learning in patients with Parkinson's disease. Neuropsychologia 1990;28:1283–93.
[61] Wagner AD, Desmond JE, Demb JB, Glover GH, Gabrielli JDE. Semantic repetition priming for verbal and pictorial knowledge: a functional MRI study of left inferior prefrontal cortex. Journal of Cognitive Neuroscience 1997;9:714–26.
[62] Wallesch CW, Karnath HO, Papagno C, Zimmermann P, Deuschl G, Lucking CH. Parkinson's disease patient's behavior in a covered maze learning task. Neuropsychologia 1990;28:839–49.
[63] Winocur G, Moscovitch M, Bruni J. Negative transfer (AB–AC) learning in normal old people and in patients with unilateral temporal-lobe or frontal-lobe lesions: heightened interference on conceptual, implicit tests of memory. Brain and Cognition 1996;50:44–58.
[64] Winocur G, Moscovitch M, Stuss D. A neuropsychological investigation of explicit and implicit memory in institutionalized and community-dwelling old people. Neuropsychology 1996;10:57–65.
[65] Yonelinas AP, Jacoby LL. Dissociations in recognition memory: effects of interference and response speed. Canadian Journal of Experimental Psychology 1994;48:516–34.