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Which processes are involved in cognitive procedural learning?

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Procedural memory is characterised by a relative resistance to pathology, making its assessment of the utmost importance. However, few studies have looked at the cognitive processes involved in cognitive procedural learning. In an initial experiment, we studied the role of different cognitive functions in massed cognitive procedural learning. Our results confirmed the existence of three separate learning phases and, for the first time, demonstrated the involvement of episodic memory and executive functions in the first learning phase. In a second experiment, we studied the effect of distributed learning conditions on the dynamics of procedural learning. This second study confirmed our results but showed that these conditions slow down the process of cognitive procedural learning. Our overall findings call into question the status of functionally autonomous memory system that is currently allotted to procedural memory, and suggest that the role of nonprocedural cognitive components should be taken into account in patient rehabilitation.

Procedural memory is defined by Cohen and Squire (1980) as the memory system in charge of encoding, storing, and retrieving the procedures that underlie motor, verbal, and cognitive skills. Procedural learning abilities are thus assessed by means of learning tasks involving a motor, verbal, or cognitive procedure. This assessment is essential in cognitive rehabilitation, its main goal being to estimate patients' abilities to learn new procedures. Occupational rehabilitation is indeed a possibility for some amnesic patients, who can learn a new skill based on the performance of complex procedures (Andrewes & Gielewski, 1999; Van der Linden & Coyette, 1995). Various types of procedural learning have been found to be preserved in amnesic patients

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(Cohen & Squire, 1980; Corkin, 1968; Milner, 1962; Saint-Cyr, Taylor, & Lang, 1988; Schmidtke, Hanschu & Vollmer, 1996). However, the ability of amnesic patients to acquire cognitive procedures is currently being called into question (Butters, Wolfe, Marone, Granholm, & Cermak, 1985; Winter, Broman, Rose, & Reber, 2001; Xu & Corkin, 2001). Some authors report a deleterious effect of pathology on patients' procedural cognitive learning abilities, as assessed by repeated administration of the Tower of Hanoi task (TH task; Cohen, Eichenbaum, Deacedo, & Corkin, 1985) or the Tower of Toronto task (TT task; Saint Cyr et al., 1988).

Tower tasks such as the TH and TT tasks, also known as disc-transfer tasks, have become a useful neuropsychological assessment tool for cognitive skill learning and frontal-executive disabilities. When they are used over just a few trials, they primarily measure executive functions, whereas when they are practised over many learning sessions, they mainly measure cognitive procedural learning. The difficulties encountered by amnesic patients are ascribed to reliance, during the acquisition process, on either executive functions (Butters et al., 1985) or episodic memory (Winter et al., 2001; Xu & Corkin, 2001), both of which are impaired in amnesia. Michel, Danion, Grange, and Sandner (1998) also claim that the difficulties schizophrenic patients have in learning the TT task reflect poor problem-solving abilities, defective episodic memory, and poor general processing. Lastly, the difficulties of healthy older subjects in learning the TT task (Peretti, Danion, Gierski, & Grange, 2002) or the TH task (Vakil & Agmon-Aschkenazi, 1997) are often interpreted as the negative effect of normal ageing on attention, episodic memory, or intellectual functions. The contribution of nonprocedural functions to cognitive procedural learning has led some authors to call into question the validity of the TH task as a cognitive procedural test.

Two alternative hypotheses can be formulated concerning cognitive procedural tests in general and the TH and TT tasks in particular. The first supports the theory put forward by Butters et al. (1985), Xu and Corkin (2001), and Winter et al. (2001), and queries the validity of the disc-transfer tasks as cognitive procedural tests because of the intervention of nonprocedural cognitive functions. This hypothesis rests on the idea that procedural memory is a functionally autonomous memory system, which can be assessed using "pure" procedural tests. However, it is the second hypothesis that we have adopted. We do not question the disc-transfer tasks' validity as procedural tests, but rather the current neuropsychological concept of procedural learning as an implicit phenomenon relying solely on procedural memory (Beaunieux, Desgranges, Lalevée, De la Sayette, Lechevalier, & Eustache, 1998). Indeed, work carried out in the fields of rehabilitation (Baddeley & Wilson, 1994) and cognitive psychology (Anderson, 1982) suggests that cognitive procedural learning requires the intervention of nonprocedural functions. This consideration contests the functionally autonomous status of procedural memory during the encoding of a new procedure, regarding procedural learning as a phenomenon requiring significant inter-systemic collaboration.

The role played by various cognitive components during the learning of complex procedures (or inter-systemic collaboration) has been theorised in the ACT model (Adaptive Control of Thoughts; Anderson, 1999). According to this model, cognitive procedural learning occurs in three qualitatively different phases (cognitive, associative, and autonomous) and involves different types of processing. Learning a new cognitive procedure requires processes that are highly controlled in the initial, cognitive phase, and more automatic ones in the autonomous phase. In the first two phases (cognitive and associative), problem-solving functions and working memory are needed to generate the new cognitive procedure that is to be automated. The autonomous phase does not require the intervention of the cognitive functions involved in the cognitive phase, and is essentially characterised by the intervention of procedural memory per se. The involvement of episodic memory and executive functions in procedural learning has been suggested (Beaunieux et al., 1998; Butters et al., 1985; Wilson, Baddeley, Evans, & Shiel, 1994) but never proved experimentally. According to this model, only in the autonomous phase does procedural memory become functionally independent. The learning of a new cognitive procedure therefore involves other cognitive functions, making the search for a "pure" procedural test entirely illusory.

In order to check this assumption, Ackerman (1988; see also Ackerman & Cianciolo, 2000) carried out a series of studies designed to pinpoint the three phases of procedural learning postulated in the ACT model via specific cognitive determinants of individual differences during skill acquisition. During the initial, cognitive phase, performance levels are associated with general intelligence. In his first study, Ackerman (1988) concluded that in the intermediate, associative phase, performance levels are related to perceptual processing. However, in 2000, Ackerman and Cianciolo reconsidered the predictive validity of this cognitive function for procedural performance, suggesting that its contribution would depend on the type of perceptual ability involved in the test used for its assessment. Lastly, in the autonomous phase, they claimed that individual differences in performance would be largely determined by psychomotor functions.

Alongside these three functions (intelligence, perceptual processing, and psychomotor functions) studied in Ackerman's experiments (1988, 1990, and Ackerman & Cianciolo, 2000), other authors have suggested that additional cognitive functions may be involved. Unfortunately, few of these authors have validated their claims in experiments. Only Woltz (1988) has both proposed and demonstrated that working memory is a major cognitive determinant of individual differences in the first two phases. Butters et al. (1985) and Saint Cyr et al. (1988) have gone no further than suggest the involvement of executive functions in the first phase of cognitive procedural learning. Similarly, Baddeley and Wilson (1994) have stressed the major contribution of episodic memory in the first two phases without actually proving it. These authors suggest that episodic memory of previous learning episodes can be called upon in order to eliminate errors on subsequent trials. In the absence of such explicit recollection, amnesic patients therefore continue to make the same errors long after the controls have mastered the task. Lastly, only Schmidtke et al. (1996, see also Schmidtke, Manner, Kaufmann, & Schmolck, 2002) have studied procedural learning with a view to establishing a link between nonprocedural cognitive functions and procedural performance levels, with direct reference to Ackerman's conceptions (1988, 1990). Although these two studies used just a small number of trials (three learning sessions of two trials each), which did not allow the subjects to go beyond the cognitive phase, they nevertheless confirmed the value of an overall approach to the procedural learning process.

An analysis of the correlations between procedural performance levels and intelligence and psychomotor scores in the light of Anderson's (1987) and Ackerman's (1988) studies would provide valuable information about the dynamics of the procedural learning process which cannot be obtained by simply examining learning indices. To sum up, the three different phases of cognitive learning can be pinpointed by studying the correlations between these intelligence and psychomotor functions and the levels of procedural performance in the first and last phases. The intermediate phase (associative phase) can then be defined by default. The definition of these three phases will then allow us to analyse the respective roles of episodic memory, working memory, and executive functions in the encoding of a new cognitive procedure in procedural memory.

Accurate knowledge of the processes involved in cognitive procedural learning is necessary in order to improve our understanding of the difficulties encountered by patients during cognitive rehabilitation based on residual procedural abilities.

EXPERIMENT 1

The aims of the first study were (1) to identify the three learning stages involved in a clinical cognitive procedural learning test (TT task) with reference to Ackerman's model (1988, 1990) by examining the contribution of intelligence and psychomotor functions, and (2) to characterise these learning phases and particularly to validate experimentally the contribution of episodic memory and executive functions to cognitive procedural learning for the first time.

A cognitive procedural learning test was administered to a large sample of subjects ($N = 100$). To enable them to reach the autonomous phase, the subjects performed 40 trials of the TT task. Moreover, with reference to the literature, we took into account all the nonprocedural cognitive functions that might be involved in the acquisition of this new procedure. We targeted our assessment on six cognitive functions potentially involved in cognitive procedural learning. With reference to Ackerman's studies (1988, 1990), and in order to distinguish between the cognitive, associative, and autonomous phases, we assessed general intelligence and psychomotor functions. In order to characterise these three phases, we also measured the efficiency of working memory, episodic memory, executive functions, and perceptual processing.

Method

Subjects

Subjects were 100 unpaid volunteers (50% males), between 18 and 35 years old (mean age = 21.8, *SD* = 3.9). Their mean educational level, assessed by the Mill Hill Scale (Deltour, 1998), was 33.9/44 (*SD* = 3.9). All subjects were screened by a health questionnaire for any history of neurological or psychiatric conditions, head trauma, and alcohol or drug abuse. Because the procedural task involved the processing of colours (see below), subjects were also screened for colour blindness. Lastly, we made sure that the TT problem was not known to any of the subjects.

Materials

General principles. The experimental protocol featured two sessions with a 1-week interval in between. The first session concerned the procedural learning of the TT task. Subjects were asked to perform 40 trials, i.e., eight blocks of five trials. In order to assess the cognitive processing involved in cognitive procedural learning, we added a set of supplementary cognitive tasks in the second session.

Procedural task (TT task). The TT task consisted of a rectangular base and three pegs. Four different-coloured discs were used: one black, one red, one yellow, and one white. The TT discs were initially stacked on the leftmost peg, with the darkest one at the bottom and the lightest one on top. The task consisted in rebuilding this configuration on the rightmost peg, obeying the following two rules: only one disc may be moved at a time, and a darker disc may never be placed on top of a lighter one. The rules were read out to the subjects and explained through examples of authorised and unauthorised moves. All the instructions were written on a sheet, which was placed near the subject. Participants were only required to solve the puzzle; no reference was made to completing it in the fewest possible moves or shortest possible time. They were required to solve eight blocks of five consecutive trials, with a 5-minute pause between each block. With reference to a pre-experiment, we also added a rule that was, in fact, a cue for the subject: begin by putting the white disc on the middle peg. This first move is vital for solving the puzzle and constitutes one of the most difficult points of this problem. This instruction was given in order to avoid a probably random choice by the subjects and to ensure that they all began directly with the correct procedure. The TT device was connected to a computer, which recorded the following variables for each subject: completion time (s) and the number of moves per trial. The minimum number of moves for the TT task is 15.

Cognitive tasks. General intellectual functions were assessed using two subtests of the Wechsler Adult Intelligence Scale (WAIS-III; Wechsler, 2001, French version): Block Design and Matrix Reasoning.

Block Design: This task assesses nonverbal intelligence abilities. A series of drawings is shown to the subject, who has to reproduce them using cubes (four to nine cubes). The cubes have two white, two red, and two two-tone sides. The subject is given the number of cubes needed to replicate the pattern. The maximum score is 68.

Matrix Reasoning: This test involves four types of nonverbal fluid reasoning: pattern completion (perceptual visual), classification, relations, and analogic reasoning. An incomplete matrix is shown to the subject and s/he must identify the missing part among five possible choices. The maximum score is 26.

To assess psychomotor abilities, we asked the subjects to carry out two disc transfer tasks.

First transfer task (TT task): The aim is to transfer the four discs (one by one) from the leftmost peg to the middle peg, then to the rightmost peg, and finally to the leftmost one. The only instruction given is to use only one hand. The total transfer time is recorded (12 moves). This transfer task was performed twice: before and after the procedural learning of the TT task. An average transfer time was calculated for the two recorded times.

Second transfer task (Tower of London): The principle is exactly the same as the previous one.

Working memory was assessed by means of two span tests: the WAIS-III digit span (Wechsler, 2001) and the visuospatial span test from the BEM 144 (Signoret, 1991). The BEM 144 scale is a French memory scale that assesses short-term and long-term memory in their verbal and visual modalities. The ability to handle information in working memory was also measured using the Letter Number Sequencing test taken from the WAIS-III:

Forward digit span: This consists of the immediate recall of numbers in the same numerical order.

Backward digit span: This consists of the immediate recall of numbers in reverse order.

Forward visuospatial span: This consists of the immediate serial reproduction of increasing spatial sequences. The material is composed of a rectangular wooden base on which nine cubes are arranged.

Backward visuospatial span: This consists of the immediate serial reproduction of increasing spatial sequences in reverse order.

The scores for each span test correspond to the maximum number of correctly recalled items. The maximum score for each one is 9.

Letter number sequencing: Increasing sequences of figures and letters are read out to the subject. S/he must recall the numbers in increasing order first, then the letters in alphabetical order. Each item consists of three trials of the same length.

Episodic memory was assessed using the California Verbal Learning Test in an abbreviated form, together with the Digit Symbol-Coding (pairing) and Digit Symbol-Coding (free recall) tests.

California Verbal Learning Test (Delis, Massman, Butters, Salmon, Cermak, & Kramer, 1991): This task is based on the memorising of 16 items belonging to four semantic categories. The list is read out once, and the subject must then perform an immediate free recall. The maximum score is 16.

Digit Symbol-Coding (pairing): Under each number, the subject must draw the symbol that was associated with it. The maximum score is 18.

Digit Symbol-Coding (free recall): This task consists in recalling as many symbols as possible. The maximum score is 9.

Executive functions were assessed using the last subtest of the Stroop Test (Stroop, 1935), the Trail Making test (Reitan, 1958), an adapted version of the Tower of London (Shallice, 1982), and a Choice Reaction Time test.

The Stroop Test: In the third subtest (word colour), the subject is asked to name the colour in which the words have been written (names of colours), without paying any attention to the word itself. An *inhibition* score is then calculated $(I = WC - (C \times W)/(C + W)$.

The Trail Making Test is used to assess flexibility. The first score (score A) corresponds to the time required to connect the numbers in numerical order. Score B reflects the time taken to alternate numbers and letters (1 A 2 B 3 C, etc.). The flexibility score corresponds to B – A.

The Tower of London: To assess planning abilities, we used an adapted version of the Tower of London (more suitable for younger subjects, Ward & Allport, 1997). In order to avoid ceiling effects and to make this test similar in complexity to the TT task, we constructed a version with four stackable beads on three pegs. Although these tests share a common form, they differ in the cognitive processes they involve: the Tower of London features different items at each trial (and thus assesses planning), whereas the TT task is constant in the type of processing it requires (learning). Subjects are shown two bases, on which four beads are laid out in two different patterns. The experimenter's base features the configuration that the subjects must copy. The subjects must solve the problem in a minimum number of moves by changing the arrangement of beads on their base. The subjects are asked not to carry out the first move until they think they have planned the right sequence of moves. We can obtain several indices: e.g., a success rate, which corresponds to the number of problems solved in an optimum way divided by the total number of items. We can also calculate a planning time, which corresponds to the total puzzle-solving time minus the transfer time.

Choice Reaction Time test: Stimuli are presented to the subject in the middle of a screen. These stimuli may be yellow circles, squares, or triangles. The following instructions are read by the subjects: "The aim of this test is to measure your reaction time. When a yellow circle appears, and only a yellow circle, press the space bar as quickly as possible." From this test, two variables can be extracted: the average reaction time, reflecting perceptual processing speed, and the number of errors made by each subject, reflecting inhibition abilities.

Perceptual processing was measured by means of two subtests of the WAIS-III: Digit Symbol-Coding and Symbol Search. We also selected the "Word" and "Colour" perceptual tasks of the Stroop Test (Stroop, 1935) and the BAMS-T (Lahy, 1978).

Digit Symbol-Coding: A series of numbers (1 to 9), each associated with a different graphic symbol, is shown to the subject as a model. Referring to this model, the subject must then match each number with the corresponding graphic symbol. Processing speed is measured by counting the number of symbols drawn underneath each number within 90 seconds. The maximum score is 133 (number of correct pairings: *Digit Symbol-Coding* raw score). Second, in order to measure psychomotor speed in the performance of the previous test, the subject is asked to copy the symbols that are shown to him/her (identical to those previously used). The score corresponds to the number of symbols copied within 90 seconds (*Digit Symbol-Coding* copy). The maximum score is 133.

Symbol Search: A series of five different symbols is presented to the subject. Two symbols are displayed to the left of these items. The subject must indicate if s/he can find either of the two symbols in the group of five. The subject has 120 seconds to process the maximum number of items. The maximum score is 60.

The Stroop Test: This task includes three subtests. In the first subtest (Word), the subject is asked to read the words *red*, *blue*, *green*, which are written in black, as fast as possible, within the space of 45 seconds. The Word score corresponds to the number of words read within 45 seconds. In the second subtest (Colour), the subject has to name the colours in which rectangles have been drawn on a sheet of paper as fast as possible, within the space of 45 seconds. The third subtest generates an inhibition score (see below). The scores for each subtest correspond to the number of correct answers.

The BAMS-T: This test is a crossing-out task, which involves a single page filled with rows of eight different symbols. Subjects are instructed to cross out every instance of the three target symbols, which are indicated at the top of the page, within the space of five minutes. Two scores are calculated: the speed and the accuracy of the perceptual processing. The speed score was calculated as follows: (total number of crossings-out)/(time in seconds). The accuracy score was calculated as follows: (number of correct crossings-out − number of omissions)/(number of correct crossings-out − number of errors).

Statistical analyses

Assessment of cognitive procedural learning. Performances on the TT task were assessed by means of two variables: the total problem-solving time (in seconds) and the number of moves per trial, which were subjected to a repeated-measures analysis of variance (repetition factor: trials).

Delimitation of the three learning phases. The three learning phases were determined with reference to Ackerman's model (1988), by studying the correlations between the intelligence and psychomotor scores and the levels of performance on the TT task in terms of total time per trial. For this analysis, we chose not to consider the number of moves per trial, as it was not sufficiently sensitive. Indeed, this variable loses its variability as soon as the subjects find the solution to the problem and thus does not take into account the automation of the cognitive procedure. The total time per trial, on the other hand, takes into account all the processes involved (both cognitive and motor components of the task).

This analysis was conducted in three steps. The first step consisted of summarising the cognitive scores, by means of a Principal Component Analysis (PCA). After standardising them in order to reduce the disparity of the units and orders of magnitude, we extracted the independent factors with maximum variance, each of which represented one of the cognitive abilities we were studying. We then calculated a factor score for each subject. The second step consisted of studying the correlations between the intelligence and psychomotor factor scores and the performance levels in terms of time per trial of the TT task. The third step consisted of a comparison of the correlations calculated for each trial by means of Steiger's test (1980). In order to establish the major cognitive determinant of the procedural performance level, we looked for significant differences between the various calculated correlations for each trial. With reference to Ackerman's model, we expected to find:

- For the cognitive phase, a significant difference in the correlations between general intellectual abilities and performance levels in terms of time per trial of the TT task on the one hand and the correlations between psychomotor abilities and performance levels in terms of time per trial of the TT task on the other hand. This difference should be in favour of general intellectual abilities.
- For the associative phase, no significant difference between the correlations.
- For the autonomous phase, a significant difference in the correlations between general intellectual abilities and performance levels in terms of time per trial of the TT

task on the one hand and the correlations between psychomotor abilities and performance levels in terms of time per trial of the TT task on the other hand. This difference should be in favour of psychomotor abilities.

This analysis allowed us to delimit the three learning phases proposed in the ACT model (Anderson, 1999).

Testing the boundaries of the learning phases. In order to test the boundaries of the phases identified in the first analysis, we then measured the degree of improvement in performances for each phase, as Ackerman (1990) postulated that it would differ each time. In the cognitive phase, there would be a noticeable improvement, with considerable individual differences. In the associative phase, subjects would start to discover the optimum solution and would remain close to this solution during subsequent trials. Improvement would be slight and variability would decrease. Lastly, the autonomous phase would be characterised by stable performance levels and the standard deviation of individual differences would be close to zero.

For each phase, the learning time scores were calculated by dividing the linear regression slope calculated on raw scores by its intercept. The learning scores were subjected to a repeated-measures analysis of variance (repetition factor: phases). Post-hoc analyses were conducted using Fisher's LSD test.

Characterising the procedural learning phases. In order to study the contribution of episodic memory, working memory, executive functions, and perceptual processing to cognitive procedural learning, we examined the correlations between these functions and the procedural performance

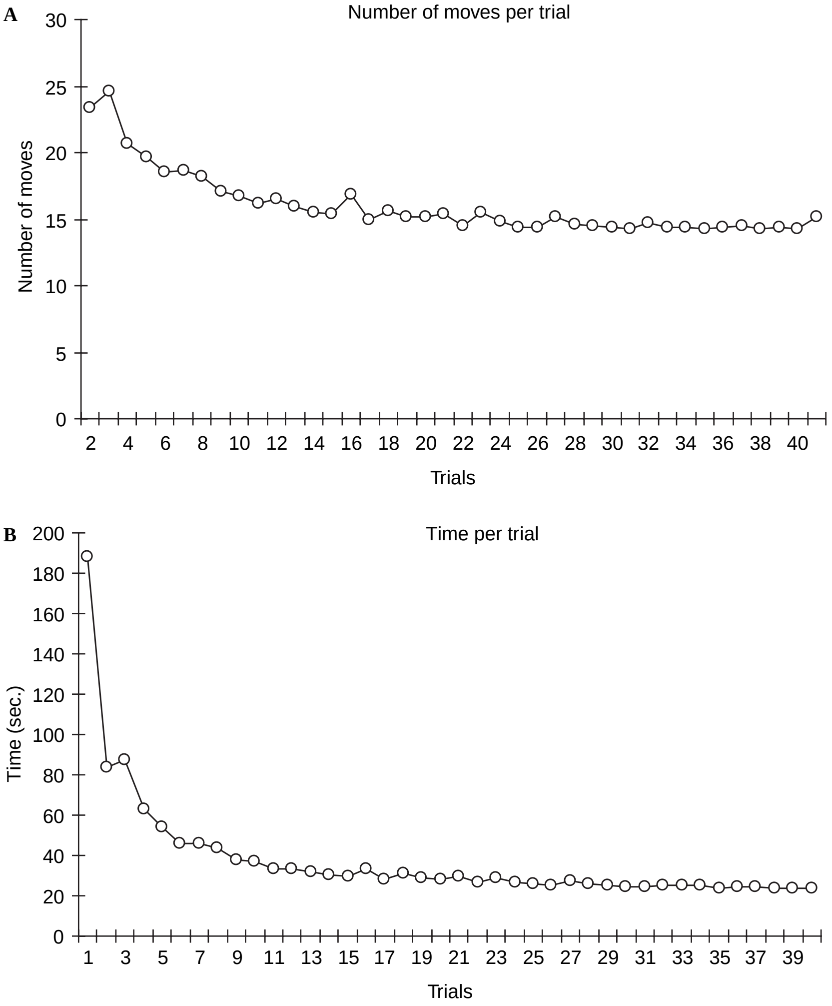

Figure 1. Performance trends in terms of moves (A) and completion time (B) per trial in the Tower of Toronto task.

level (total time per trial) in relation to the previously defined boundaries.

Results

Assessing cognitive procedural learning

Figure 1 presents the results obtained in terms of the number of moves and time per trial. First, in terms of moves (Figure 1A) the results showed a significant effect of trial repetition on mean performance level, $F(39, 3900) = 23.19$; $p < .0001$. There was an overall decrease in the number of moves needed to solve the puzzle across the 40 trials.

The analysis of variance carried out on the data for time per trial (Figure 1B) showed a significant effect of trial repetition, $F(39, 3900) = 56.95$; $p < .001$. The subjects improved their performances with practice, the completion time decreasing across the skill acquisition trials.

Delimitation of the three learning phases

The Principal Component Analysis of the cognitive indices revealed five distinct factors that explained 55% of variance (Table 1).

The first factor (19% of variance) is explained by the scores on the forward digit span, backward digit span, forward visuospatial span, and letter number sequencing tests. This factor can be interpreted as a working memory factor. Factor 2 (12.5% of variance) is determined by perceptual processing ability scores—Digit Symbol-Coding, DSC (copy), Symbol Search, and BAMS-T (speed). Factor 2 can be regarded as the perceptual processing speed factor. The third factor (9% of variance) contains all episodic memory scores—California Verbal Learning test, DSC (pairing), and DSC (free recall). This factor can be seen as an episodic factor. The fourth factor (7.5% of variance) is explained by the psychomotor scores and can be regarded as the psychomotor factor. The fifth factor (7% of variance) is determined by intelligence ability scores—Block Design, Matrix Reasoning, backward visuospatial span, and Tower of London (planning). We only observed unidimensional variables.

The contribution of intelligence and psychomotor functions to performance levels during procedural learning was examined through the correlations between procedural performance levels and cognitive scores (factor scores) across the trials. Correlations between intelligence and

TABLE 1
Principal Component Analysis: Factor solution

	Factor 1	*Factor 2*	*Factor 3*	*Factor 4*	*Factor 5*
Block Design	.09	.26	.23	−.15	**.67**
Matrix Reasoning	.18	.06	.12	.06	**.70**
Digit Symbol-Coding (raw score)	.08	**.78**	.18	.05	.11
Digit Symbol-Coding (copy)	−.04	**.69**	−.16	−.27	−.01
Symbol Search	.27	**.73**	.03	−.06	.14
BAMS-T (speed)	−.11	**.72**	.24	.08	−.04
Mean Choice Reaction Time	−.08	−.44	.002	.23	−.22
Tower of Toronto (transfer task)	−.04	−.12	−.09	**.89**	.08
Tower of London (transfer task)	.02	−.19	.006	**.90**	−.06
Forward digit span	**.76**	−.01	−.07	.15	.06
Backward digit span	**.64**	.03	.22	−.07	.06
Forward visuospatial span	**.51**	.06	−.13	−.15	.37
Backward visuospatial span	.23	.20	.12	.14	**.55**
Letter Number Sequencing	**.70**	.01	.10	.18	.10
California Verbal Learning Test	.19	.14	**.53**	−.12	−.008
Digit Symbol-Coding (pairing)	.04	.02	**.86**	.01	.16
Digit Symbol-Coding (free recall)	−.006	.05	**.84**	−.0006	.19
Stroop (inhibition)	.39	.22	.16	.03	−.17
Tower of London (planning)	−.28	−.14	.004	.09	**.60**
Choice Reaction Time (no. of errors)	−.20	−.05	.02	−.37	−.06
Variance explained (%)	19	12.5	9	7.5	7

Salient loadings (those greater than .500; $p < .05$) are in boldface type.
BASM-T = Perceptual processing task.

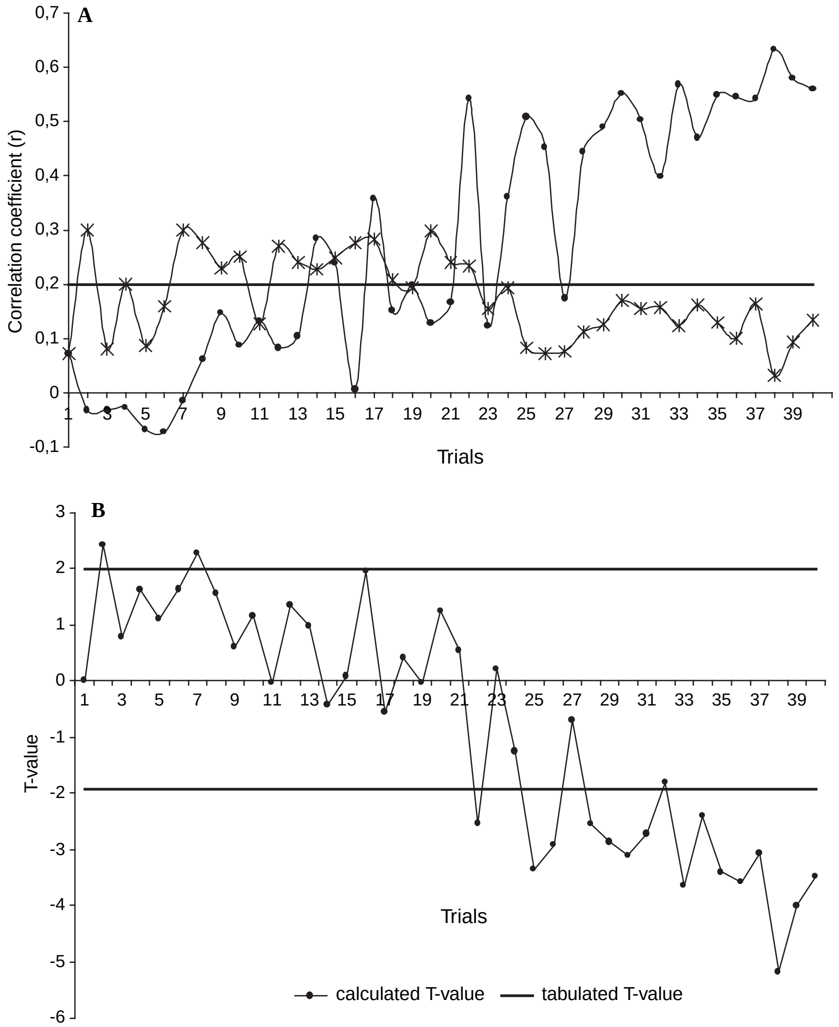

Figure 2. (A) Correlations between procedural performance levels (time in seconds) and the factor scores of intelligence and psychomotor abilities. The boldface horizontal lines correspond to the statistical threshold $p = .05$. The correlations located above these lines are significant. (B) Calculated T-value, assessing the existence or otherwise of a significant difference between the various correlations calculated for each trial and shown in Figure 2A. The boldface horizontal lines correspond to the tabulated T-value $p = .05$. The calculated T-values located above and under these lines are significant (see text).

psychomotor scores and procedural performance levels across the trials are shown in Figure 2. The correlations above 0.2 are significant at $p < .05$.

General intelligence abilities were significantly correlated with procedural performance levels in the first half of the learning process, up to the 22nd trial. As for psychomotor abilities, these were significantly correlated with procedural performance levels from the 15th trial onwards (Figure 2A).

In order to establish the major cognitive determinant of the procedural performance level, we looked for significant differences between the various calculated correlations for each trial by means of Steiger's test (1980). The comparison of the correlations between performance levels in terms of time per trial of the TT task and general intelligence abilities on the one hand, and psychomotor abilities on the other hand, confirmed our predictions (Figure 2B). During the first trials (trials 1 to 7), there was a significant difference between the contributions of intellectual and psychomotor abilities to the levels of procedural performance, in favour of the former. Between trials 8 and 22, there was no difference in contributions. Lastly, between trials 23 and 40, there was a significant difference between the contributions of intellectual and psychomotor abilities to the levels of procedural performance, in favour of the latter.

With reference to the model proposed by Ackerman (1988), these results are in line with the ACT model, as they demonstrate the existence of three phases in cognitive procedural learning: a cognitive phase in the first third of learning, an associative phase in the middle third and an autonomous phase in the last third.

Testing the boundaries of the learning phases

In order to test the boundaries of the phases established by the previous analysis, we studied the capacities for improvement in terms of time within each phase, defined as follows: the cognitive phase was studied from trial 1 to 7, the associative phase from trial 8 to 22, and lastly the autonomous phase from trial 23 to 40. Learning scores showed that completion times decreased across these three phases (Table 2).

A repeated-measures analysis of variance showed a significant effect of phase repetition on learning scores, $F(2, 198) = 117.35$; $p < .0001$. As expected, the post-hoc analysis showed that the total effect of repetition could primarily be explained by a difference between the cognitive and associative phases on the one hand ($p < .0001$) and the autonomous phase on the other ($p < .0001$). The comparison of the associative and autonomous phases did not reach significance in terms of performance improvement ($p < .06$), although we did note a reduction in the standard deviation (see Table 2).

Characterising the procedural learning phases

In order to characterise the three learning phases, we also studied the correlations between episodic memory and working memory scores (Figure 3A) and perceptual processing abilities, executive functions (Figure 3B), and procedural performance levels across the trials.

TABLE 2
Mean learning scores per phase in terms of completion time

Phases	*Mean*	*Standard Deviation*
Cognitive	−0.1	0.06
Associative	−0.02	0.05
Autonomous	−0.005	0.005

The learning time scores were calculated by dividing the linear regression slope calculated on raw scores by its intercept.

Episodic abilities were involved to a small extent at the beginning of the learning process, but declined across the trials. For working memory, the correlations were significant only in the 4th and 7th trials. In the case of perceptual processing abilities, correlations remained significant and stable throughout the TT task learning process.

Lastly, we wished to study the contribution of executive functions to procedural performance levels. Because the Principal Component Analysis did not enable us to extract an "executive functions" factor, we studied the correlations between performance levels and the different executive scores. The results revealed inconstant significant correlations between procedural performance levels and flexibility, which were particularly dominant at the beginning and end of the learning process. We also observed significant correlations between the numbers of errors on the choice reaction time test and procedural performance levels, especially during the first six trials (data not shown). We did not observe any significant correlations between the planning or inhibition abilities assessed by the Stroop test and procedural performance levels (data not shown).

Discussion

This first experiment confirmed the beneficial effect of trial repetition on performances in terms of the number of moves and the time taken to solve the TT task. In addition, the Principal Component Analysis of the cognitive scores revealed the existence of five factors corresponding to the cognitive components that we had set out to assess: working memory, perceptual processing abilities, episodic memory, psychomotor abilities, and general intelligence. The study of the contribution of general intelligence and psychomotor functions to procedural performance levels generally confirmed the model proposed by Ackerman (1988, 1990), showing the existence of three distinct phases during the learning of the TT task. The study of the learning indices enabled us to confirm the boundaries of these phases. With reference to these boundaries, we demonstrated the involvement of episodic and working memory during the cognitive phase. Executive functions were involved in a more dominant way in the cognitive and autonomous phases. Lastly,

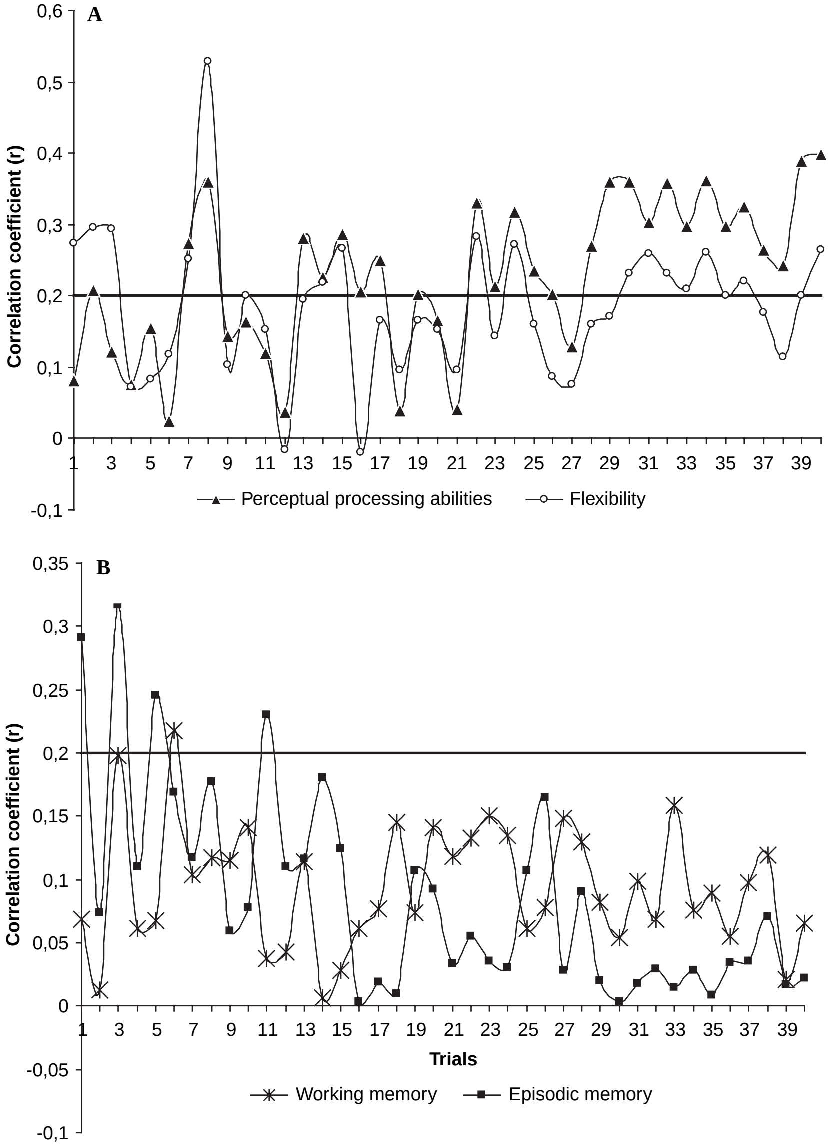

Figure 3. (A) Correlations between procedural performance levels (time in seconds) and the factor scores of perceptual processing abilities. (B) Correlations between procedural performance levels (time in seconds) and the factor scores of working and episodic memories. The boldface horizontal lines correspond to the statistical threshold $p = .05$. The correlations located above these lines are significant.

perceptual processing abilities did not seem to be specific to any procedural learning phase.

The beneficial effect of trial repetition on performance during the TT test in young subjects confirmed the findings of Peretti et al. (2002), who reported equivalent results with the same material in a group of twenty young subjects across 24 trials.

The first finding of the analysis of the cognitive determinants of procedural performance levels was that general intelligence plays an important role in predicting individual differences in the early stages of cognitive procedural learning, during the development of the cognitive procedure. This result supports Ackerman's model (1988). The last learning phase is mainly determined by psychomotor abilities. This cognitive function, which, according to Ackerman (1988), is involved in the autonomous phase, was correlated with performance levels from the 15th trial onwards. This correlation initially increased, stabilising at a very significant level at around the

29th trial—a point at which the subjects reached an asymptotic level of performance. The procedural performance level at the end of the learning process was mainly determined and limited by psychomotor abilities.

The presence of strong arguments in favour of precise demarcations between the cognitive and autonomous phases enables us to make up for the lack of specificity of perceptual processing abilities when locating the associative phase. Indeed, the data obtained from functional cerebral imaging suggest that the associative phase corresponds to a mixed phase. The fMRI study conducted by Sakaï, Hikosaka, Miyauchi, Takino, Sasaki, and Pütz (1998), which focused on the acquisition of a motor procedure, showed that the cerebral substrates involved in the associative phase corresponded to those involved in the other two phases, albeit to a lesser degree. Similarly, our data enabled us to define the associative phase as corresponding to the joint involvement of the cognitive determinants engaged in the other two phases, i.e., general intelligence and psychomotor abilities. The cognitive phase would thus correspond to the phase during which general intelligence alone determined the level of performance. This phase finished with trial 7, as psychomotor abilities became one of the determinants of the second phase, along with general intelligence. This double involvement continued until trial 22. This period thus defined the associative phase. Lastly, the autonomous phase was characterised by an end to the involvement of general intelligence.

In line with Ackerman's postulate (1988), the testing of the above-defined boundaries of the phases revealed a clearer improvement in performances in the cognitive phase and a very significant reduction in this improvement in the last two phases. In the cognitive phase, the subjects started out with a low level of performance. The margin for improvement was therefore greater. We did not observe any difference between the two last phases, although they could be distinguished by the standard deviation values. The delimitation of the boundaries would thus appear to have been correctly established.

In relation to the above-defined boundaries, working memory contributed to performance levels at the cognitive phase, in line with Anderson's proposition (1987). However, unlike Woltz (1988), we did not observe any significant correlations in the associative phase.

The characterisation of the different learning phases also revealed a contribution of episodic memory during the cognitive phase, albeit to a less extent than intelligence. It nevertheless supported our learning phase interpretation and confirmed Wilson et al.'s suggestions (1994) that episodic memory is involved in this cognitive phase. This contribution can be given several non-exclusive interpretations. The first would be that, during the first trial, the subject tries to remember whether s/he has ever encountered a similar problem before. This memory system may also play a role during the learning process by searching the memory for previously used strategies and errors made during previous trials. Its contribution can also be regarded as necessary for retaining the test instructions in memory. The relatively weak involvement of episodic memory during the cognitive phase could be due to the massed learning condition, which may require a less significant contribution from episodic memory than the sort of distributed learning that is practised in neuropsychological rehabilitation.

The contribution of flexibility to procedural performance levels in the cognitive phase supports the findings of Miyake, Friedman, Emerson, Witzki, Howerter, and Wager (2000), Butters et al. (1985), and Saint Cyr et al. (1988). Executive functions would appear to enhance the use of the problem-solving strategies that make it possible to generate the cognitive procedure needing to be encoded. The correlations observed at the end of the learning process between flexibility and procedural performance levels could thus be regarded as a sign of automation. Indeed, the most flexible subjects were also those who recorded the shortest completion times and reach the optimum solution most quickly. This is because in order to reach the optimum completion time, they had to be able to work out the correct procedure. This development requires flexibility, as shown by the correlations observed in the first trials.

Lastly, and in accordance with Ackerman's assumptions (Ackerman & Cianciolo, 2000) about the non-specific involvement of perceptual processing abilities in the associative phase, we did not observe any specificity of this component for any given learning phase. Significant correlations between perceptual processing abilities and procedural performance levels remained stable throughout the learning process. In our study, we can explain the involvement of this cognitive function by the nature of our procedural test, which required perceptual as well as motor processing (handling of coloured discs).

These data corroborate our hypothesis that procedural memory is functionally dependent in the early stages of encoding, only becoming functionally autonomous when the procedure is fully automated. Furthermore, these data call into question certain authors' ideas about the criteria of a suitable procedural test (Butters et al., 1985; Winter et al., 2001; Xu & Corkin, 2001). It is indeed impossible to design a test that is at the same time new and automated for the subject. A task can only be purely procedural when the subject has practised it sufficiently to be able to carry it out automatically. For this reason, we believe that the learning of disc-transfer tasks (Tower of Hanoi and Tower of Toronto) is of major clinical interest, in that it allows us to predict patients' difficulties when learning the complex procedures involved in neuropsychological rehabilitation.

For the first time ever, this initial experiment presents an analysis of the contribution of cognitive components to all phases of clinical cognitive procedural test learning, in the light of the procedural learning model proposed by Ackerman (1988, 1990). Thanks to an extensive study of the procedural learning process (40 trials) involving a large number of subjects ($N =$ 100), our work has shown, in line with Anderson's model (1999), the existence of three phases, during which subjects discover and automate the cognitive procedure. As well as confirming the existence of three separate phases of cognitive procedural learning, we demonstrate experimentally—and for the very first time—the involvement of episodic memory and executive functions during the cognitive phase. However, this experiment was conducted under massed procedural learning conditions, which are seldom encountered in neuropsychological rehabilitation. It consequently seemed important to study the effect of distributed learning conditions on the dynamics of cognitive procedural learning.

EXPERIMENT 2

The aim of this second experiment was to gain a better understanding of the effects of distributed cognitive procedural learning on the dynamics of the learning process. In neuropsychological rehabilitation, patients are generally taught complex procedures under distributed learning conditions. Teaching a patient how to use an electronic diary or a computer may therefore take months. However, we can hypothesise that this learning condition slows down the automation process of the cognitive procedure. A better understanding of the effects of distributed cognitive procedural learning on the dynamics of learning could explain the cognitive procedural learning difficulties observed in patients. However, no study has specifically looked into this problem.

Because our first experiment focused on a population of young subjects who did not truly represent the majority of brain-injured patients, a sample of older subjects was subjected to a distributed cognitive procedural learning test (TT task), as well as to supplementary cognitive tests. We based our assessment on four cognitive functions involved in cognitive procedural learning in the first experiment: intelligence, psychomotor abilities, working memory, and episodic memory.

Method

Subjects

A total of 40 unpaid volunteers took part in this experiment. They were aged between 26 and 56 years old (mean age $=46.6$, $SD=8.5$). Inclusion criteria were the same as in Experiment 1.

Materials

General principles. The experimental protocol featured five sessions, each separated by a 1-day interval. The first four sessions concerned the procedural learning of the TT task. In order to assess the cognitive processes involved in cognitive procedural learning, we added a set of supplementary cognitive tasks in the fifth session.

Procedural task: The TT task. The cognitive procedural task was the same as in the first experiment. However, the learning conditions were different. The TT task was learned over four sessions. Each session was separated by an interval of 24 hours. Subjects were asked to perform 10 trials in each learning session.

Cognitive tasks. *General intellectual abilities* were assessed using the block design subtest of the Wechsler Adult Intelligence Scale (WAIS-III; Wechsler, 2001, French version).

Psychomotor abilities were assessed using the same transfer TT task as in the first experiment.

Working memory was assessed by means of two span tests: the WAIS-III digit span (Wechsler, 2001) and the visuospatial span test from the BEM 144 (Signoret, 1991).

Episodic memory was assessed by means of Grober and Buschke's test (Grober & Buschke, 1987) which assesses verbal episodic memory. It consists of one list of 16 words belonging to 16 different semantic categories, presented with an explicit instruction to memorise and reproduce them. This task lasts about 20 minutes, and delayed free and cued recalls, as well as recognition, were assessed 20 minutes afterwards.

Statistical analyses

Assessment of cognitive procedural learning. Performances on the TT task were assessed by means of two variables: the total problem-solving time (in seconds) and the number of moves per trial. Procedural data were analysed using a repeated-measures analysis of variance with Session and Trial as within-subject factors. We considered that there was an improvement in procedural performance when the interaction between the two effects was significant. Post-hoc analyses were conducted using Fisher's LSD test.

Delimitation of the three learning phases. The three learning phases were determined by studying the correlations between the cognitive determinants (intelligence and psychomotor abilities) and the levels of performance on the TT task in terms of total time per trial (in seconds). This analysis was conducted in two steps. The first step consisted of studying the correlations between cognitive scores and performance levels in terms of time per trial of the TT task. The second step

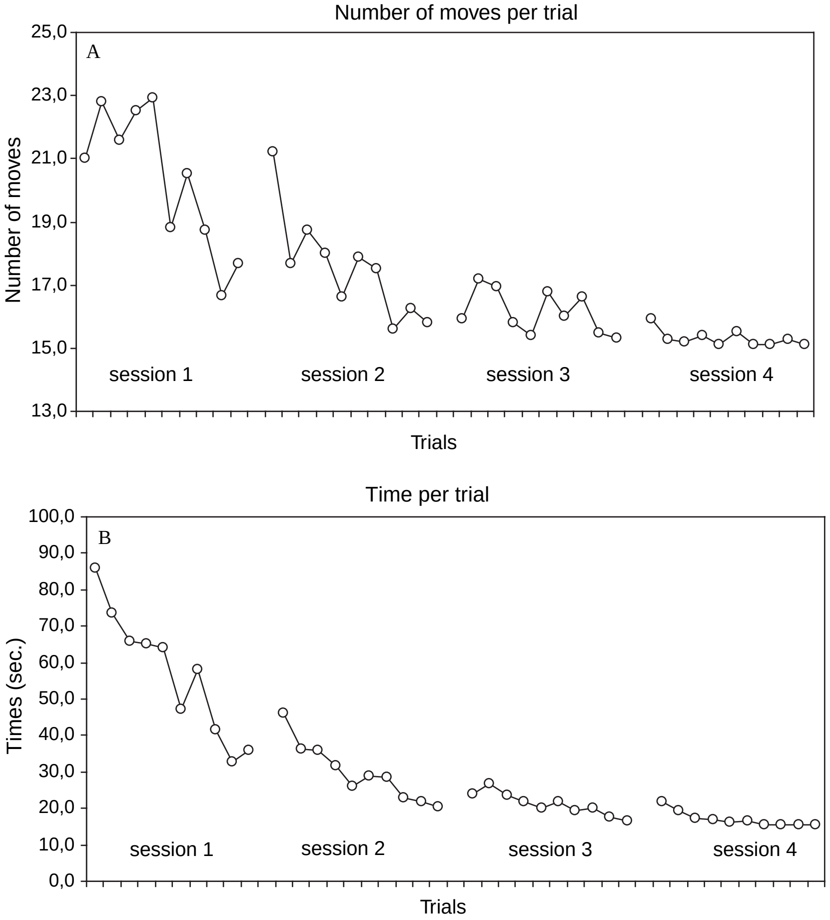

Figure 4. Performance trends in terms of moves (A) and completion time (B) per trial during the four learning sessions in the Tower of Toronto task.

consisted of a comparison of the correlations calculated for each trial by means of Steiger's test (1980). Our predictions concerning the significant differences were the same as in Experiment 1.

Characterising the learning phases. The involvement of working memory and episodic memory within the three defined learning phases was studied by means of the correlations between procedural performance levels (time per trial) and episodic and working memory scores.

Results

Assessing cognitive procedural learning

Figure 4 presents the results obtained in terms of the number of moves and time per trial. First, in terms of *moves* (Figure 4A), the results showed a significant effect of trial repetition, $F(9, 351) = 9.6$; $p < .0001$, as the subjects' performances improved during every single session. Second, there was a significant effect of session repetition $F(3, 117) = 39.2$; $p < .001$, with an overall decrease in the number of moves needed to solve the puzzle across the 40 trials. However the size of this effect changed across the sessions: interaction effect, $F(27, 1053) = 3.2$; $p < .0001$, with improvements in performances gradually tailing off. Similarly, the analysis of variance carried out on the data for time per trial (Figure 4B) showed a trial effect on mean performance level, $F(9, 3351) = 28.8$; $p < .001$, a significant effect of session repetition, $F(3, 117) = 91.2$; $p < .001$, and a significant interaction between the two, $F(27,$

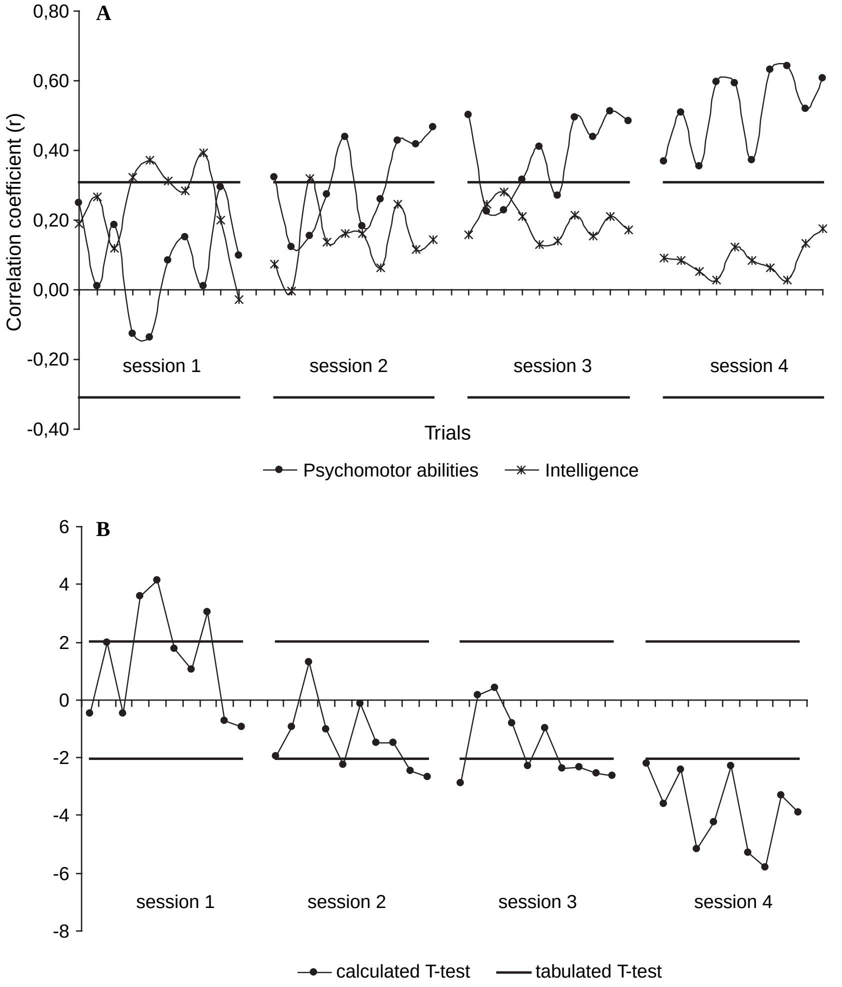

Figure 5. (A) Correlations between procedural performance levels (time in seconds) and the factor scores of intelligence and psychomotor abilities. The boldface horizontal lines correspond to the statistical threshold $p = .05$. The correlations located above these lines are significant. (B) Calculated T-value assessing the existence or otherwise of a significant difference between the various correlations calculated for each trial and shown in Figure 5A. The boldface horizontal lines correspond to the tabulated T-value $p = .05$. The calculated T-values located above and under these lines are significant (see text).

1053) = 9.4; $p < .001$. With practice, the subjects improved their performances. Completion times decreased across the skill acquisition trials, but progress in performances gradually tailed off across the sessions.

Analysis of the cognitive determinants of procedural performance levels: Delimitation of the three learning phases

The contribution of cognitive determinants to performance levels during procedural learning was examined through the correlations between procedural performance levels and intelligence and psychomotor ability scores across the 40 trials. Correlations between cognitive scores and procedural performance levels across the trials are shown in Figures 5 and 6. The correlations above 0.31 are significant at $p < .05$. First of all, in order to check the dynamics of the three learning phases across the four sessions, we studied the correlations between procedural performance levels and scores of general intelligence and psychomotor abilities (Figure 5).

General intelligence abilities were mainly significantly correlated with procedural performance levels in the first learning session (Figure 5A). As for psychomotor abilities, these were significantly correlated with procedural performance levels in the last three sessions, the number of significant correlations gradually increasing. In order to identify the major cognitive determinant of procedural performance levels, we looked for significant differences between the various correlations calculated for each trial by means of Steiger's test (1980).

The comparison of the correlations between performances levels in terms of time per trial of the TT task and general intelligence abilities on the one hand, and psychomotor abilities on the other hand, confirmed our predictions (Figure 5B). During the first session, there was a significant difference between the contributions of intellectual and psychomotor abilities to pro-

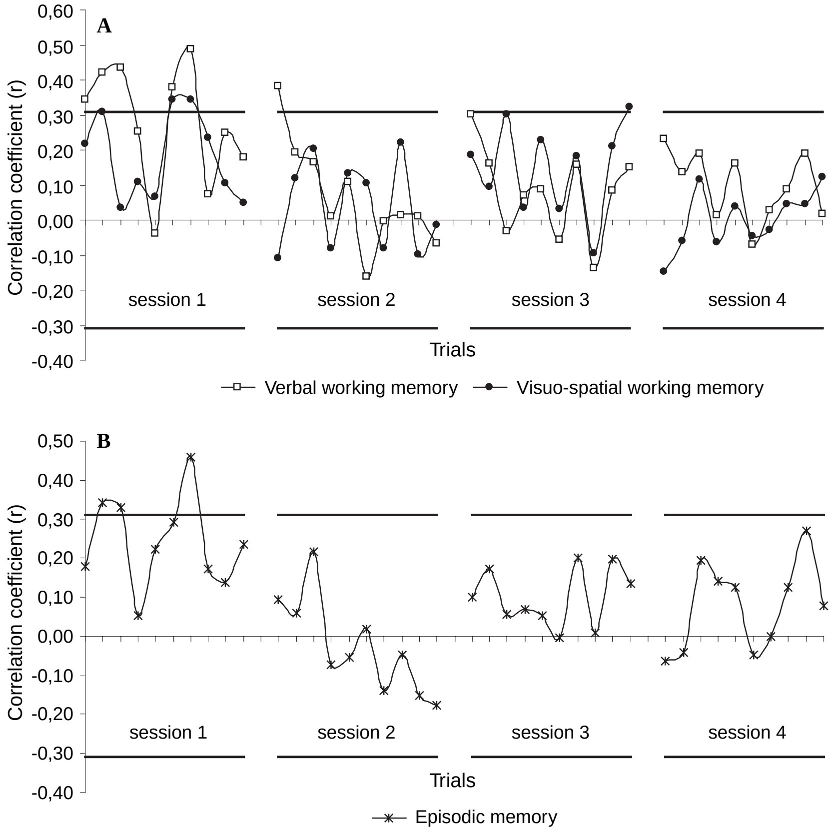

Figure 6. (A) Correlations between procedural performance levels (time in seconds) and the scores of verbal and visuospatial working memory. (B) Correlations between procedural performance levels (time in seconds) and the scores of episodic memory. The boldface horizontal lines correspond to the statistical threshold $p = .05$. The correlations located above and under these lines are significant (see text).

cedural performance levels, in favour of the former. During the second session, there was no difference in contributions, except during the last two trials. Lastly, during the third and the fourth sessions, there was a significant difference between the contributions of intellectual and psychomotor abilities to procedural performance levels, in favour of the latter, which played an increasingly important role across the trials. With reference to the model proposed by Ackerman (1988), these results confirmed the existence of three phases in cognitive distributed procedural learning: a cognitive phase in the first learning session, an associative phase mainly in the second session and an autonomous phase in the last two sessions.

Characterising the learning phases

Next, in order to check the involvement of episodic and working memory in distributed procedural learning, we also studied the correlations between working memory (Figure 6A) and episodic memory scores (Figure 6B) and procedural performance levels across the 40 trials.

For spatial and verbal working memory, the correlations were mainly significant in the first session. Verbal working memory also seemed to play a role in the resumption of learning in the second and third sessions. Episodic memory was only involved in the first learning session and its role gradually declined over the last three sessions.

Discussion

First of all, this second experiment confirmed the existence of three phases during cognitive procedural learning in the distributed learning condition. The data showed that procedural learning did indeed take place (in terms of both moves and time) and that it changed across the learning sessions. The analysis of the correlations between performances levels in terms of time per trial of the TT task and general intelligence abilities on the one hand, and psychomotor abilities on the other hand, confirmed the existence of three distinct learning phases.

The hypothesis that distributed learning conditions might have an effect on the dynamics of procedural learning was confirmed. Indeed, these more ecological learning conditions had the effect of lengthening the associative phase and making the automation of the cognitive procedure more gradual. The automation that appeared at the end of the second session was compromised by the length of the retention interval. At the start of the third session, subjects returned to the associative phase for some trials, before entering the autonomous phase near the end. In the fourth session, they were fully in the autonomous phase. This phenomenon was accompanied by the continuing involvement of verbal working memory in procedural performances during the resumption of learning in sessions 2 and 3. This contribution of working memory to procedural performance levels during the associative phase contradicted the findings of Experiment I. However, this difference can be explained by a difference in working memory scores. In the first experiment, the working memory efficiency score was a composite factorial score, which took verbal and visuospatial storage capacities into account as well as the efficiency of the central executive (cf. Table 1). Conversely, in Experiment 2, the verbal working memory score only measured verbal storage (digit span). These data are in line with Woltz's study (1988), which suggested that working memory verbal storage capacities are involved in both the cognitive and associative phases.

Contrary to our assumption in Experiment 1, the distributed learning conditions did not seem to have any effect on the involvement of episodic memory, as the extent of its contribution remained the same as before. These results contradict the findings of Xu and Corkin (2001) and Winter et al. (2001), who regarded the difficulties encountered by amnesic patients in the distributed learning of the Tower of Hanoi task as a reflection of their episodic deficit. However, this divergence of results can be explained by a difference in the learning paradigm. Their studies featured learning sessions comprising just four trials, which made it difficult for the patients to move beyond the cognitive phase before the retention interval. Given the significant involvement of episodic memory in the cognitive phase, it is indeed probable that the patients' difficulties observed during the resumption of learning were due to their episodic deficit. Conversely, as the subjects in our study were given 10 trials per session, they were able to leave the cognitive phase by the end of session 1. This may explain the absence of any contribution from episodic memory in procedural performances in the following sessions.

CONCLUSION

This study above all emphasises the importance of taking account of inter-systemic collaboration during the learning of complex procedures. The data we recorded undermine the functionally autonomous status of procedural memory in the encoding of novel and complex procedures. Furthermore, they confirm the involvement of nonprocedural cognitive components (intelligence, working memory, and episodic memory) during the first two phases of cognitive procedural learning. This inter-systemic collaboration during the learning of complex procedures has some direct clinical consequences, for while it is necessary for encoding cognitive procedures in procedural memory, it may become an obstacle in situations of normal ageing (Peretti et al., 2002) or pathology (Michel et al., 1998; Schmitke et al., 2002; Winter et al., 2001; Xu & Corkin, 2001). These considerations could help us to understand why some patients fail to reach the autonomous phase. Our data confirm the idea that it is essential to compensate for patients' deficits by adapting learning conditions and teaching aids (Baddeley & Wilson, 1994; Beaunieux et al., 1998). Adapting learning to patients' specific deficits should make it possible to exploit their residual procedural abilities (Beaunieux et al., 1998). Within this framework, the preliminary assessment of cognitive abilities by means of the transfer tasks (Tower of Hanoi or Tower of Toronto) should make it possible to understand the origin of the difficulties encountered by patients during procedural learning, and thus make it possible to develop more relevant teaching aids.

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