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The application of rules in morphology, syntax and number processing: A case of selective deficit of procedural or executive mechanisms?

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Declarative memory is a long-term store for facts, concepts and words. Procedural memory subserves the learning and control of sensorimotor and cognitive skills, including the mental grammar. In this study, we report a single-case study of a mild aphasic patient who showed procedural deficits in the presence of preserved declarative memory abilities. We administered several experiments to explore rule application in morphology, syntax and number processing. Results partly support the differentiation between declarative and procedural memory. Moreover, the patient's performance varied according to the domain in which rules were to be applied, which underlines the need for more fine-grained distinctions in cognition between procedural rules.

Keywords: Procedural memory; Declarative memory; Executive functions; Language; Calculation.

INTRODUCTION

Most linguistic models present a formal distinction between lexicon and grammar (e.g., Chomsky, 1995; de Saussure, 1959; Pinker, 1994; Pinker & Jackendoff, 2005). The thousands of words which an individual knows are encoded in the lexicon. This linguistic component includes all idiosyncratic information about words, including phonological forms as well as all unpredictable information such as the number and nature of verb arguments (e.g., the verb donner 'to give' requires the following three syntactic arguments: Subject, Object, and Indirect Object) or inflected forms of irregular verbs (e.g., aller 'to go' – il va 'he goes'; il ira 'he will go') and adjectives (e.g., the masculine and feminine forms of the adjective 'soft' are mou and molle, respectively). A large part of language, however, is highly predictable. These regular patterns can be characterized by means of another component, the grammar. This component refers to the organizing principles of the language, represented under the form of rules specifying the combination of linguistic representations (morphemes and words) into a vast number of words, phrases, and sentences.

From a cognitive viewpoint, most psycholinguistic models (e.g., Clahsen, 1999; Marslen-Wilson & Tyler, 1997; Pinker, 1999) also propose a distinction

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between lexicon and grammar. According to the 'Words-and-Rules' theory (WR), words are encoded and retrieved for comprehension and production in the mental lexicon. This long-term memory store comprises all words with sound-meaning arbitrary relationships, including stems of verbs and adjectives as well as all the inflected forms of irregular verbs and adjectives. Words can also be assembled through specific mechanisms that combine morphemes via the application of 'rules of language' (Pinker & Ullman, 2002). These rules are required for regular verb and adjective inflections, word derivation, and syntax. Within this model, for example, the production of an inflected regular verb entails the activation of the verb stem in the mental lexicon and the application of the grammatical rules for agreement (Pinker, 1999; Pinker & Ullman, 2002). By contrast, the production of an inflected irregular verb only requires the recovery of the whole inflected form in the mental lexicon.

Although functionally and neuro-anatomically independent, the mental lexicon and the mental grammar are not disconnected from other cognitive functions. According to certain theoretical propositions, both linguistic abilities interact with long-term memory functions, in particular, declarative and procedural memory systems. In an attempt to reconcile language with long-term memory functions, Ullman and co-workers (Ullman, 2001, 2004; Ullman & Corkin, 1997; Ullman & Pierpont, 2005) proposed a neuroanatomical, integrative model of memory, the Declarative/Procedural model (D/P). According to this model, declarative memory, which comprises semantic and episodic memory, depends on medial temporal lobe structures, and underlies the mental lexicon, a long-term memory store comprising all arbitrary, idiosyncratic knowledge about words. Procedural memory, rooted in frontal/basal ganglia circuits, subserves the learning and processing of rules and, with respect to language, underlies the mental grammar which is responsible for the acquisition and computation of rule-based linguistic procedures.

Declarative and procedural memory are also linked to executive functions. Executive processes are implicated in high-level mental control processes, such as novel problem solving, shifting of mental sets, inhibition of prepotent or previous responses, and monitoring and updating of working memory representations. For example, with respect to language, the learning and application of rules proceed on complex linguistic structures selected in declarative memory and which must be maintained and updated by executive functions, until the end of the process.

Executive functions and procedural memory represent distinct cognitive functions subserved by similar brain structures. The basal ganglia, Broca's area and prefrontal regions sustain procedural memory but are also implicated in maintenance, updating and manipulation of sequence information (e.g., Ruchkin, Grafman, Cameron, & Berndt, 2003; Smith & Jonides, 1999). Because of this overlapping in brain representations, patients presenting with procedural deficits usually show impairment of executive functions as well. For example, children with specific language impairment (SLI) (Im-Bolter, Johnson, & Pascual-Leone, 2006) or patients with Parkinson's disease (PD) (Colman et al., 2009) often present with difficulties in verbal inflectional morphology but also show executive deficits. Although frequently associated following brain damage, the nature of the relationship between procedural memory and executive functions remains essentially unspecified. In a recent review related to the functional origin of SLI, Ullman and Pierpont (2005) suggested that deficits affecting the monitoring and updating of working memory representations are concomitant and may contribute to language impairment. However, according to these authors, they are neither the functional cause of impairments of morphology and syntax nor necessary to their presence, which is rather a direct consequence of an impaired procedural system. This assumption is essentially intuitive and further research is needed to elucidate the exact nature of the association between executive functions and procedural memory in language and cognitive functions. Until now, support for the procedural origin of language impairments mainly comes from studies exploring processes in verbal inflectional morphology. However, whereas demands on executive functions are relatively low in conjugation tasks, the situation is quite different in the syntactic domain in which, depending on the task, large amounts of complex information need to be maintained and updated by executive functions in working memory during processing. Using conjugation, sentence-picture matching, and calculation tasks, Teichmann et al. (2005, 2008) recently showed that Huntington's disease (HD) patients were not only impaired in rule application in verbal morphology but also in the domains of syntax and arithmetic. These data are particularly interesting because they widen the study of the involvement of procedural memory in cognition. However, the experimental tasks used also make substantial demands on executive functions, which are usually impaired in affections such as HD (e.g., Ho et al., 2003; Peinemann et al., 2005). This increased demand may make it difficult to dissociate cognitive processes of executive functions from procedural memory.

In this study, we report an explorative single-case study of a mild aphasic patient, FG, who showed procedural deficits in the presence of preserved declarative memory abilities. Like Teichmann et al. (2005, 2008), we extend the discussion of the D/P model to morphology, syntax, and number processing, using experimental tasks intended to minimize executive demands and in which rule application was varied.

CASE REPORT

FG is a 74-year-old right-handed man. He has a grade eleven education and worked as an auxiliary nurse. He had suffered from a chronic bipolar disease since 1982, with multiple episodes requiring many hospitalizations. He came to our attention in July 2005 for acute exacerbation of a bipolar disorder with suspected psychotic features requiring inpatient treatment. At admission, symptoms were compatible with manic exacerbation. Psychotic features were not confirmed. The Mini-Mental State (Folstein, Folstein, & McHugh, 1975) was administered to the patient, who obtained 24/30, a score within the normal range (24–28). However, the examination revealed signs of his primary psychiatric disorder (exalted mood and paranoid suspicion). Moreover, an English-sounding foreign accent as well as mild agrammatism were noted. FG's past medical records reported the presence of this foreign accent in January 2003. It was first noticed at the psychiatric outpatient clinic consultation, shortly after he was discharged from the inpatient service, which was required for manic exacerbation of his bipolar disorder in the fall of 2002. The presence of mild agrammatism was also recorded at the same period.

Neuropsychological evaluation

FG's performance on the neuropsychological tests is shown in Table 1. Neuropsychological testing showed no impairment in tasks exploring orientation to time and space. FG's performance was normal on the task exploring concentration and selective attention (Symbol Digit Modalities Test; Smith, 1982). He showed good face recognition and presented no clinical signs of visual agnosia (BORB; Riddoch & Humphreys, 1993). There were no signs of unilateral neglect.

Praxis abilities were well preserved (PENO; Joanette et al., 1995). FG performed normally on tasks exploring episodic memory. His performance was within the normal range for the immediate story retelling subtest of the PENO battery (Joanette et al., 1995), for the two recalls of the DMS-48, a visual forced-choice recognition test (Barbeau et al., 2004), as well as for the pictorial recognition memory test and the short recognition memory test for faces (Camden Memory Tests; Warrington, 1996). The patient's short-term memory was normal in the visuospatial modality (Milner, 1971), whilst the patient presented with a mild deficit in the verbal modality. FG presented with deficits on tests exploring working memory and executive functions. He presented with a severe impairment on the interference condition of the Brown–Peterson task (Brown, 1958), a test that taps the ability to encode, maintain, and manipulate information in working memory (see Table 1). His performance on the colour Stroop Test (Golden, 1978) showed abnormal sensitivity to interference. He obtained normal scores in the word reading and colour naming but his performance was impaired in the colour-word conditions. FG had an abnormal performance on the Trail Making Test (Reitan & Wolfson, 1993). While in part A he was slow but had no errors, his performance was much poorer (very slow performance and numerous errors) on Part B in which he was asked to alternate between connecting numbers and letters in progressive sequential order. FG's performance was impaired (2 *SD* below the normal range) on the D-Kefs Tower Test (Delis, Kaplan, & Kramer, 2001), a complex task that measures the executive functions of spatial planning, rule learning, and inhibition of impulsive responding. Finally, FG's performance corresponded to low average on the Brixton spatial anticipation test (Burgess & Shallice, 1997), an instrument that measures the ability to detect rules in sequences of stimuli. In this task, most of the patent's errors consisted in the application of inadequate rules.

Language evaluation

With regard to language, speech output was fluent and well articulated, with no signs of word-finding difficulties. The patient however presented with mild expressive agrammatism. There were no

TABLE 1
Performance of FG and norms (mean and *SD* or range) on neuropsychological tests

Test	*FG's score*	*Norm*
Attention, Working memory and executive functions		
Symbol Digit Modalities test	28	33.31 (9.8)
Corsi block tapping test forward	5	5.2 (.8)
Corsi block tapping test backward	4	4.9 (1.1)
Forward digit span	4	5.5 (1.1)
Backward digit span	3	4 (1.2)
Brown-Peterson test		
– No interference	100%	98.33% (4.47)
– Mean of interference scores	42%[1]	97.22% (4.46)
Stroop Test		
Color name reading	74 s	48.5 s (25–86)
– Color naming	105 s	69.4 s (46–123)
– Interference	249 s[1]	142.4 s (88–204)
Trail Making Test		
Part A	61 s[1]	41.3 s (15)
Part B	253 s[1]	111.4 s (72.2)
Visual-perceptual tests		
– BORB		
– Length match task (30)	28	26.9 (1.6)
– Size match task (30)	27	27.3 (2.4)
– Orientation match task (30)	24	24.8 (2.6)
– Minimal feature view match (25)	25	23.3 (2.0)
– Foreshortened view task (25)	25	21.6 (2.6)
– Object decision – easy subtest (32)	30	30.5 (1.4)
– Object decision – hard subtest (32)	25	27.0 (2.2)
Motor control tests		
Pantomime imitation subtest (PENO) (35)	29	31.69 (2.6)
Arbitrary gesture imitation subtest (PENO) (35)	33	32.54 (1.6)
Episodic memory		
Immediate story retelling subtest (PENO) (23)	9	11.62 (2,6)
DMS-48		
– First recall (48)	44	46.08 (2.4)
– Second recall (48)	45	46.56 (1.92)
Pictorial recognition memory test (30)	28	28.6 (1.54)
Short recognition memory test for faces (25)	24	22.1 (2.1)

[1]Indicates a score below the norm or outside the normal range.

phonemic or verbal paraphasias but speech was sometimes telegraphic with omissions of function words and grammatical bound morphemes as well as impoverished syntactic structure. Following is an example of his narrative speech, produced as a description of the scene the 'Vol de banque' from the protocole Montreal-Toulouse d'examen linguistique de l'aphasie –MT-86 (Nespoulous et al., 1992).

> Des voleurs, des gangsters, puis téléphone avec le monsieur *(Thieves, gangsters, then telephone with the man)*. Une police *(A policeman)*. Un p'tit gars courir en arrière de police *(A little guy (to) run behind the policeman)*. Une voiture, une voiture de police, je crois *(A car, a police car I think)*. Dans banque, une madame qui. avec un fusil *(In bank, a lady that ..with a gun)*. Un homme avec la face bouchée, puis vite avec lever les mains à deux personnes *(A man with his face blocked, then quick with (to) lift hands to two persons)*.

FG's agrammatic speech was also characterized by a strong tendency to substitute clitic pronouns (which precede the verb in French) by their disjoint counterparts, leading to incorrect pronominalized structures, as illustrated by the following extracts of conversational speech.

> 'Ils comprennent MOI ici en français' *(instead of 'ils me comprennent ici en français')*
>
> 'Il a essayé d'aider LUI' *(instead of 'il a essayé de l'aider')*
>
> 'Il donner À MOI beaucoup' *(instead of 'il me donne beaucoup')*

TABLE 2
Performance of FG and norms (mean and *SD* or range) on language tests

Test	*FG's score*	*Norm*
Language		
BECLA		
– Same-different judgement on spoken non-word pairs (36)	30	31.67(1.15)
– Allographic matching on graphemes (26)	25	25.67 (.58)
– Auditory lexical-decision (20)	18	19 (1.73)
– Written lexical-decision (20)	20	19.67 (.58)
– Repetition of words and non-words (25)	25	24 (.58)
– Reading of words (25)	24	24.17 (.58)
– Reading of non-words (25)	15	22.5 (.82)
– Written spelling of words (36)	24	31.19(3.06)
– Written spelling of non-words (15)	10	13.17(1.86)
Picture naming (DO-80) (80)	72	74.9 (2.94)
Letter fluency (PENO)	5*	45.46(16.4)
Category fluency (PENO)	14*	47.85 (9.8)
Pyramids and Palm Trees Test (52)	47	49.4 (1.74)
Token test (36)	29	29–36
Spoken word/sentence-to-picture matching (MT-86) (47)	44	44.6 (2.19)
Written word/sentence-to-picture matching (MT-86) (12)	12	10.81 (.81)

*Indicates a score below the norm or outside the normal range.

Auditory and visuo-verbal input components assessed with the BECLA (Macoir, Gauthier, & Jean, 2005) were largely preserved (same vs. different judgment tasks on spoken and written syllables; lexical decision on spoken and written words). Comprehension abilities at the lexical-semantic level (Pyramids and Palm Trees Test; Howard & Patterson, 1992) as well as at the syntactic-semantic level (Token test and MT-86; De Renzi & Faglioni, 1978; Nespoulous et al., 1992) were normal (see Table 2). Repetition was flawless for both words and nonwords (BECLA). The patient's performance in reading tasks (BECLA) was characteristic of phonological dyslexia. Written spelling of words and nonwords was impaired (BECLA). FG produced lexicalization errors for nonwords while he exclusively produced phonological plausible errors for words, with a performance affected by orthographic regularity and lexical frequency. FG's performance was normal in confrontation naming (DO-80; Deloche & Hannequin, 1997) but he showed difficulties in letter and semantic category fluency tasks (Joanette et al., 1995) (see Table 2), a performance that could be attributed to the deficit in executive functioning.

FG showed many characteristics usually reported for foreign accent syndrome (FAS): there were no signs of dysarthria (no slow, slurred, groping or laboured articulation) or apraxia of speech (no dysfluency and no problems with phoneme sequencing) but acoustic analysis performed on speech samples recorded on digital audiotape showed the presence of abnormalities at the segmental and suprasegmental levels. Unfortunately, we had no premorbid recording of the patient's speech (Poulin, Macoir, Paquet, Fossard, & Gagnon, 2007). However, FG himself as well as one of his close friends, who has known him for over 30 years, confirmed that he never had this particular strange accent before its sudden appearance in January 2003.

Radiological findings

Neuroimaging studies were performed while the patient was in euthymic condition (the reader will find MRI and PET pictures in Poulin et al., 2007). A magnetic resonance imaging (MRI) study including sagittal FLAIR and T2-weighted sequences and axial FLAIR, proton density, T1- and T2-weighted sequences was performed on December 8, 2005 using the standard protocol. The first interpretation was normal except for slight diffuse cerebral atrophy considered normal for his age. An 18F-fluorodeoxyglucose brain positron emission tomography was obtained with a dual-head coincidence camera (Vertex MCD-AC, Phillips). The reconstructed images showed diffuse hypometabolism in the frontal, parietal and temporal lobes bilaterally whereas the cerebellum, occipital lobe and subcortical structures were spared. There was also a focal deficit in the area of the anterior left temporal lobe with prominence of the sylvian sulcus. When compared to the MRI, these deficits were related to asymmetric atrophy, which was retrospectively seen in the left temporal and frontal opercular/insular region (Poulin et al., 2007).

Summary and diagnosis

In summary, FG presented with a sudden onset of agrammatism, FAS, dyslexia and agraphia. He also showed a working memory deficit and executive dysfunction. These clinical signs were related to altered cerebral activity on the FDG-PET scan. Because of the acute onset and stability of the symptoms in FG, the presence of a neurodegenerative process is highly improbable. Except for cognitive function deficits, none of the DSM-IV-TR (American Psychiatric Association, 1994) criteria for the diagnosis of dementia was met in FG. He presented with abnormalities in the left anterior temporal lobe, a cortical localization compatible with frontotemporal dementia (FTD). However, except for executive function deficits, the patient's clinical profile did not meet the clinical diagnosis features of FTD (Neary et al., 1998). With respect to language, he did not show any of the supportive diagnosis features of FTD (aspontaneity, echolalia, perseveration, etc.). Finally, progressive nonfluent aphasia (PNFA) is a clinical syndrome associated with FTD (Neary et al., 1998) in which agrammatism is sometimes observed (Grossman & Ash, 2004). However, FG did not present any of the PNFA core diagnostic features (nonfluent spontaneous speech, phonemic paraphasias, anomia). Moreover, FAS has never been reported in PNFA, as in any other forms of dementia. Because of the focal deficit seen on the brain imaging, involving the left insular and anterior temporal cortex, two brain regions frequently involved in aphasic syndrome but also in FAS, a cerebral stroke was considered the best explanation to account for FG's language deficits (Poulin et al., 2007).

EXPERIMENTAL STUDY

As pointed out by Ullman and Corkin (1997), anterior aphasic patients often show impairment of procedures while declarative memory may be largely spared. In FG, we investigated the nature of the processes at issue in rule application in two linguistic domains (morphology and syntax) and in a nonlinguistic domain (arithmetic). The first two experiments explored rule application in verbal and adjectival morphology. The third experiment investigated rule application in sentence processing. Experiment 4 investigated rule application in the numerical domain.

For each of these experiments, FG's performance was compared to the results of four male controls matched for age (mean age = 75.25 years, SD = 3.09; modified t-test = –.36; p = .74) and education level (mean education = 10.75 years, SD = 0.5; modified t-test = .45; p = .68). FG and control subjects gave informed consent to participate in the study, according to the Declaration of Helsinki (BMJ 1991;302:1194).

Rule application in morphology

The domain of inflectional morphology has been the subject of numerous studies relating to the lexical versus procedural nature of linguistic processes (e.g., Penke & Westermann, 2006; Ullman & Corkin, 1997). In all these studies, the explored processes were restricted to verbal inflectional morphology. In the following two experiments, we also explored the conjugation of verbs but extended the study to the adjectival French inflectional morphology. The ability to perform a verbal or an adjectival inflection task requires the subject to: (a) perceive, comprehend, and produce verbs and adjectives; (b) comprehend the information that indicates the inflection to be performed; (c) retrieve words in declarative memory and, for some stimuli; (d) apply inflection rules. According to some theorists of speech production (e.g., Bock, 1982, 1996; Levelt, 1992), the stages of lexical retrieval (i.e., retrieving a word from the mental lexicon) and syntactic planning (i.e., assignment of grammatical functions, and elaboration of a syntactic structure encoding hierarchical syntactic relationships, word order, and inflection) are generally automatic processes that do not recruit much executive functions. In the following two experiments, FG was administered verbal and adjectival inflection tasks, in which the application or non-application of morphological rules was contrasted.

Experiment 1: rule application in verbal conjugation tasks

In this experiment, FG was asked to conjugate verbs and non-verbs, a task directly based on Teichmann et al.'s (2005) study. Non-verbs were used to minimize recourse to lexical information and more directly assess the application of conjugation rules.

Method

Stimuli. For real verbs, we selected an experimental list of 36 stimuli equally distributed between regular, subregular, and irregular verbs. In French, most verbs (~90%) are regular (ending with -er; e.g., manger 'to eat') and are conjugated by the application of inflection rules. For example, the conjugation of a verb ending with -er (manger 'to eat') in the third person singular of the future tense (il mangera 'he will eat') requires, after having retrieved the verbal root (mang-) in the lexicon, the application of the following two inflectional rules: (1) add the affix of the future tense: +er and (2) add the affix for the third person singular of the future tense: +a). Twelve regular verbs were selected for the conjugation task. Verbs ending with -ir or -oir (e.g., sortir 'to go out' and prévoir 'to envisage') are less numerous in French (~3% for each type). Their conjugation is also obtained by the application of inflection rules (e.g., +ir and +a or +r and +a for the third person singular of the future tense: il sort-+ir+a, 'he will go out'; il prévoi+r+a, 'he will envisage'). Following Teichmann et al. (2005) and because these rules are much less productive in French (i.e., verbs ending with -ir and -oir are less numerous and no new verbs with these endings are created in French), verbs ending in -ir and -oir were considered subregular verbs. Twelve subregular verbs were selected for the conjugation task. In addition to regular and subregular verbs, the French verbal system also comprises highly irregular verbs (e.g., aller 'to go' infinitive form: je vais 'I go', first person singular of the present tense; j'irai 'I will go', first person singular of the future tense), which are considered suppletive forms since their different conjugated forms are unpredictable and are therefore listed as separate lexical entries in the mental lexicon. Twelve highly irregular verbs were also selected for the conjugation task. Regular, subregular, and irregular verbs were matched for length (10 bisyllabic and 2 trisyllabic verbs of each type) and lexical frequency (Baudot, 1992) (mean frequency: regular verbs = 190.608; subregular verbs = 169,5; irregular verbs = 189.9; $p = .155$).

A list of 24 non-verbs was constructed from the list of regular and subregular verbs by keeping the infinitive ending with its adjacent consonant and substituting all the phonemes of the verb stem so that the corresponding verb could not be easily recovered. For example, the corresponding non-verb for the real verb finir 'to finish' was bounir. The experimental list of non-verbs comprised 12 regular and 12 subregular non-verbs matched for length.

Procedure. FG was first tested with verbs, then with non-verbs. He was asked to perform the following conjugation tasks: (a) from the infinitive to the third person singular in the present tense and vice versa (regular and subregular verbs and non-verbs: application of 1 rule); (b) from the third person singular in the present tense to the third person singular in the future tense and vice versa (regular and subregular verbs and non-verbs: application of 2 rules); and (c) from the infinitive to the third person singular in the future tense and vice versa (regular and subregular verbs and non-verbs: application of 2 rules). FG was thus administered 216 stimuli for the real verbs set (36 verbs × 6 tasks) and 144 stimuli for the non-verbs set (24 non-verbs × 6 tasks). To minimize demands on working memory, stimuli were presented to FG on a computer screen in random order. Stimuli were inserted in a short inducing phrase (e.g., present to future: Aujourd'hui il dort 'today he sleeps'), immediately followed by a carrying phrase ('Demain il . . .' 'tomorrow he . . .'), that FG was asked to complete orally, after the experimenter had read it aloud. The inducing phrase as well as the carrying phrase remained in front of the patient until he produced a response, with no time limit. For each task, 4 practice items were presented (2 regular and 2 subregular) and feedback was provided for correct and incorrect responses.

Results. As shown on Table 3, FG's performance was largely preserved for the conjugation tasks involving real verbs. The only task in which he was slightly below the mean of the control subjects was the conjugation of subregular verbs from the infinitive to future and vice versa ($\chi 2 = 3.75$, $p < .05$). However, FG's performance was significantly below the mean of the control subjects for three of the non-verb conjugation tasks. For regular non-verbs, the patient was impaired for the two conjugation tasks requiring the application of two rules (conjugation from the present to the future tense and vice versa: $\chi 2 = 10.23$, $p = .001$, and conjugation from the infinitive to the future tense and vice versa: $\chi 2 = 40.4$, $p < .001$) whilst he performed similarly to the control subjects for the conjugation task with one rule application (i.e.,

TABLE 3
Performance of FG and control subjects (number and percent correct; values in brackets correspond to *SD*) in the verb and non-verb conjugation tasks

	Regular verbs		*Subregular verbs*		*Irregular verbs*	
Conjugation tasks	*FG*	*Controls*	*FG*	*Controls*	*FG*	*Controls*
Infinitive ↔ present (24)	24 (100%)	24 (100%)	22 (92%)	23.75 [.25] (99%)	24 (100%)	24 (100%)
Present ↔ future (24)	24 (100%)	24 (100%)	22 (92%)	22 [.71] (92%)	24 (100%)	24 (100%)
Infinitive ↔ future (24)	24 (100%)	24 (100%)	17 (71%)	23 [.58] (96%) *	24 (100%)	24 (100%)
	Regular non-verbs		Subregular non-verbs			
	FG	Controls	FG	Controls		
Infinitive ↔ present (24)	24 (100%)	23.75 [.05] (99%)	18 (75%)	22.25[.16] (96%)		
Present ↔ future (24)	14 (58%)	24 (100%)***	13 (54%)	21 [.29] (87.5%)*		
Infinitive ↔ future (24)	1 (4%)	24 (100%)***	24 (100%)	23.75 [.05] (99%)		

Difference between FG and controls: *$p < .05$; ***$p \leq .001$.

infinitive to present and vice versa). For subregular non-verbs, he was impaired in the conjugation from the present to the future tense and vice versa ($\chi 2 = 4.94$, $p < .05$) in which the application of two rules is required whilst he was unimpaired for the two other conjugation tasks, requiring the application of one (i.e., conjugation from the infinitive to the present tense and vice versa) or two (i.e., conjugation from the infinitive to the future and vice versa) inflection rules.

With respect to error types, except for two errors involving the stem (il matrivera → 'il matri' instead of 'il matrive'; il sirraloira → 'il siroit' instead of 'il sirraloit'), all the errors produced by FG on subregular verbs resulted from a deficit in rule application (e.g., inappropriate application of the inflection rule of the future on the infinitive form of the verb instead of the verb stem for the conjugation of subregular verbs from the infinitive to the future: courir 'to run' → 'il courira' instead of 'il courra'). The application of inflection rules was also impaired for the conjugation of non-verbs. For the conjugation of regular and subregular non-verbs from the future to the present tense and vice versa, the addition or deletion of the affix for the third person singular (+ or – /a/) was always correct but FG had difficulties with the application of morphological rules for tense (e.g., future to present: correct deletion of the /a/ but not of the /r/ resulting in an infinitive non-verb: il pramira → 'il pramir' instead of 'il pramit'). For the conjugation of regular non-verbs from the future tense to the infinitive, the patient correctly removed the future and third person singular affixes but incorrectly associated the affix for the preterit past tense (in 9/11 errors) instead of that for the infinitive (e.g., il midera → 'midèrent' instead of 'mider') or, for the two remaining errors, incorrectly associated the affix for the infinitive of a subregular verb (e.g., il roinera → 'roinir' instead of 'roiner'). In the opposite direction, all the 12 errors consisted in the application of the specific rule for subregular verbs (e.g., roinner → 'il roinéra' instead of 'roinera').

Experiment 2: rule application in adjectival inflection tasks

In this experiment, we extended the study of procedural processes in morphology to adjectives and non-adjectives since distinctions in terms of inflection rules can also be observed in French in this particular domain. As for the verbal domain, non-adjectives were used to minimize recourse to lexical information and more directly assess the application of inflection rules.

Method

Stimuli. For real adjectives, we selected an experimental list of 35 stimuli comprising 10 'no-rule' adjectives, 20 'rule' adjectives, and 5 irregular adjectives. In French, most adjectives (Saint-Pierre, 2006) only have one sound form that is used for both the masculine and the feminine form (e.g., il/elle est modeste 'he/she is modest'). We call these adjectives 'no-rule adjectives', because their production requires no inflection operation. In many other adjectives (Saint-Pierre, 2006) however, the gender inflection requires the application of an inflection rule. For example, in the adjective petit 'little' the pronunciation of the final consonant depends on its morphological status: the final consonant is pronounced in the feminine form (une petite fille /pœtit/ 'a little girl') but not in the masculine form (un petit garcon /pœti/ 'a little boy'). For these 'rule adjectives', the inflection rule can be stated as 'add/delete the underlying final consonant' (Macoir & Béland, 1998). The French adjectival system also comprises irregular adjectives (e.g., beau 'beautiful' masculine form – belle, feminine form), whose inflected forms are unpredictable and are therefore listed as separate lexical entries in the mental lexicon. Five irregular adjectives were also selected for the gender inflection task. 'No-rule-' and 'rule-' adjectives were controlled for length (all bisyllabic) and matched for lexical frequency according to Baudot (1992) (mean frequency: no-rule adjectives = 9.65; rule adjectives = 14.15; $t(28) = -.219$; $p = .83$). Irregular adjectives are much more frequent in French and are not comparable to regular and subregular adjectives in terms of lexical frequency (mean frequency = 425.4).

A list of 30 non-adjectives was constructed from the list of 'no-rule adjectives' and 'rule-adjectives' by keeping the second syllable, and thus the specific ending, and by changing (substitution and addition) all the phonemes of the first syllable so that the corresponding adjective could not be easily recovered. For example, the corresponding 'rule non-adjective' for the 'rule-adjective' chanceux 'lucky' was oubreux, whose feminine form would be oubreuse. The experimental list of non-adjectives comprised 10 'no-rule' and 20 'rule' bisyllabic non-adjectives.

Procedure. FG was first tested with adjectives, then with non-adjectives. He was asked to perform the following two gender inflection tasks: from the masculine to the feminine and vice versa. As for verbal inflection, tasks were administered with a written support, the stimuli being presented to FG on a computer screen in random order. Stimuli were inserted in a short inducing phrase (e.g., masculine: 'il est gris' 'he/it is grey'), immediately followed by a carrying phrase ('elle est . . .' 'she/it is . . .') that FG was requested to complete orally, once the experimenter had read it aloud. The inducing phrase as well as the carrying phrase remained in front of the patient until he produced a response, with no time limit. For both tasks, 3 practice items were presented (1 'no-rule' and 2 'rule') and feedback was provided for correct and incorrect responses.

Results. FG's performance was flawless for the inflection of real 'no-rule' (20/20, 100%), 'rule' (40/40, 100%), and irregular (10/10, 100%) adjectives. The patient performed similarly to the control subjects for the inflection of 'no-rule non-adjectives' but, as shown in Table 4, his performance was below the mean of the controls for the two 'rule non-adjectives' inflection tasks requiring the application of an inflection rule (masculine to feminine: $\chi 2 = 6.23$, $p < .01$; feminine to masculine: $\chi 2 = 10.23$, $p < .01$).

With respect to error types, all of the errors produced for the masculine-to-feminine 'rule non-adjectives' inflection task consisted in the non-application of the inflection rule, leading to the production of the adjective in its presentation form (e.g., il est udais → 'elle est udais'). These errors also accounted for 71% (10/14) of the errors produced in the feminine-to-masculine 'rule non-adjectives' inflection task, the remaining errors consisting in the inappropriate substitution of the

TABLE 4
Performance of FG and control subjects (number and percent correct) in the adjective and non-adjective gender inflection tasks

	'No-rule adjectives' (10)		*'Rule adjectives' (20)*		*Irregular adjectives (5)*	
Gender inflection	*FG*	*Controls*	*FG*	*Controls*	*FG*	*Controls*
Masculine ↔ feminine	10 (100%)	10 (100%)	20 (100%)	20 (100%)	5 (100%)	5 (100%)
Feminine ↔ masculine	10 (100%)	10 (100%)	20 (100%)	20 (100%)	5 (100%)	5 (100%)
	'No-rule non-adjectives' (10)		'Rule non-adjectives' (20)			
	FG	Controls	FG	Controls		
Masculine ↔ feminine	9 (90%)	10 (100%)	13 (65%)	20 (100%)**		
Feminine ↔ masculine	10 (100%)	9.75 [.5] (97.5%)	6 (30%)	17 [3.16] (85%)**		

Difference between FG and controls: $^{**}p < .01$.

final consonant of the inflected non-adjective (e.g., elle est satrive /satriv/) by another final consonant ('il est satrise /satriz/' instead of 'satrif').

In the morphological domain, FG's abilities to access lexical representations in declarative memory were largely preserved. However, he encountered difficulties when the tasks required the application of inflection rules to non-verbs and non-adjectives.

Rule application in syntax

In the present section, in line with Teichmann et al.'s (2005) study, we extended the exploration of rule application to the domain of syntax.

Experiment 3: rule application in sentence-anagram task

In this experiment, we studied syntactic rule application in FG through a sentence-anagram task, which consisted in reorganizing the different sentence constituents in order to compose a grammatical sentence. The ability to perform this task requires the subject to: (a) recognize and retrieve the verb with all the information regarding meaning, associated thematic roles and agent structure from the declarative memory; (b) construct the grammatical structure encoding hierarchical syntactic relationships and word order by applying syntactic rules; and (c) map the thematic roles ('who did what to whom') onto the grammatical roles (Schwartz, Fink, & Saffran, 1995). This task was chosen because it allowed us to investigate syntactic rule application such as those governing the nominalization/pronominalization principles of verb arguments in French, while minimizing demands on working memory and executive resources. Indeed, no time limit was imposed, and the words to rearrange remained in front of the patient until he produced a satisfactory response.

Method

Stimuli. In this task, four syntactic structures consisting in two types of 'nominalized' active sentences (16 sentences with a two-place verb requiring 2 arguments and 16 sentences with a three-place verb requiring 3 arguments) and two types of their 'pronominalized' counterparts were used. Both types of nominalized active sentences were matched for length (mean = 8 words in each sentence type) as well as both types of pronominalized active sentences (mean of 5 and 4 words for two-place verb and three-place verb sentences, respectively). Two- and three-place verbs were matched for lexical frequency according to Baudot (1992) (mean frequency: two-place verbs = 69.75; three-place verbs = 81.9; $t(30) = -0.562$; $p = .579$).

In addition to lexical activation of words in declarative memory, sentence construction requires the application of syntactic rules. By manipulating the number (2 vs. 3) and the type (nouns vs. pronouns) of verb arguments, it is possible to distinguish a gradation in the complexity of syntactic contexts. Regardless of the number of their arguments (2 or 3), nominalized active sentences may then be produced by constructing a sentence structure based on a simple general rule consisting in setting verb arguments according to the canonical word order in French (Subject–Verb–Object). With a two-place verb like creuser 'to dig' only two arguments (the subject and the object) are required (e.g., *le garcon creuse un trou* 'the boy digs a hole'), while for a three-place verb like confier 'to confide' three arguments (the subject, the direct object and the indirect object) are necessary to form a grammatical sentence (e.g., *la fille confie un secret à ses parents* 'the girl confides a secret to her parents'). In order to make uniform surface structures for the two types of nominalized active sentences, a modifier prepositional-phrase (i.e., not required by the verb) was added to the two-place verb sentences (e.g., *le garcon creuse un trou avec ses parents* 'the boy digs a hole with his parents'). Proceeding in this way, both types of nominalized active sentences are equivalent in surface, although in depth the argument structure of a three-place verb is more complex than that of a two-place verb (Kim & Thompson, 2004; Thompson, 2003). This difference in depth structure of both types of nominalized active sentences is particularly evident in their pronominalized counterparts. In French, pronominalized active sentences constitute non-canonical syntactic structure requiring moving pronominalized arguments (i.e., clitics or unaccented pronouns) before the verb (Kayne, 2000, 2005). To compose a pronominalized active sentence with a two-place verb, a rule is then required to correctly set the accusative-clitic pronoun after the subject pronoun (e.g., *il le creuse* 'he digs it'). A prepositional-phrase such as *avec ses parents* 'with his parents' is not a compulsory complement of the verb and cannot be pronominalized. In this particular case, the noun-phrase only can be pronominalized by a disjoint pronoun 'eux' (e.g., *il le creuse avec eux* 'he digs it with

TABLE 5
Performance of FG and control subjects (number and percent correct; values in brackets correspond to *SD*) corresponding to the syntactic structures used in the anagram task

Syntactic structures		*Examples*	*FG*	*Controls*
Canonical (nominalised active)	1	Le garçon creuse un trou avec ses parents *(the boy digs a hole with his parents)*	16/16 (100%)	16 [0] (100%)
	2	La fillette confie un secret à ses amies (*(the girl confides a secret to her friends)*	15/16 (94%)	16 [0] (100%)
Non-canonical(pronominalized active)	1′	Il le creuse avec eux *(He digs it with them)*	14/16 (87.5%)	16 [0] (100%)
	2′	Elle le leur confie *(She confides it to them)*	8/16** (50%)	15.75 [0.2] (8%)

Note: 1 = 2 arguments and 1 modifier; 1' = 2 clitic pronouns and 1 disjoint pronoun; 2 = 3 arguments; 2' = 3 clitic pronouns. Difference between FG and controls: ***p* < .01.

them'). With a three-place verb, however, the third argument corresponds to a compulsory prepositional-phrase. As such, it may be pronominalized by a dative-clitic pronoun. A second rule is then required to correctly put the dative-clitic pronoun after the accusative-clitic one, the latter being put after the subject pronoun (e.g., *elle le leur confie* 'she confides it to them') (see Table 5).

Procedure. FG was first tested with nominalized active sentences, then with pronominalized active sentences. Words of each sentence were printed individually on paper cards and were randomly presented to the patient who was asked to rearrange them to form a sentence (e.g., *garcon /avec /le / creuse /un /parents /trou /ses*; 'boy /with /the /digs /a / parents /hole /his' or: *avec / le/ eux /creuse/ il*; 'with /it / them/ digs/ he'). There was no time limit and FG was allowed to make as many sentence construction attempts as he wished. For each task, two practice items were presented and feedback was provided for correct or incorrect responses.

Results. While FG's performance was at the control level for nominalized active sentences (31/32, 97%), he showed substantial difficulties in rearranging pronominalized active sentences (22/32, 69%), and the difference was significant (χ^2 = 7.03, $p < .01$) (see Table 5). This result is essentially due to impaired performance for rearranging pronominalized active sentences with a three-place verb as compared to a two-place verb (8/16, 50% vs. 14/16, 87.5%; χ^2 = 3.54, $p < .056$). For pronominalized active sentences, FG performed similarly to the controls for two-place verb sentences (14/16 vs. 16/16, $\chi 2$ = .53, p = .24). However, as shown in Table 5, his performance declined dramatically for pronominalized sentences with a three-place verb, for which he performed at chance level, well below the mean of the control subjects (8/16 vs. 15.75/16, χ^2 = 8.77, $p < .01$)

With respect to error types, except for one error implying the movement of a clitic pronoun in front of the verb (*elle le confie* *<u>leur</u>* instead of *elle le leur confie* [literally: 'she it confides *them' instead of 'she it them confides']), all the errors resulted in a deficit in the application of rules required to set the pronouns (i.e., setting the dative-clitic pronoun after the accusative-clitic pronoun; setting the accusative-clitic pronoun after the nominative-clitic pronoun) (e.g., **il leur la indique* instead of *il la leur indique*; **il lui le soumet* instead of *il le lui soumet* [literally: '*he him it submits' instead of 'he it him submits']).

Rule application in number processing

In the present section, we extend the study of procedural memory deficits to the numerical domain.

Experiment 4: Rule application in single-digit calculation tasks

Like the linguistic domain, numerical processing is also based on representations encoded in long-term declarative memory and on the application of rules. Number processing involves the ability to transcode numbers from one numerical code (e.g., Arabic number: 18) to another (e.g., written verbal number: eighteen) and the ability to perform multi (e.g., 356 + 277) or single-digit calculations (4 × 8) in the four arithmetic operations. The ability to perform multi-digit calculations requires the application of arithmetical rules or algorithms (i.e., calculation procedure required to solve a complex arithmetical problem; e.g., for a multi-digit multiplication: start at the rightmost column, retrieve the product of the digits, write the digit corresponding to the result at the bottom of the column, etc.), but also recruits substantial working memory resources (e.g., Hitch, 1978; Logie, Gilhooly, & Wynn, 1994) for sequential planning, temporary storage, execution of computational algorithms and subvocal rehearsals of running totals (Baddeley & Logie, 1999). As opposed to multi-digit calculation, single-digit calculation operates more automatically and requires less executive and working memory resources (DeStefano & Lefevre, 2004; Lefevre & Kulak, 1994). In fact, the ability to perform a single-digit calculation requires the subject to: (a) perceive, comprehend, and produce numbers; (b) process the operational sign that indicates the calculation to be performed; (c) retrieve arithmetic facts in declarative memory and, for a few problems; (d) apply specific rules. In this experiment, FG was administered a single-digit calculation task, in which the application or non-application of numerical rules was contrasted.

Method

Stimuli. Most basic arithmetic problems with single digits, such as 7 + 4 = 11 or 7 × 4 = 28, are stored as facts in declarative memory (McCloskey, Aliminosa, & Sokol, 1991). However, for a few of them, the resolution of the calculation problem requires the application of specific rules (McCloskey, 1992; McCloskey et al., 1991) that can be selectively affected or spared (Pesenti, Depoorter, & Seron, 2000; Semenza & Granà, 2006; Semenza, Granà, & Girelli, 2006) following brain damage. For multiplication, this is the case for problems involving a zero and a nonzero operand (e.g., 0 × 8) for which the result is not encoded as an arithmetic fact but requires the application of the '$n \times 0 = 0$' or '$0 \times n = 0$' rule. For divisions, it is also the case for the '$0 \div n$' problem that requires the application of the '$0 \div n = 0$' rule, as well as for the '$n \div n$' problem that requires the application of the '$n \div n = 1$' rule.

The single-digit mental calculation set comprised 279 simple problems. The set of non-rule based additions comprised 60 problems in which numbers from 1 to 9 had to be added to numbers from 2 to 9 with the larger always presented first (e.g., 9 + 3 =). The set of non-rule based subtractions comprised 45 problems in which numbers from 1 to 8 had to be subtracted from numbers from 1 to 9 (e.g., 9–3 =). The set of mental multiplications comprised 99 non-rule-based and rule-based problems. The non-rule-based multiplications consisted in 81 simple problems in which numbers from 1 to 9 had to be multiplied by numbers from 1 to 9 (e.g., 9 × 3 =). The rule-based multiplications comprised 18 problems involving zero and a nonzero operand (i.e., 0 × 1 through 0 × 9 and 1 × 0 through 9 × 0). Finally, the set of mental divisions comprised 56 non-rule-based and rule-based problems. The non-rule-based divisions consisted in 27 simple problems in which numbers from 4 to 20 had to be divided by numbers from 2 to 10 (e.g., 9 ÷ 3 =). The rule-based divisions comprised 9 problems involving zero divided by a number from 1 to 9 (e.g., 0 ÷ 3 =) and 20 problems for the '$n \div n = 1$' rule where numbers from 1 to 20 had to be divided by themselves (e.g., 9 ÷ 9 =).

Procedure. For each operation, single-digit mental calculation problems were presented orally in random order with no time limit to respond.

Results. As shown on Table 6, FG's performance was largely preserved for all non-rule-based single-digit calculation problems. He was slightly below the controls for mental division but the difference was not significant ($\chi 2 = 2.43$, $p = .11$). However, his ability to apply specific calculation rules in the four rule-based single-digit mental operations was substantially impaired ($p < .001$). For rule-based multiplications, the errors were of the type '$n \times 0 = \mathrm{n}$' (e.g., 5 × 0 = 5) and '$0 \times n = n$' (0 × 5 = 5). For rule-based divisions, the errors were of the type '$0 \div n = n$' (e.g., 0 ÷ 5 = 5) and '$n \div n = 0$' (e.g., 5 ÷ 5 = 0).

GENERAL DISCUSSION

FG, a patient with mild anterior aphasia, presented with a procedural deficit affecting the application of rules in two linguistic domains as well as in number processing. His ability to retrieve linguistic and numerical lexical representations, however, was largely preserved. The requirements of the tasks used in the four experiments in terms

TABLE 6
Performance of FG and control subjects (number and percent correct; values in brackets correspond to *SD*) in calculation tasks

Calculation tasks	*FG*	*Controls*
Non-rule-based single-digit calculation		
– Additions (60)	59 (98%)	58.75 [1.25] (98%)
– Subtractions (45)	45 (100%)	44.5 [.5] (99%)
– Multiplications (81)	77 (95%)	80.5 [.06] (99%)
– Divisions (27)	23 (85%)	27 (100%)
Rule-based single-digit calculation		
– $0 \div n = 0$ (9)	0 (0%)	8 [.17] (89%) ***
– $n \div n = 1$ (20)	1 (5%)	14.66 [.28] (73%) ***
– $n \times 0 = 0$ (9)	0 (0%)	8.67 [.19] (96%) ***
– $0 \times n = 0$ (9)	0 (0%)	9 (100%) ***

Difference between FG and controls: ***$p < .001$.

of working memory and executive functions were substantially reduced so that these results allow a better evaluation of the specific nature of procedural deficits. Overall, these data partly support the differentiation between declarative and procedural memory. Some situations requiring the application of rules, however, remained unimpaired in FG and different performance patterns emerged according to the domain of application. Importantly, and consistent with many other results recently reported in the literature (Colman et al., 2009; Longworth, Keenan, Barker, Marslen-Wilson, & Tyler, 2005; Penke & Westermann, 2006; Terzi, Papapetropoulos, & Kouvelas, 2005), our results clearly indicate that the D/P model (Ullman, 2001, 2004) should be revised to account for effects linked to application domains as well as the complexity or the specificity of rules.

The application of rules in morphology

FG underwent tasks exploring the application of rules in the verbal and adjectival morphological domains. His abilities to access lexical representations in declarative memory were largely preserved whilst he encountered difficulties when the tasks required the application of inflection rules in both domains. In the verbal domain, he performed similarly to the control subjects for regular and irregular verb inflection but showed difficulties in one of the three subregular verb conjugations. When asked to conjugate non-verbs, he showed substantial difficulties in three of the six conjugation tasks. In the adjectival domain, FG was unimpaired for real adjectives inflection, while he presented with a deficit for the two ‘rule non-adjectives’ inflection tasks requiring the application of an inflection rule.

The overall pattern of performance reported in FG can be partially accounted for by the D/P model (Pinker, 1999; Ullman, 2001; Ullman & Corkin, 1997). According to this model, procedural memory plays a role in all subdomains of grammar, including inflectional morphology and syntax. As a whole, the results reported here support the distinction between declarative (well preserved in FG) and procedural (affected in FG) memory. However FG showed almost no problems for real regular and subregular verb conjugation or for real adjectives, results that run counter to the D/P model. When presented with non-lexicalized novel information such as non-verbs and non-adjectives, he could not resort to lexical representations, and inflection rules had to be applied through procedural mechanisms only. Similar results and interpretation had been reported for French-speaking HD patients in Teichmann et al.’s (2005) study.

Another explanation could be that the patient’s inflectional deficits for novel words originate from his executive disorders affecting controlled cognitive processes (i.e., novel problem solving, shifting of mental sets, inhibition of prepotent or previous responses). That would be less the case with rule application for real verbs and real adjectives, which would be processed more automatically, thus demanding less cognitive resources. An executive origin for past tense inflection deficits in cerebrovascular, PD and HD patients was also proposed by Longworth and her colleagues (Longworth et al., 2005). None of these patients with striatal dysfunction showed selective impairment of regular past tense morphology. Moreover, PD and HD patients showed a tendency to perseverate on the cue (i.e., the verb stem) in real verb inflection or, like FG, to produce an existing inflection when they were requested to produce the past tense of non-verbs. According to Longworth et al. (2005), the absence of deficit for regular past tense morphology as well as the inability to suppress semantically appropriate alternatives in non-verb inflection is suggestive of a general executive non-language-specific deficit affecting the inhibition of competing alternatives. Such an interpretation was also recently proposed by Colman et al. (2009) to account for the performance of 28 Dutch-speaking PD patients who showed no influence of regularity on verb production and whose score correlated significantly with executive performance in set-switching and working memory tasks.

The application of rules in syntax

Syntactic rule application was explored in FG through a sentence-anagram task consisting in rearranging the sentence constituents in order to compose a grammatical sentence. Interestingly, data from this task show that all processes of rule application are not equally impaired in FG. We found that FG performed perfectly well in rearranging canonical sentence structures (i.e., the nominalized active sentences), for which a simple layout of verb arguments according to the canonical word order in French (subject–verb–object) is required. However, when he had to rearrange pronominalized active sentences, which requires moving and setting clitic pronouns before the verb (non-canonical sentences), FG's performance was impaired. More specifically, FG encountered difficulties with the rearrangement of pronominalized active sentences with a three-place verb but not with pronominalized active sentences with a two-place verb, for which his performance was comparable to that of controls. These findings are interesting because they show, first, that FG's difficulties do not follow a clear dichotomy between preserved canonical sentences and impaired non-canonical sentences, as expected, for instance, by the hypothesis of an additional executive cost for non-canonical sentences, or by the Derived Order Problem hypothesis (DOP; Bastiaanse & Van Zonneveld, 2005; Burchert, Meissner, & De Bleser, 2008). This neurolinguistic theory states that agrammatic production deficits arise from specific difficulties in syntactic movement rules, which implies a straight dissociation between canonical (no movement) and non-canonical (movement) sentences. In fact, our data show that FG exhibits difficulties with rule application, but this is restricted to sentences entailing moving and setting several clitic pronouns before the verb (i.e., pronominalized active sentences with a three-place verb). Crucially, the fact that FG performed well in rearranging pronominalized active sentences with a two-place verb rules out the possibility of an explanation of FG's performance based solely on executive difficulties in manipulating or moving pronominalized arguments in the sentence-anagram task. FG's difficulties in composing certain non-canonical sentences would not, therefore, result from an impairment in the application of movement rule (i.e., moving clitics in front of the verb) but rather in the precise setting of several clitic pronouns according to the specific rules of French (i.e., put the dative-clitic pronoun after the accusative-clitic pronoun, the latter being put after the subject pronoun, *elle le leur confie* 'she confides it to them'). Convincing evidence in favour of this explanation comes from FG's error analysis. All of the errors except one implied an impairment in the correct setting of clitic pronouns, after they had been moved (e.g., **il lui le soumet* instead of *il le lui soumet* [literally: '*he him it submits' instead of 'he it him submits']). In other words, only the sentences, involving accusative and dative clitic pronouns before the verb, and rules specifying their relative ordering, are affected in FG.

One possibility is that FG's poor performance for combining several clitic pronouns results from a reduction in working memory and executive resources. According to numerous authors, a 'resource reduction' could indeed impair processing for sentences when several syntactical operations are required (like moving arguments), leading to a pattern of performance where complex sentences are more affected than less complex ones (Caplan & Hildebrandt, 1988; Caplan, Waters, Dede, Michaud, & Reddy, 2007; Frazier & Friederici, 1991; Gibson, 1998; Just & Carpenter, 1992). This type of explanation, initially suggested by Linebarger, Schwartz et Saffran (1983) to account for the discrepancy in agrammatic patients between poor performance on sentence-picture matching tasks (which recruit substantial executive resources) and well-preserved performance on grammaticality judgement tasks (which only require syntactic operations), is based on the hypothesis of a trade-off deficit in these patients between the cognitive cost implied by the syntactic operations and that of other operations implied by the task. A 'resource consuming' task such as a sentence-picture matching task, which requires, in addition to syntactic operations to run, analyzing visual information and maintaining this information in working memory in order to judge whether the picture correctly (or not) describes the meaning of the spoken sentence, is therefore strongly expected to tax working memory and executive resources.

A reduction in working memory and executives resources is not likely to explain FG's performance on the sentence-anagram task. First, contrary to the sentence-picture matching task, the sentence-anagram task does not imply maintaining visual or spoken information in working memory since the words to rearrange remained in front of the patient until he produced a response, with no time limit. Second, FG exhibited difficulties arising when several rules were required, that is when he had to rearrange sentences comprising four words only (i.e., pronominalized active sentences with a three-place verb). His performance, however, was perfect when he had to rearrange the eight words of the 'nominalized' version of these sentences, indicating that the problem was not due to a length effect of the sentence to be composed, nor to an effect of the semantic-syntactic complexity of the verb since the same verbs were used in both nominalized and pronominalized active sentences with a three-place verb. Finally, to explore further the procedural versus resource reduction hypothesis in FG, we administered a follow-up grammaticality judgement task using the same stimuli (half of which were ungrammatical, e.g., **il lui le soumet* instead of *il le lui soumet* [literally: '*he them it submits' instead of 'he it them submits']; **le ministre soumet le president au rapport* instead of *le ministre soumet le rapport au president* [literally: '*the minister submits the president to the report' instead of 'the minister submits the report to the president']). Interestingly, FG presented the same pattern of performance as in the sentence-anagram task with a perfect performance for judging nominalized active sentences with a three-place verb (15/16) while he performed at chance level for their pronominalized counterparts (9/16). By minimizing the importance of the contribution of working memory resources, these findings militate in favour of a procedural deficit in FG, not easily explainable by executive deficits only. Overall, the findings obtained with FG in syntax strongly suggest a procedural deficit in using syntactic algorithms needed to combine several rules, such as correctly setting several clitic pronouns according to the specific rules of French.

The application of rules in calculation

Following Teichmann et al. (2005), we extended the study of procedural memory deficits to the numerical domain. FG was proposed tasks exploring the application of rules in single-digit mental calculation tasks. He had no difficulty in retrieving arithmetical facts, a result confirming that the preservation of the declarative memory component is not limited to verbal material but also holds for number processing. FG was however severely impaired when presented with single-digit mental calculation problems requiring the application of a specific rule.

According to studies in which subjects were asked to verify or solve single-digit problems (e.g., 3 + 2) under various processing conditions (e.g., random generation of letters), the use of working memory and executive functions is directly tied to the general attentional requirements of the task (for a review, see DeStefano & Lefevre, 2004). In the present study, single-digit problems were presented without any additional processing load. As opposed to multi-digit calculations, they can be processed automatically and require less executive and working memory resources (DeStefano & Lefevre, 2004; Lefevre & Kulak, 1994). Working memory and executive limitations cannot account for differences between otherwise equivalent arithmetic tasks, one which is based on retrieval of item-specific facts in declarative memory and the other based on rule application.

The calculation system may break down in a highly selective way and damage transcoding or calculation abilities. Dissociation between knowledge of facts and execution of procedures has been reported several times in adult brain-damaged patients (Dehaene & Cohen, 1997) as well as in learning-disabled children (Temple, 1991). In result-verification tasks, HD patients in Teichmann et al.'s (2005) study showed preserved abilities in two-digit multiplication problems while they presented a procedural deficit in two-digit subtraction problems. According to the authors, multiplication problems are easier than subtraction problems because they can be solved by simple access to arithmetic facts whereas the latter require the application of rules. However, in addition to these processes, multi-digit problems also recruit substantial working memory and executive resources (e.g., Hitch, 1978; Logie et al., 1994). In the present study, we also demonstrate that calculation procedures and numerical facts retrieval rely on distinct cognitive processes in a task in which the processing load was substantially reduced. As with other reported cases (Pesenti et al., 2000; Semenza et al., 2006), FG presented with a procedural deficit in calculation affecting problems (i.e., '$n \times 0 = 0$'; '$0 \times n = 0$'; '$0 \div n = 0$'; '$n \div n = 1$') for which the application of specific rules is required. Based on theoretical models of number processing (McCloskey, 1992; McCloskey et al., 1991), we can consider that a few single-digit problems require calculation rules. Results for special-case single-digit problems such as '$n \times 0$' are not encoded in long-term declarative memory and must therefore be solved through the application of specific rules. In the D/P model, we suggest that, because of a procedural impairment, FG was affected in the application of these specific calculation rules.

CONCLUSIONS

From a neuroanatomical viewpoint, Koechlin and Jubault (2006) showed that the executive control mechanisms for rule application are cortically implemented in regions including the inferior parietal cortex, the supplementary motor area, and the insula. A similar involvement of the insula, the impaired brain structure in FG, was also reported in other studies related to rule learning and rule application (Seger & Cincotta, 2005; Ullman & Corkin, 1997; Ullman et al., 2005). Moreover, as in FG, five of the six anterior aphasic patients reported by Ullman et al. (1997) to support the D/P model (Pinker, 1999; Ullman, 2001) presented with larger lesions involving temporal or temporoparietal areas. Overall, data from our study partially support the D/P model and the distinction in cognition between the activation of representations encoded in long-term declarative memory on the one hand and the application of internally represented rules in procedural memory on the other. Like Teichmann et al. (2005), we reported this differentiation in morphological and syntactic abilities as well as in calculation. In addition, the originality of our study lies in the fact that we showed that FG's performance in the three domains cannot be entirely explained by his concomitant deficit in executive functions, but was rather the direct consequence of a general procedural impairment. However, we also showed that FG's performance varied according to the domain in which rules were to be applied. Various attempts to differentiate rules in procedural memory have already been made in the literature, most of them in artificial grammar or motor learning. For example, according to the propositions of Koechlin and Jubault (2006), the application of internal rules is sustained by executive control mechanisms managing the execution of structured behavioural plans over time. Along with Dehaene and Changeux's computational model of action planning (Dehaene & Changeux, 1997), Koechlin and Jubault suggested that behavioural plans are composed of interconnected hierarchical levels of actions, whose activation is processed in cascade. In line with Koechlin and Jubault's viewpoint, rather than just considering that rules differ from each other in terms of 'complexity', a better conceptualization of the organization of rules in procedural memory might be to envision rules as sequence components that would be successively activated while performing a task. For instance, in French, the singular third person in the future tense requires first affixing -er then affixing -a to the lexical root of first group verbs, which represent the dominant case.

As a whole, our data underline the need for more fine-grained distinctions in cognition between procedural rules. The differentiation between declarative and procedural processes is congruent with theoretical propositions (e.g., Dominey, Hoen, Blanc, & Lelekov-Boissard, 2003; Goschke, Friederici, Kotz, & van Kampen, 2001) focusing not only on grammar but also on the management of nonlinguistic sequences. Studies aimed at exploring different domains of cognition should also be performed in order to clarify the issue of the complexity and domain-dependence of procedural mechanisms. The question related to the automaticity and implicit application of rules on the one hand, and the executive and controlled processes on the other, should also be addressed in further studies.

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