Is the frontal dysexecutive syndrome due to a working memory deficit? Evidence from patients with stroke

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Although frontal dysexecutive disorders are frequently considered to be due to working memory deficit, this has not been systematically examined and very little evidence is available for impairment of working memory in frontal damage. The objective of this study was to examine the components of working memory, their anatomy and the relations with executive functions in patients with stroke involving the frontal or posterior cortex. The study population consisted of 29 patients (frontal: n = 17; posterior: n = 12) and 29 matched controls. Phonological loop (letter and word spans, phonological store; rehearsal process), visuospatial sketchpad (visuospatial span) and the central executive (working memory span, dual task and updating process) were examined. The group comparison analysis showed impairment in the frontal group of: (i) verbal spans ($P < 0.03$); (ii) with a deficit of the rehearsal process ($P = 0.006$); (iii) visuospatial span ($P = 0.04$); (iv) working memory span ($P = 0.001$) that disappeared after controlling for verbal span and (v) running memory ($P = 0.05$) unrelated to updating conditions. The clinical anatomical correlation study showed that impairment of the central executive depended on frontal and posterior lesion. Cognitive dysexecutive disorders were observed in 11/20 patients with central executive deficit and an inverse dissociation was observed in two patients. Receiver operating characteristic curve analysis indicated that cognitive dysexecutive disorders had the highest ability to discriminate frontal lesions (area under curve = 0.844, 95% confidence interval: 0.74–0.95; $P = 0.0001$; central executive impairment: area under curve = 0.732, 95% confidence interval: 0.57–0.82; $P = 0.006$). This study reveals that frontal lesions induce mild impairment of short-term memory associated with a deficit of the rehearsal process supporting the role of the frontal lobe in this process; the central executive depends on lesions in the frontal lobe and posterior regions accounting for its low frequency and the negative results of group studies. Finally, the frontal dysexecutive syndrome cannot be attributed to central executive impairment, although it may contribute to some dysexecutive disorders.

Keywords: brain injury; ischaemic stroke; frontal lobe; executive functions; working memory
Introduction

Disorders of executive functions are one of the most frequent cognitive deficits and are observed in many brain diseases. Following Luria’s approach (1966), the term ‘executive functions’ was coined by Lezak (1982), and was initially circumscribed to goal setting, action initiation and inhibition, planning, shifting and verification. This domain has been extended to include behavioural changes observed in frontal lesions (Baddeley and Wilson, 1988). These higher-order functions account for cognitive and behavioural control and depend mainly on frontal lobes and fronto-subcortical networks. They are assessed using conventional executive tests, such as Modified Card Sorting, Stroop, Trail Making, verbal fluency and Tower of London tests (Godefroy et al., 2010). Although an impressive number of studies have documented the frequency and variability of executive disorders, their underlying mechanisms and related anatomy remain largely undetermined, resulting in a long list of cognitive dysexecutive disorders (i.e. demonstrated on cognitive tests; Godefroy et al., 2010). A better understanding of the underlying cognitive deficits would help to clarify the dysexecutive syndrome, its assessment and its anatomy. Three main explanations for dysexecutive disorders have been proposed: a deficit of a supervisory system involved in the control of action (Norman and Shallice, 1986), a deficit of attention and sustained alertness (Posner and Petersen, 1990) and a disorder of working memory (Baddeley, 1986). On the basis of animal data (Golman-Rakic, 1987), the working memory approach has gained considerable influence ( Miyake et al., 1999; Baddeley, 2000; D’Esposito, 2007). According to Baddeley (1986), working memory involves two modality-specific storage components (phonological loop and visuospatial sketchpad) and an attentional controlling system (central executive) that operates on temporary stored information and is involved in task coordination, inhibition, switching and updating (Baddeley, 1996; Miyake et al., 2000). The term ‘central executive’ was coined by Baddeley and Hitch (1974) in their initial version of the working memory model and should be differentiated from ‘executive functions’, which was subsequently proposed by Lezak (1982) to describe the processes individualized by Luria (1966). The hypothesis that executive functions depend on the intervention of the central executive is based on three lines of argument: (i) most executive tests are complex and consequently load working memory; (ii) the overlap between processes involved in conventional executive tests (i.e. Modified Card Sorting, Stroop, Trail Making, verbal fluency and Tower of London tests) and cognitive operations proposed to depend on the central executive (task coordination, inhibition, switching and updating); and (iii) the anatomical overlap as both executive functions and central executive involve the prefrontal cortex. The relationship between the central executive and frontal lobe has been mainly documented by functional imaging studies showing the prominent activation of the prefrontal cortex in conditions involving the central executive (D’Esposito et al., 1995, 2000; Colette and Van der Linden, 2002). Conversely, evidence for impairment of the central executive in frontal lesions, especially stroke, remains very limited. Frontal lesions spare digit and spatial spans (D’Esposito et al., 1999), whereas contradictory results have been reported for delayed response tasks (D’Esposito et al., 1999, 2006). Shallice and Vallar (1990) reviewed case studies assessing mechanisms of impairment of the phonological loop (storage versus rehearsal mechanism) and showed prominent impairment of storage that is usually related to a left parietal lesion. The deficit of the rehearsal mechanism is reported in rare cases, mostly in patients with a left inferior frontal lesion ( Belleville et al., 1992; Waters et al., 1992; Vallar et al., 1997). Processes depending on the central executive (task coordination, switching and updating) are usually assessed using a dual task paradigm (requiring coordination of the execution of diverse sets of tasks), working memory span (requiring a simultaneous combination of online processing and information storage) and running memory task (requiring updating of relevant information and suppression of no-longer-relevant data; Pollack et al., 1959; Morris and Jones, 1990). Most studies on the central executive in focal lesions have focused on task coordination and none have systematically examined all working memory processes. Impairment of dual task due to a frontal lesion has been reported in only two studies (Cowey and Green, 1996; Leclercq et al., 2000) and only one showed that this impairment was more marked than in lesions of the posterior cortex (Cowey and Green, 1996). One (Baddeley et al., 1997) of the four negative studies (Vilkki et al., 1996, 2002; Baddeley et al., 1997; Andres and Van der Linden, 2002) showed poor performance in the subgroup of frontal patients with behavioural changes. Two studies using sequential dual tasks (Godefroy et al., 1999; Stabulum et al., 2000) reported more marked response slowing in patients with frontal lesions, but this impairment was not related to other deficits of controlled processes (Godefroy et al., 1999). There is, therefore, little evidence that frontal lesions impair the central executive as defined by Baddeley et al. (1997). This contrasts with impairment of the central executive reported in diffuse diseases, such as Alzheimer’s disease (Baddeley et al., 1991; Colette et al., 1999; Huntley et al., 2010), traumatic brain injury ( McDowell, 1997; Azouvi et al., 2009; Barbey et al., 2011; Hillary et al., 2011) and Parkinson’s disease (Morris et al., 1988; Pillon et al., 2001; Beato et al., 2008). However, no study has examined whether working memory impairment underlies dysexecutive disorders, i.e. the emergence of dysexecutive cognitive disorders is conditioned by impairment of working memory.

The objective of this study was to examine working memory, executive function and the relationship between the two. It was performed in stroke, a disease that frequently impairs executive functions (Tatemichi et al., 1994; Sachdev et al., 2004; Godefroy et al., 2010) and which is suitable for examining associations and dissociations between deficits (Godefroy et al., 1998; Müller and Knight, 2006).

Materials and methods

Population

Consecutive patients aged 18–70 years referred to the Lille stroke centre for recent stroke (<1 month) visualized by brain imaging...
were considered for inclusion. Exclusion criteria were: (i) sensory-motor deficit, hemineglect or aphasia precluding cognitive assessment (Godefroy et al., 2002); (ii) illiteracy; (iii) alcoholism or severe general comorbidity; (iv) previous neurological and psychiatric diseases except for depression or anxiety; (v) recent introduction of psychoactive or anti-epileptic medication; and (vi) absence of informed consent. This study included 29 patients and 29 age and education-matched controls (Table 1). Neuroradiological analysis was performed using MRI scans according to a method providing good inter-observer reliability (Godefroy et al., 1998; Supplementary material). It determined the presence of a lesion in the 22 regions of interest on each side and white matter abnormalities (Fazekas et al., 1987). Lesion analysis (Fig. 1) indicated that 17 patients (seven females; 10 males) had a lesion restricted to the anterior region (frontal group) and 12 patients (10 females; two males) had a lesion limited to the posterior region (posterior group; Table 1). Demographic characteristics did not differ except for gender due to a higher proportion of females in the control and posterior groups. For this reason, all analyses first assessed the gender effect; as this effect was never significant, only group comparison analyses are reported. This study was approved by the institutional review board.

Neuropsychological assessment

Neuropsychological assessment was performed with a mean post-stroke interval of 17.4 ± 10.6 days. Results of the general neuropsychological assessment are provided in Table 1 (see Supplementary material for detailed methods and results of general neuropsychological assessment). Briefly, the general neuropsychological assessment showed that: (i) general intellectual efficiency (Raven, 1965; Beauregard, 1971; Folstein et al., 1975) was spared; (ii) the frontal group presented impairment of digit and spatial span (Weschler, 1989), episodic memory (Signoret, 1991) and most behavioural (Godefroy et al., 1996) and cognitive (Godefroy et al., 2010) assessments of executive functions using conventional tests [including verbal fluency, Stroop (1935), Trail Making (Reitan, 1958), Tower of London (Shallice, 1982) and Modified Card Sorting tests (Nelson, 1976)]; and (iii) the posterior group presented impairment of episodic memory and two executive assessments (verbal fluency and Modified Card Sorting test).

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<thead>
<tr>
<th>Table 1 Demographic characteristics, lesions and performance on tests assessing executive functions</th>
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<td>Frontal group</td>
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<td>Age (years)</td>
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<td>Education (years)</td>
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<td>Stroke type: infarct/haemorrhage</td>
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<td>White matter abnormalities 0/1/2/3</td>
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<td>Deep structures: left/right</td>
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<td>Trail Making test</td>
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<td>Stroop</td>
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<td>Interference index</td>
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Results are expressed as mean ± SD except lesion location (number).
a Significant difference with controls.
b Significant difference between both patient groups.
Examination of working memory components

According to the model of Baddeley (1996), we examined the phonological loop (phonological short-term store and the rehearsal process), the visuospatial sketchpad and the central executive (working memory span, dual task coordination and running memory span) by means of computerized tests. Auditory stimuli were presented through loudspeakers and visual stimuli were displayed in the centre of the monitor screen. Responses were provided either verbally or using a touch-sensitive screen. To control for a possible decrease of storage capacity, tasks assessing the phonological loop and central executive used list length at each subject’s span level.

Assessment of the phonological loop

According to Belleville’s procedure (1996), the following functions were assessed: (i) phonological abilities using rhyme judgement and homophony judgement tasks; (ii) overall capacity using span tasks (consonant, word); (iii) short-term store using phonological similarity effect; and (iv) the rehearsal process using the word length effect. Except for phonological abilities, performance was analysed using stimuli delivered according to both auditory and visual modalities.

In the rhyme judgement and homophony judgement tasks, reference words were displayed one by one on the monitor screen (Supplementary material). Four stimulus words (one target and three distractors) were displayed. The subject had to indicate which word rhymed with (rhyme judgment test) or sounded like (homophony judgment test) the reference word.

Verbal span tests used dissimilar consonants (‘f, h, l, j, r, k, m’) and monosyllabic words (‘sac’, ‘lune’, ‘train’, ‘mur’, ‘jambe’, ‘neige’, ‘chien’, ‘clef’, ‘bois’ (bag, moon, train, wall, leg, snow, dog, key, wood)). Five series of various lengths (from two to seven) were presented. In both auditory and visual modalities, items were displayed at a rate of one item per 1.5 s. Span was determined as the longest series length allowing correct recall of at least three out of five series.

The phonological similarity effect was determined by comparison of recall of dissimilar (‘f, h, l, j, r, k, m’) and similar sounding consonants (‘b, c, d, g, p, t, v’). List length corresponded to each subject’s letter span. In both auditory and visual modalities, letters were displayed at a rate of 1.5 s. Performance was determined by the number of correctly recalled lists of similar ($n = 5$ trials) and dissimilar ($n = 5$ trials) consonants on auditory and visual modalities. The dependant variable was the similarity index (number of correctly recalled lists of similar consonants minus dissimilar consonants) computed for both auditory and visual modalities.

The word length effect was determined by comparison of recall of lists of monosyllabic and four-syllable words (‘ordinateur’, ‘bibliothèque’, ‘photographie’, ‘anniversaire’, ‘appartement’, ‘médicament’, ‘dessinateur’, ‘télévision’, ‘publicité’ (computer, library, photography, birthday, apartment, drug, draughtsman, television, publicity)). List length was adjusted to each subject’s word span. Word length effect was assessed for both auditory and visual modalities. Words were displayed at a rate of 1.5 s. Performance was assessed by the number of correctly recalled lists of monosyllabic ($n = 5$ trials) and four-syllable ($n = 5$ trials) words on auditory and visual modalities. The dependent variable was the word length index (number of correctly recalled lists of monosyllabic words minus four-syllable words) computed for both auditory and visual modalities.

Assessment of the visuospatial sketchpad

The spatial span test procedure was similar to that described by Owen et al. (1990). The subject was required to reproduce a sequence of illuminated squares (rate: one square per second) within an array of nine blocks by pointing to each location in the same order. Five series of different lengths were presented. Span was determined as the longest series length allowing correct recall of at least 3/5 series.

Central executive

Assessment of the central executive included working memory span, dual task coordination and a running memory task. Working memory span used three-syllable non-words as stimuli. Non-words were constructed by adding a syllable between the first and last syllables of French disyllabic words [e.g. ‘maison’ (‘house’) led to ‘mai/ta/son’] matched according to occurrence frequency and imagery. Stimuli were produced aloud (one item/2 s). Subjects had to identify each word by deleting the middle syllable (e.g. ‘mai/ta/son’ = ‘maison’) and then remember them. The efficiency of syllabic deletion was checked before testing. Series of increasing length from two to five words were presented with the same procedure as the verbal span.

The computerized dual task used a visuomotor tracking task and an auditory-verbal memory task. Each task (lasting 2 min) was performed first as a single task condition and then as a combined task condition (Baddeley et al., 1986). The visuomotor tracking task required the subject to track with the index finger a square (2 cm) unpredictably moving on the centre of the touch-sensitive screen. For each subject, the target speed was determined to achieve a time on target between 40 and 60%. The verbal memory task required the subject to recall a series of dissimilar consonants at lengths corresponding to each subject’s span level. The mu index was used to quantify the dual task decrement (Baddeley et al., 1997). This index was computed as
follows: \[ \mu = \frac{1 - (pm + pt)/2}{100} \times 100 \] where \( pm \) is the proportional loss of memory performance under dual-task conditions and \( pt \) is the proportional loss in tracking score.

The running memory task (Pollack et al., 1999) was derived from that developed by Morris and Jones (1990). It used strings of alphabetical series, dissimilar consonants and abstract drawings. Strings of alphabetical series (‘b, c, d, e, f, g’) were used to assess the updating process \( per se \), as they represented ‘overlearned’ material, hence not requiring short-term storage. The procedure was similar across conditions: strings of items (alphabetical series, consonant, abstract drawings) were presented one by one at a 1.5 s rate in the centre of the computer screen. The subject was instructed to recall the last \( N \) items, where \( N \) corresponds to the subject’s span. Four updating conditions were used: a null update condition (list length = subject span) and conditions with 2, 4, 6 updating (list length = subject span + 2, 4 or 6 items). For each material (alphabetical series, consonant, abstract drawings), 20 lists (five per updating condition 0, 2, 4, 6) were presented after 10 practice trials. Performance was defined by the number of lists correctly recalled (/5) in each updating condition (\( n = 4 \)) for each material (\( n = 3 \)).

### Statistics

Group comparisons were performed by one-way and repeated ANOVA with group (frontal, posterior and control groups) as between-subject factor and task conditions as within-subject factor. Response time was log-transformed. Post hoc analyses used the Bonferroni test for the factor ‘Group’ and, when relevant, contrast analyses for the factor ‘Condition’.

Individual performance was assessed using cut-off scores at the 5% level. The presence of dysexecutive disorders was determined using performance on conventional tests of executive functions and behavioural disorders. According to a previously validated method (Godefroy et al., 2010), cognitive dysexecutive disorders were considered to be present when at least two of the following indices were impaired: (i) \( \leq 1 \) fluency test impaired; (ii) \( \leq 1 \) impaired completion time on Trail Making test, naming and reading subtests of the Stroop; (iii) \( \leq 1 \) impaired perseveration rate on Trail Making test B and Modified Card Sorting test; (iv) Stroop interference index; (v) category achieved on the Modified Card Sorting test. A central executive index was computed by summing the impairment on working memory in the frontal group.

### Results

#### Phonological loop

**Rhyme judgement and homophony judgement tasks**

Performance was analysed by two one-way ANOVAs using the group factor (frontal, posterior, controls) as between-subject factor. In the rhyme judgement task, a significant group effect \( F(2,51) = 3.5, P = 0.037 \) was observed due to impairment of the frontal group (\( P = 0.03; \) Table 2). The homophony judgement task did not differ between groups (\( P = 0.2 \)). This analysis indicates that rhyme judgement was impaired in the frontal group.

#### Consonant and word spans

Consonant and word spans were analysed by two ANOVA’s using the group factor (frontal, posterior and control groups) as between-subject factor with repeated measures on modality (auditory, visual).

Consonant span analysis (Table 2) showed a significant group effect \( F(2,54) = 4.92, P = 0.039 \) due to lower span in the frontal group (\( P = 0.03 \)) and a modality effect \( F(1,54) = 14.92, P = 0.0005 \) was due to shorter span on visual presentation (group \( \times \) modality: \( P = 0.75 \)).

Word span analysis showed a significant group effect \( F(2,55) = 5.72, P = 0.006 \) due to shorter span in the frontal group (\( P = 0.034 \)) with no modality effect (\( P = 0.11; \) group \( \times \) modality: \( P = 0.55 \)).

These analyses show that word and consonant spans were shorter in the frontal group, indicating decreased verbal short-term memory in the frontal group.

#### Phonological similarity effect

Performance (similarity index) was analysed by ANOVA using the group factor (frontal, posterior and control groups) as between-subject factor with repeated measures on modality (auditory, visual). No factor was found to be significant (group: \( P = 0.15; \) modality: \( P = 0.8 \); modality \( \times \) group: \( P = 0.5; \) Table 2; Supplementary material). This analysis indicates that the phonological similarity effect did not differ across groups.

#### Word length effect

Performance (word length index) was analysed by ANOVA using the group factor (frontal, posterior and control groups) as between-subject factor with repeated measures on modality (auditory, visual). The significant group effect \( F(2,51) = 6.8, P = 0.002 \) consisted of a lower word length effect in the frontal group (frontal = 1.77 ± 1.2; posterior = 2.88 ± 1.3;
controls = 2.67 ± 1.2) compared with controls (P = 0.006) and the posterior group (P = 0.007; Table 2; Supplementary material). The modality effect was significant [F(1,51) = 9.26, P = 0.004] due to a lower word length effect on the verbal modality than on the visual modality (verbal = 2.1 ± 1.3; visual = 2.8 ± 1.3; group x modality interaction: P = 0.9). This analysis indicates that the word length effect was higher for visually presented words and lower in the frontal group.

In summary, assessment of the phonological loop was impaired in the frontal group with lower letter and word spans, a mild but significant deficit of rhyme judgement, and a lower effect of word length, suggesting a deficit of the rehearsal component. Inversely, the storage component was spared as shown by analysis of the similarity effect.

**Visuospatial sketchpad**

Spatial span was analysed by ANOVA using the group factor (frontal, posterior and control groups) as between-subject factor. The group effect [F(2,54) = 5.2, P = 0.036] was significant due to a shorter span (frontal = 4.6 ± 1.06; posterior = 5 ± 1; controls = 5.5 ± 1.06) in the frontal group (P = 0.035; Table 2). This analysis indicates that the frontal group had shorter visuospatial spans.

**Central executive**

**Working memory span**

Working memory span was analysed by ANOVA using a group factor (frontal, posterior and control groups) and showed a significant group effect [F(2,51) = 11.2, P = 0.0001] due to shorter span in both the frontal (P = 0.0001) and posterior (P = 0.001) groups (frontal = 2.1 ± 0.7; posterior = 2.3 ± 1.1; controls = 3.1 ± 0.7). This deficit could be due to lower short-term memory capacity or may be specifically due to the combination of a span task and a concurrent processing task. This issue was addressed by calculating the span decrement due to the concurrent processing task (span decrement = word span in visual presentation – working memory span). The span decrement (frontal: 1.65 ± 0.8; posterior: 1.67 ± 0.8; controls: 1.52 ± 1.2) did not differ between groups (P = 0.9). This analysis indicates that both patient groups had lower working memory span and that this impairment disappeared after controlling for short-term memory capacity.

**Dual task test**

Mu index was analysed by ANOVA using a group factor (frontal, posterior and control groups). No difference was observed between groups [F(2,51) = 1.34, P = 0.3] (frontal = 88.2 ± 16.8; posterior = 92.5 ± 17.7; controls = 95.3 ± 10.1). Dual task performance did not differ between groups.

**Running memory task**

The number of correct recalls was analysed by ANOVA using a group factor (frontal, posterior and control groups) with repeated analyses on material factors (alphabetical series, drawings, consonants) and number of updates (0, 2, 4, 6). It showed a significant effect of (i) group [F(2,48) = 6.1, P = 0.03] due to lower performance in the frontal group (frontal = 2.96 ± 1.6; posterior = 3.2 ± 1.5; controls = 3.47 ± 1.6; P = 0.05); (ii) material [F(2,48) = 51.4, P = 0.0001], due to lower recall of consonants compared to alphabetical series (P = 0.001) and drawings (P = 0.04; alphabetical series = 4.3 ± 1.1; drawings = 2.97 ± 1.6; consonants = 2.6 ± 1.6); (iii) update number [F(3,48) = 57, P = 0.0001], due to lower recall in six update conditions compared with the other conditions (zero update = 4.2 ± 1.1; two updates = 3.44 ± 1.5; four updates = 2.85 ± 1.6; six updates = 2.57 ± 1.7; P = 0.01; Table 3). The material x update interaction was significant due to a more marked decrease of recall in the six update conditions for consonants than for drawings (P = 0.04) and
alphabetical series \( (P = 0.0001) \). Finally, the group × material × update number interaction \( (P = 0.001) \) was significant (Fig. 2) due to a less marked reduction of recall with increasing updates in the frontal group compared with controls \( (P = 0.005) \) for drawings (frontal: \(-0.7 \pm 1.4\); posterior: \(-1.2 \pm 1.2\); controls: \(-2.76 \pm 1.5\) ). The reverse pattern was observed for alphabetical series for which increasing updates did not reduce recall in controls \( (P = 0.3 \pm 0.9) \) but did in patients (frontal: \(-1.2 \pm 1.3\); posterior: \(-1.4 \pm 1.4\); \( P = 0.04 \), both; group × material: \( P = 0.7 \); group × update number: \( P = 0.25 \)). Patient recall was therefore not disproportionately sensitive to the number of updates. However, in contrast with controls, patients did not benefit from over-learned alphabetical series.

This analysis indicates a global recall deficit in the frontal group with no disproportionate sensitivity to the number of updates and the lack of benefit for the over-learned alphabetical series. In summary, central executive assessment was impaired in both patient groups for working memory span, but this disappeared after controlling for short-term memory capacity, and in the frontal group for the running memory task without disproportionate sensitivity to the number of updates. The dual task was not impaired.

### Clinical–anatomical correlation

Impairment of the central executive index was more frequent in the frontal (9/17) and posterior (4/12) groups than in controls (0/29; \( P = 0.001 \), both). Bivariate analyses (Supplementary Table 3) showed that it was more frequent in right lesions of the frontal basal region and of the posterior part of the centrum semiovale. A strong tendency was observed for left lesions of frontomesial, frontobasal, temporal lateral areas and right lesions of the middle frontal gyrus. Multivariate analyses selected right lesions of frontobasal \( [ \text{odds ratio (OR): 18.4, 95\% confidence interval (CI): 1.7}–203; P = 0.02] \) and posterior centrum semiovale \( [ \text{OR: 18.4, 95\% CI: 1.7}–203; P = 0.02] \) regions. These lesions correctly classified 20 (69\%) patients \( (\chi^2 = 12.2; P = 0.002) \). This analysis indicates that central executive impairment depends on frontal and posterior lesions.

### Table 3 Running memory: mean number of correct responses at span according to update numbers

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<th>Frontal group</th>
<th>Posterior group</th>
<th>Controls</th>
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<tr>
<td><strong>Alphabetic series</strong></td>
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<tr>
<td>0 updates</td>
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<td>4.67 ± 0.49</td>
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<td>1.83 ± 1.26</td>
</tr>
<tr>
<td><strong>Drawings series</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 updates</td>
<td>3.20 ± 1.42</td>
<td>3.58 ± 1.00</td>
<td>4.52 ± 0.74</td>
</tr>
<tr>
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<td>2.67 ± 1.50</td>
<td>3.00 ± 1.60</td>
<td>3.31 ± 1.51</td>
</tr>
<tr>
<td>4 updates</td>
<td>2.40 ± 1.68</td>
<td>3.08 ± 1.24</td>
<td>2.79 ± 1.68</td>
</tr>
<tr>
<td>6 updates</td>
<td>2.47 ± 1.46</td>
<td>2.42 ± 0.90</td>
<td>1.76 ± 1.48</td>
</tr>
</tbody>
</table>

### Figure 2 Running memory task: effect of updating number (slope) on correct response for alphabetic series (triangle), consonants (square) and drawings (circle) in frontal (black symbols and lines), posterior (grey symbols and lines) and control (white symbols and dotted lines) groups.
Relationship with conventional executive tests

Cognitive dysexecutive disorders determined on conventional executive tests were more frequent in the frontal (11/17) and posterior (9/12) groups than in controls (0/29; \( P = 0.0001 \), both). Impairment of central executive index was more frequent (\( P = 0.0001 \)) in patients with cognitive dysexecutive disorders: 11 patients presented impairment of both functions. However, 11 patients had a dissociated deficit: nine had dysexecutive disorders without central executive impairment and two presented the reverse pattern. Thus, there were an equal number of cases with associated and dissociated deficits (\( n = 11, \) both). The ROC curve analysis (Supplementary Fig. 1) indicated that cognitive dysexecutive disorders had the highest area under curve (AUC = 0.844, 95% CI: 0.74–0.95; \( P = 0.0001 \)) suggesting a good to excellent ability to discriminate frontal lesions from non-frontal lesions. The AUC of central executive disorders was lower (AUC = 0.732, 95% CI: 0.57–0.82; \( P = 0.006 \)).

This analysis indicates that about one-half of patients with cognitive dysexecutive disorders on conventional tests had no central executive impairment and reciprocally that central executive impairment may be observed in a few patients with no cognitive dysexecutive disorders.

Discussion

This study shows that frontal damage was associated with a mild deficit of verbal spans, a decreased word length effect suggesting impairment of the rehearsal process of the phonological loop and a mild deficit of spatial span suggesting an alteration of the visuospatial sketchpad. Results also showed that frontal damage was associated with impairment of some central executive tests, impairment of working memory span that disappeared after control for short-term capacity and impairment of running memory without a disproportionate decrease of performance with updating number. The clinical–anatomical correlation study showed that central executive impairment depended on frontal and posterior lesions. Finally, one-half of patients with cognitive dysexecutive disorders on conventional tests had no central executive impairment and a reverse pattern (impaired central executive without cognitive dysexecutive disorders) was observed in a few patients.

The demonstration of impairment in verbal and spatial spans in the frontal group was unexpected, as pooled analysis of previous studies showed that these functions are usually spared in patients with frontal lesions (D’Esposito et al., 1999, 2006) and that severe deficits are observed in the context of parietal lesions (Warrington and Shallice, 1969; Shallice and Vallar, 1990; Godefroy et al., 1999). Accordingly, the present impairment of the frontal group is characterized by a mild decrement of letter, word and spatial spans. This contrasts sharply with the major impairment of short-term memory capacity observed in parietal lesions, in which span is usually \( \geq 2 \) (Warrington and Shallice, 1969). Both lines of results suggest that deficits of short-term memory are mainly due to parietal lesions and that frontal damage induces a mild decrement of spans.

The decrement of consonant and word spans is likely to be due to impairment of the phonological loop. This is supported by the relative sparing of phonological processing: the sole deficit concerned rhyme judgement and although significant, was very moderate. More importantly, the spared similarity effect with a reduced word length effect indicates preservation of the phonological store and impairment of the rehearsal process. These results converge to indicate that frontal lesions induce a deficit of the rehearsal process of the phonological loop. This supports the case studies that show deficits of rehearsal process in patients with lesions of Broca’s area (Shallice and Vallar, 1990) and subcortical and premotor regions (Vallar et al., 1997). This is consistent with functional activation studies showing that activation of Broca’s area is related to the rehearsal component and that the left inferior parietal region is related to the phonological store (Paulesu et al., 1993; Ahw et al., 1996).

Although some tests assessing the central executive were impaired in patient groups, these impairments cannot be attributed to a disorder of the central executive per se. The working memory span was impaired in both patient groups; however, the impairment completely disappeared after adjustment for short-term memory capacity. This indicates that impairment of working memory span is simply due to decreased short-term memory capacity and therefore cannot be attributed to impairment of the combination of memory task and a concurrent processing task. Dual task paradigm was spared at the group level. This finding is consistent with most previous group studies of focal lesions (Vilkki et al., 1996, 2002; Baddeley et al., 1997; Andres and Van der Linden, 2002). It is likely to be due to the low frequency of deficits on these tasks (Godefroy et al., 2010). The running memory test was impaired in the frontal group; however, this impairment cannot be attributed to a deficit of updating processes, as it would have induced a disproportionate decrement of performance with increasing number of updates. The reverse pattern was observed, indicating that frontal patients do not benefit from the easiest condition requiring no updating. This inability to benefit from easiest conditions was also observed for alphabetical series, in which a disproportionate decrement with increasing update number was observed in patients. The deficit of the frontal group is likely to be due to their inability to take advantage of an easy condition as observed in a simple reaction time test (Godefroy et al., 2002). The running memory impairment therefore cannot be attributed to a deficit of updating processes. Overall, these results do not clearly demonstrate that frontal patients have a deficit of combination of online processing and information storage that depends on the central executive. Accordingly, the clinical–anatomical correlation study shows that central executive impairment depends on lesions involving the frontal and posterior regions.

Finally, this study showed that about one-half of patients with cognitive dysexecutive disorders on conventional tests have no central executive impairment. This result strongly argues against the central executive theory of dysexecutive disorders, which would have predicted that all dysexecutive patients would present central executive impairment. In addition, a double dissociation was observed as a few patients with impaired central executive had no dysexecutive disorders. This double dissociation rules out a
potential difference in sensitivity between working memory tasks and conventional executive tasks, as this would result in a simple dissociation (i.e. all patients with impairment on low sensitivity tasks are impaired on highly sensitive tasks). This double dissociation therefore supports the relative independence of central executive and cognitive dysexecutive disorders. Although working memory is certainly involved in executive tests, there is no evidence to suggest that the critical point is the ability to manipulate temporarily stored information, even in patients with well-characterized dysexecutive syndrome. The main conclusion of this study is that central executive impairment contributes to certain dysexecutive disorders but that it cannot be regarded to be the sole origin of dysexecutive disorders.

**Supplementary material**

Supplementary material is available at Brain online.

**References**


