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Executive function and fluid intelligence after frontal lobe lesions

María Roca,[1,2] Alice Parr,[3] Russell Thompson,[3] Alexandra Woolgar,[3] Teresa Torralva,[1,2] Nagui Antoun,[4] Facundo Manes[1,2] and John Duncan[3]

1 Institute of Cognitive Neurology (INECO), Buenos Aires, Argentina
2 Institute of Neurosciences, Favaloro University, Buenos Aires, Argentina
3 MRC Cognition and Brain Sciences Unit, 15 Chaucer Road, Cambridge CB2 7EF, UK
4 Department of Radiology, Addenbrooke's Hospital, Hills Road, Cambridge, UK

Correspondence to: John Duncan,
MRC Cognition and Brain Sciences Unit,
15 Chaucer Road,
Cambridge CB2 7EF,
UK
E-mail: john.duncan@mrc-cbu.cam.ac.uk

Many tests of specific 'executive functions' show deficits after frontal lobe lesions. These deficits appear on a background of reduced fluid intelligence, best measured with tests of novel problem solving. For a range of specific executive tests, we ask how far frontal deficits can be explained by a general fluid intelligence loss. For some widely used tests, e.g. Wisconsin Card Sorting, we find that fluid intelligence entirely explains frontal deficits. When patients and controls are matched on fluid intelligence, no further frontal deficit remains. For these tasks too, deficits are unrelated to lesion location within the frontal lobe. A second group of tasks, including tests of both cognitive (e.g. Hotel, Proverbs) and social (Faux Pas) function, shows a different pattern. Deficits are not fully explained by fluid intelligence and the data suggest association with lesions in the right anterior frontal cortex. Understanding of frontal lobe deficits may be clarified by separating reduced fluid intelligence, important in most or all tasks, from other more specific impairments and their associated regions of damage.

Keywords: executive function; fluid intelligence; frontal lobe
Abbreviations: IQ = intelligence quotient

Introduction

The fact that the prefrontal cortex plays a key role in higher cognitive skills and in the achievement of effective behaviour is well supported by evidence from lesion and neuroimaging studies. Although many theories have been proposed, the mechanisms by which the prefrontal cortex attains its goals remain unknown. Commonly, the prefrontal cortex is supposed to support 'executive functions', broadly conceived as processes that organize and control cognitive function. Proposed executive processes include functions such as planning, monitoring, energizing, switching and inhibition (Stuss, 2007). Over the past 100 years many clinical and experimental tests have been used to measure these proposed executive functions. Commonly, different functions have been presumed to be associated with different subregions within the prefrontal cortex (Stuss *et al*., 2002). However, evidence regarding the separability of executive functions is often inconsistent, and strong double dissociations are the exception rather than the rule.

As an example, the Wisconsin Card Sorting Test (Grant and Berg, 1948) is one of the most widely used executive tests, thought to assess problem solving, strategic planning, use of environmental feedback to shift set, and inhibition of impulsive responding. Even though poor performance on this test has

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been associated specifically with dorsolateral lesions (Milner, 1963; Rezai *et al*., 1993), evidence of a clear specificity to this region is scant and Wisconsin Card Sorting Test deficits have been found after superior medial and orbitofrontal lesions (Stuss *et al*., 1983, 2000), as well as after non-frontal damage (Anderson *et al*., 1991; Horner *et al*., 1996). Moreover, functional neuroimaging studies have shown widespread activation of frontal and non-frontal brain regions during the Wisconsin Card Sorting Test (Barceló and Santome-Calleja, 2000). Within the frontal lobes, lateral, anterior cingulate and ventral activations have been described (Buchsbaum *et al*., 2005).

A second example is a range of tasks used to measure emotional or evaluative aspects of decision-making, often linked to ventromedial prefrontal cortex. The Iowa Gambling Task, for example, requires decision-making based on a history of positive and negative rewards, and has shown some evidence for selective deficit following ventromedial lesions (Bechara *et al*., 2000). Impairments can also follow dorsolateral lesions, however, suggesting that both ventral and dorsal aspects of the prefrontal cortex must interact in performance of this task (Manes *et al*., 2002). Similar questions concern the ability to make inferences about others' thoughts and feelings, commonly referred to as theory of mind. Based on neuroimaging and lesion findings, several authors have proposed a critical role of the anteromedial frontal lobe in this 'mentalizing' capacity (Gallagher and Frith, 2003; Frith and Frith 2006), but again, some studies show contradictory results (Bird *et al*., 2004).

In parallel to these proposals of specific executive functions, perhaps associated with specific regions of frontal cortex, is the importance of the frontal lobe in 'general intelligence' or Spearman's *g* (Spearman, 1904, 1927). The concept of *g* was introduced to explain universal positive correlations between different cognitive tests; to some extent, Spearman proposed, some common *g* factor contributes to success in all cognitive activities. The best tests of *g*—i.e. the tests most predictive of a general ability to do well—are so-called fluid intelligence tests, calling for novel problem solving with simple visual or other materials (Cattell, 1971; Carroll, 1993). Widely used examples are Raven's Matrices (Raven, 1938; Raven *et al*., 1988) and Cattell's Culture Fair (Institute for Personality and Ability Testing, 1973). Fluid intelligence reflects current ability for abstract thought and reasoning, and is impaired after frontal lesions (Duncan *et al*., 1995). It contrasts with tests of prior knowledge and educational achievement (e.g. vocabulary)—so-called tests of 'crystallized intelligence' (Cattell, 1971) which are less dependent on frontal lobe function.

The importance of the frontal lobe in *g*—in particular in fluid intelligence—raises the question of relations between *g* and executive deficit. As fluid intelligence is positively correlated with all tasks—including any putative test of executive function—we may ask how well executive deficits are explained by a fluid intelligence loss. Though many previous studies describe deficits in specific executive tests following frontal damage, there has been no systematic study of relations to fluid intelligence for different tests and lesion locations.

Two models may be considered. The first, following Spearman (1904), proposes that *g* is a measure of some specific processing activity, important in controlling many different forms of behaviour. In functional imaging studies, fluid intelligence tests produce extensive activity on the lateral frontal surface, in particular around the inferior frontal sulcus and anterior insula/frontal operculum; in the dorsal anterior cingulate/pre-supplementary motor area; and along the intraparietal sulcus (Prabhakaran *et al*., 1997; Esposito *et al*., 1999; Duncan *et al*., 2000; Bishop *et al*., 2008). Consistent with a role in *g*, the same pattern of activity is associated with increased demand in many different cognitive domains, including perception, episodic and working memory, response selection and inhibition, etc. (Duncan and Owen, 2000; Duncan, 2006). In corresponding regions of the monkey brain, especially lateral prefrontal cortex, electrophysiology shows a picture of highly plastic neural function, the same cells adapting to code different kinds of task-relevant information in different behavioural contexts (Duncan, 2001; Miller and Cohen, 2001). In any task, the result is a dense, broadly distributed representation of relevant stimuli, responses, rules, rewards, etc. Elsewhere we have proposed that this flexible internal model of task-relevant content is important in controlling diverse forms of behaviour (Duncan, 2001). It may be especially taxed when relevant information is complex and novel, as in typical problem solving tasks, and might thus provide much of the processing basis for *g* (Duncan, 2005; Duncan *et al*., 2008). A closely related idea is the 'global workspace' (Dehaene *et al*., 1998, 2003), a limited-capacity representation of task-relevant content for diverse kinds of behaviour.

Predictions for this model are illustrated in Fig. 1A and B. The figure shows possible relationships between fluid intelligence scores and deficits in specific executive tests (*X* and *Y*). In the first case (Fig. 1A), *X* deficits in the patient group are entirely mediated through a change in *g*. In controls, there is the expected positive correlation between *X* and fluid intelligence, reflecting the contribution of *g* to success in *X*. In patients, the loss in *g* is reflected by reduced fluid intelligence scores, and this loss in fluid intelligence entirely explains the corresponding loss in *X*; for controls and patients with the same fluid intelligence, expected scores on *X* are equal (equivalent to no group difference between patients and controls once fluid intelligence is covaried). In Fig. 1B, in contrast, deficits in *X* reflect a specific frontal component of the task that is unrelated to *g*. Though *g* contributes to *X*—shown by the positive correlation—it does not explain the deficit in the patient group. *X* is impaired even when patients and controls are matched in *g*.

A different model is illustrated in Fig. 1C and D. The classical alternative to Spearman's concept of *g* is the proposal that tests of general intelligence reflect the average or combined activity of many separate cognitive processes (Thomson, 1951). One plausible possibility is that complex tasks such as Raven's Matrices involve a variety of different executive functions, perhaps mediated by separate regions of frontal cortex. If this is so, then in different frontal groups we should find a pattern of dissociations between different executive tests. Figure 1C and D illustrate the simplest possible case, in which performance on a fluid intelligence test is some increasing function, $f(X, Y)$, of just two executive functions, each well measured by its own separate test. In each panel, results are compared for regions of frontal damage selectively impairing *X* and *Y*. If *X* is impaired (Fig. 1, patient group 1),

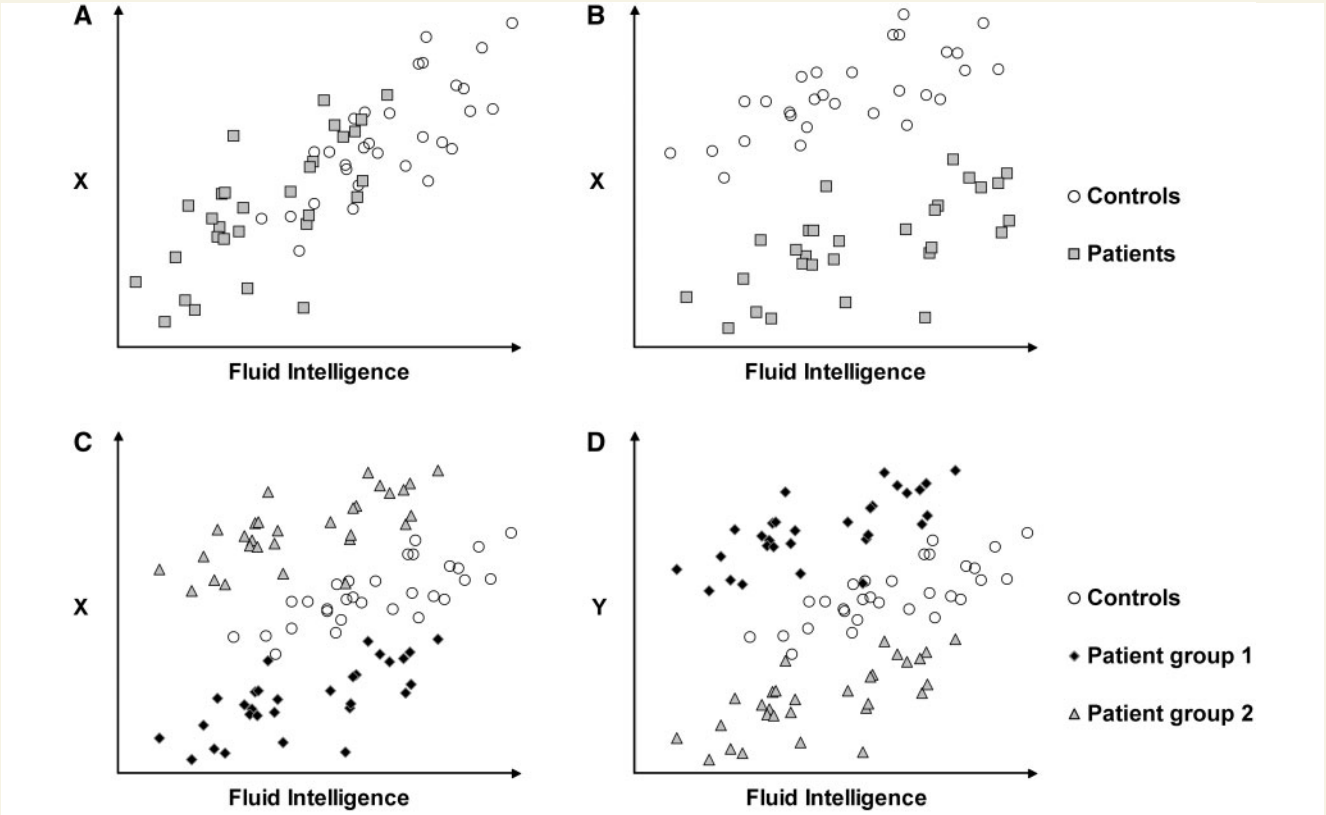

Figure 1 Potential relationships between fluid intelligence and deficits in specific executive tests *X* and *Y*. Higher values on each scale indicate better performance. (**A**) Deficit fully explained by *g*. (**B**) Deficit in specific function unrelated to *g*. (**C** and **D**) Predictions for model with fluid intelligence a joint function of separate executive processes *X* and *Y*.

then on average, a given value of *f*(*X*, *Y*) will reflect relatively poor scores on *X*, and relatively good scores on *Y*. In this group, matching with controls for fluid intelligence must result in poorer patient performance for test *X*, but better performance for test *Y*; the latter reflecting the high premorbid value of *Y* that would be required to achieve the obtained f(*X*, *Y*) after damage to *X*. When *Y* is impaired (Fig. 1, patient group 2), the opposite relations hold. The arguments are easily extended to a model with any larger number of separable executive functions. For such models, the expectation is a pattern of freely dissociating executive deficits, providing that deficits (i) are associated with separate regions of damage; and (ii) can be separately measured with different cognitive tests.

In the present study we examined the role of fluid intelligence in a broad variety of executive deficits. In Experiment 1 we used two classical tasks, the Wisconsin Card Sorting Test and Verbal Fluency (Benton and Hamsher, 1976). In Experiment 2 we employed a more comprehensive set of executive and social functioning tasks. First, we used the Ineco Frontal Screening battery (Torralva *et al*., 2009*b*), a brief clinical tool that includes assessment of motor sequencing and inhibition, working memory and several other tasks based on the clinical literature. Second, we used two further cognitive tests, the Iowa Gambling Task, putatively associated with ventromedial frontal lesions (Bechara *et al*., 2000), and the Hotel Task (Manly *et al*., 2002, Torralva *et al*., 2009*a*), developed from an earlier test that detected difficulties in strategy production among frontal patients with otherwise good executive test scores (Shallice and Burgess, 1991). Third, we included two tests more related to social function, Faux Pas (Stone *et al*., 1998) and Mind in the Eyes (Baron-Cohen *et al*., 1997). In both experiments, fluid intelligence was measured with the Culture Fair (Institute for Personality and Ability Testing, 1973). In addition to comparing frontal patients as a group with controls, we searched for associations between specific task deficits and lesion locations. One simple and influential subdivision distinguishes between right-lateral, left-lateral, inferior medial and superior medial areas (Stuss *et al*., 2000, 2002, 2005; Stuss, 2006; Shallice *et al*., 2007). In a first set of analyses, we compared these lesion subgroups for each executive test. In a second approach, we examined lesion overlaps for executive deficits over and above those predicted by fluid intelligence.

Methods

Experiment 1

Subjects

Patients with chronic focal frontal lesions were recruited from the Cambridge Cognitive Neuroscience Research Panel at the MRC Cognition and Brain Sciences Unit ($n = 36$) in Cambridge, UK and from the Institute of Cognitive Neurology Research Data Base in

Buenos Aires, Argentina ($n = 8$). Lesion aetiology was mostly tumour resection or cerebrovascular (Table 1) and all patients gave informed consent prior to inclusion. The mean age of patients was 51.1 years (SD = 12.4, range = 27–69). Premorbid intelligence was estimated using the revised National Adult Reading Test (Nelson and Willison, 1991) for British subjects and the WAT-BA (Del Ser *et al*., 1997; Burin *et al*., 2000) for Argentineans. Mean estimated premorbid Intelligence Quotient (IQ) was 110.3 (SD = 12.6).

Healthy control subjects were recruited from the volunteer panel of the MRC Cognition and Brain Sciences Unit ($n = 33$) and were matched with patients for age and National Adult Reading Test-estimated IQ. The mean age of controls was 48.4 years (SD = 12.9,

Table 1 Patient characteristics

Patient		Age	Sex	Aetiology	Side	Estimated premorbid IQ	Years post onset	Included in expt 2
Inferior medial								
1	MB	45	F	Tumour	Left	108	9	–
2	MB	45	M	Haemorrhage	Left	108	4	–
3	CM	54	F	Tumour	Left	118	2	–
4	MS	61	F	Tumour	Right	111	2	Y
5	DP	41	M	Tumour	Bilateral	115	1	Y
6	SV	41	F	Tumour	Bilateral	128	2	Y
7	MEA	59	F	Tumour	Bilateral	108	3 months	–
Superior medial								
1	JT	56	M	Tumour	Left	82	4	–
2	GD	44	F	Tumour	Left	102	12	–
3	DT	69	M	Infarct	Left	111	4	–
4	PP	58	F	Tumour	Left	103	2	Y
5	CE	64	M	Aneurysm	Right	120	2	–
6	A (T) C	66	M	Infarct	Left	97	3	–
7	JM	65	M	Tumour	Right	122	1	–
8	LB	29	F	Tumour	Right	88	8 months	Y
Left lateral								
1	SD	37	F	Aneurysm and Haematoma	Left	110	3	–
2	AD	61	F	Infarct	Left	120	3	Y
3	PM	47	M	Tumour	Left	121	3	Y
4	TG	33	M	Abscess	Left	121	1	–
5	YS	64	F	Infarct	Left	98	2	Y
6	WB	29	M	Tumour	Left	98	2	Y
7	RS	59	F	Infarcts	Bilateral	128	6 months	Y
Right lateral								
1	PP	51	M	Tumour	Right	115	2	–
2	KH	41	M	Tumour	Right	124	4	–
3	SS	46	F	Tumour	Right	97	3	Y
4	MS	68	M	Infarct	Right	121	1	Y
5	CG	50	F	Tumour	Right	111	30	–
6	GB	42	M	Tumour	Right	100	8	Y
7	ET	47	F	Infarct	Right	126	2	Y
8	AS	62	M	Tumour	Right	94	1	–
9	RB	53	M	Tumour	Right	106	2	Y
10	PB	53	F	Tumour	Right	87	8 months	–
11	RH	68	F	Tumour	Right	118	20	Y
12	PG	28	F	Tumour	Right	110	3	–
13	MD	68	M	Infarct	Right	127	2	Y
14	JB	60	M	Tumour	Right	127	8 months	Y
Multiple								
1	DR	55	M	Tumour	Right	101	2	–
2	FG	39	F	Tumour	Right	106	2	Y
3	DC	27	M	Abscess	Bilateral	100	2	–
4	MD	65	F	Tumour	Bilateral	111	14	–
5	BR	67	F	Tumour	Left	116	4	–
6	IB	38	F	Tumour	Bilateral	120	1	Y
7	NM	46	M	Tumour	Right	88	2	Y
8	MR	46	M	Tumour	Bilateral	132	2	–

Where ages and times post onset differed for Experiments 1 and 2, values given are for Experiment 1.

range = 19–70) and mean National Adult Reading Test-estimated IQ was 109.6 (SD = 12.3).

Neuroradiological assessment

MRI scans were performed for all patients and interpreted by a neurologist with experience in structural neuroimaging, who was blind to the experimental results (FM). Lesions were traced using MRIcro (Rorden and Brett, 2000; http://www.sph.sc.edu/comd/rorden/mricro.html) and normalized to a standard template using statistical parametric mapping-5 software (Wellcome Department of Imaging Neuroscience, London, England; www.fil.ion.ucl.ac.uk) with cost-function masking to mask the lesion from the calculation of the normalization parameters (Brett *et al*., 2001). Using the Brodmann area maps provided with MRIcroN (http://www.sph.sc.edu/comd/rorden/mricron), templates were created for four frontal regions: inferior medial (Brodmann area 24, 25, 32, plus medial parts of Brodmann area 10, 11, all extending up to level of genu of corpus callosum); superior medial (Brodmann area 24, 25, 32 and medial 10, 11, all above level of genu, plus medial parts of Brodmann area 6, 8, 9); left lateral (Brodmann area 43–47, plus lateral parts of Brodmann area 6, 8, 9, 10, 11); and right lateral (Brodmann area as for left lateral). To separate lateral from medial we used a fixed *X* coordinate of ±15 in Montreal Neurological Institute (MNI) atlas space. For each patient, we calculated the percentage of each region included in the lesion. For subgroup analysis, patients were assigned to one of the four subgroups based on which region had the greatest percentage damage. Using this criterion, seven patients were classified as inferior medial, eight as superior medial, seven as left lateral and 14 as right lateral (Table 1). Patients with lesions involving more than 20% of each of two or more regions were excluded from subgroup comparisons ($n = 8$; Table 1, 'multiple'). Lesion overlaps for left lateral, right lateral, inferior medial and superior medial subgroups are shown in Fig. 2.

Neuropsychological assessment

Culture Fair (Institute for Personality and Ability Testing, 1973)

To assess fluid intelligence we used the Culture Fair, Scale 2 Form A, a standard test of novel problem solving with a loading of 0.81 on a general intelligence factor (Institute for Personality and Ability Testing, 1973). The test has four timed sets of problems (series completions, odd-one-out, matrices, topological relations), all involving geometrical figures. Scores were converted to IQs using the standardized table of norms (Institute for Personality and Ability Testing, 1973).

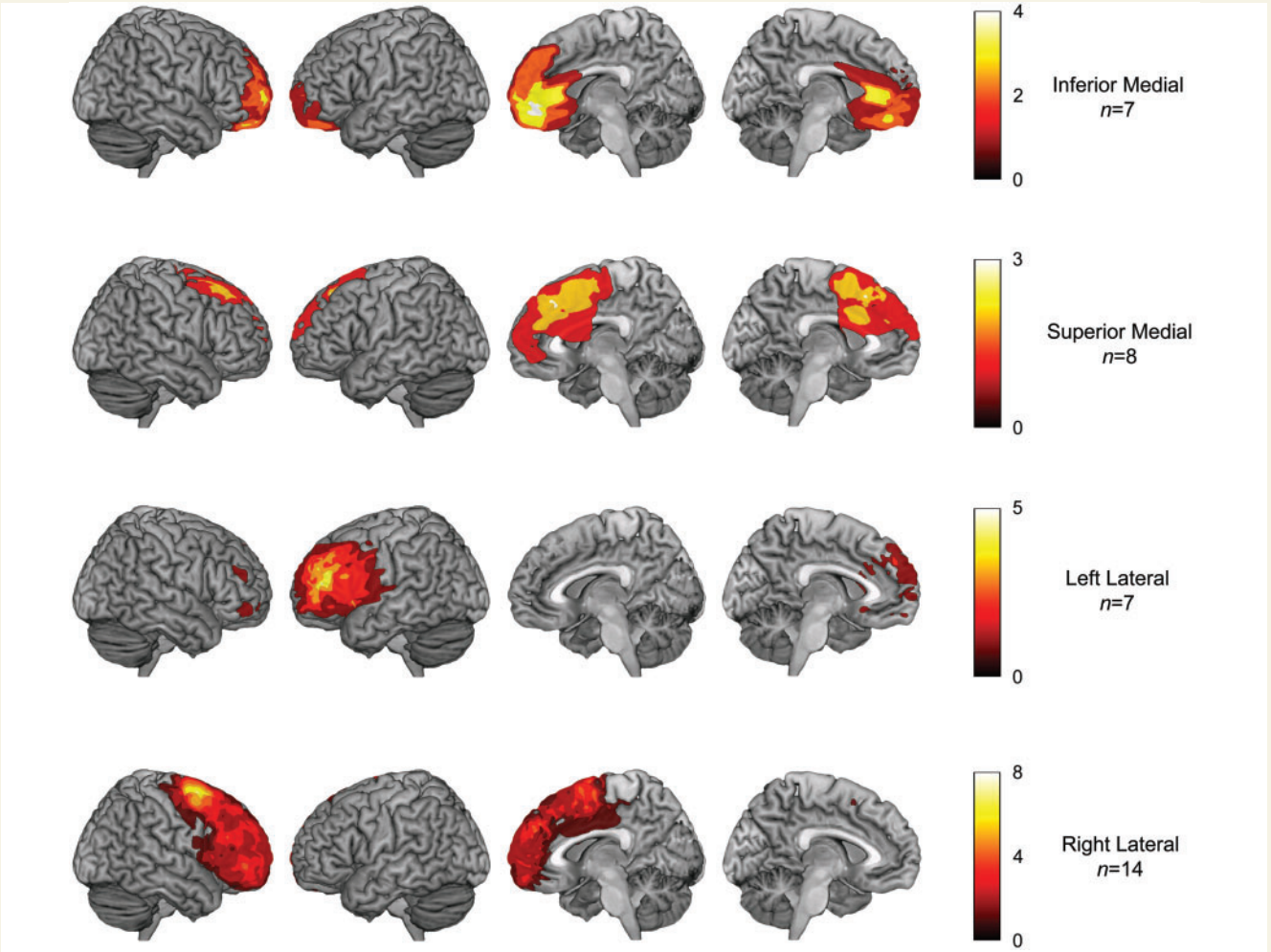

Figure 2 Lesion overlaps for patients with predominantly inferior medial, superior medial, left lateral and right lateral lesions. Colour scales show numbers of affected patients for each brain voxel.

Wisconsin Card Sorting Test (Nelson, 1976)

For the Wisconsin Card Sorting Test we used Nelson's modified version of the standard procedure. Cards varying on three basic features—colour, shape and number of items—must be sorted according to each feature in turn. The participant's first sorting choice becomes the correct feature, and once a criterion of six consecutive correct sorts is achieved, the subject is told that the rules have changed, and cards must be sorted according to a new feature. After all three features have been used as sorting criteria, subjects must cycle through them again in the same order as they did before. Each time the feature is changed, the next must be discovered by trial and error. Data were available for 41/44 patients. Score was total number of errors, either before successful completion of all six task stages, or after a maximum of 48 cards.

Verbal Fluency (Benton and Hamsher, 1976)

In verbal fluency tasks, the subject generates as many items as possible from a given category. We used the standard phonemic version, asking subjects to generate words beginning with the letters F, A and S in successive blocks of 1 min/letter. Data were available for 43/44 patients. Score was the total number of correct words generated.

Experiment 2

Subjects

A subgroup of 21 patients was recruited for Experiment 2 (15 patients from the Cambridge Cognitive Neuroscience Research Panel and 6 from the Institute of Cognitive Neurology Research Data Base; see Table 1). Lesion aetiology was again mostly cerebrovascular disease or tumour resection, and all patients gave informed consent to participate in this second part of the study. The mean age of patients was 55.7 years (SD = 14.2, range = 29–77) and mean estimated premorbid IQ was 111.8 (SD = 13.4). Experiment 2 included three inferior medial patients, two superior medial, five left lateral, eight right lateral and three multiple (Table 1).

A new set of healthy control subjects was recruited from the volunteer panel of the MRC Cognition and Brain Sciences Unit ($n = 7$), and through advertisement in Buenos Aires ($n = 18$). The mean age of controls was 55.0 years (SD = 14.4, range = 29–79) and mean National Adult Reading Test- or WAT-estimated IQ was 114.0 (SD = 12.0).

Neuropsychological assessment

Argentinean patients ($n = 6$) were tested at the same time for Experiments 1 and 2, while the time between experiments ranged from 2 to 10 years in British patients ($n = 15$). For British patients the Culture Fair was re-administered at the second test. Additional tests comprised:

The Ineco Frontal Screening (Torralva *et al.*, 2009*b*)

The Ineco Frontal Screening is a brief, sensitive, and specific tool for the detection of early executive dysfunction. It includes eight subtests:

(I) *Motor Programming (Luria, 1966; Dubois et al., 2000)*. In this subtest we asked subjects to perform the Luria series 'fist, edge, palm' by initially copying the administrator three times, and then by repeating the series six times alone. If subjects achieved six consecutive series by themselves, the score was 3, if they achieved at least three consecutive series on their own, the score was 2; if they failed at achieving at least three consecutive series alone, but achieved three when copying the examiner, the score was 1; otherwise the score was 0;

(II) *Interference (Dubois et al., 2000)*. Subjects were asked to hit the table once when the administrator hit it twice, or to hit the table twice when the administrator hit it only once. To ensure the subject had clearly understood the task, a practice trial was performed in which the administrator first hit the table once, three times in succession, and then twice, three more times. After the practice trial, the examiner completed the following series: 1–1–2–1–2–2–2–1–1–2. If subjects made no errors, the score was 3; if they made one or two errors, the score was 2; for more than two errors, the score was 1, unless the subject copied the examiner at least four consecutive times, in which case the score was 0;

(III) *Go–No go (Dubois et al., 2000)*. This task was administered immediately after Test II. Subjects were told that now, when the test administrator hit the table once, they should also hit it once, but when the examiner hit twice, they should do nothing. To ensure the subject had clearly understood the task, a practice trial was performed in which the administrator hit the table once, three times in succession, and then twice, three more times. After the practice trial the examiner completed the following series: 1–1–2–1–2–2–2–1–1–2. If subjects made no errors, the score was 3; for one or two errors the score was 2; for more than two errors the score was 1, unless the subject copied the examiner at least four consecutive times, in which case the score was 0;

(IV) *Backwards Digit Span (Hodges, 1994)*. For this task, subjects were asked to repeat a progressively lengthening string of digits in the reverse order. Two trials were given at each successive list length, beginning at 2 and continuing to a maximum of 7. If subjects passed either trial at a given list length, then the next length was administered. The score was the number of lengths at which the subject passed either trial, maximum 6;

(V) *Months (Hodges, 1994)*. The patient was asked to list the months of the year backwards, starting with December. If subjects made no errors, the score was 2; for one error, the score was 1; otherwise the score was 0. Data were available for 15/21 patients;

(VI) *Spatial Working Memory (Wechsler, 1987)*. In this task, the examiner presented the subject with four cubes and pointed at them in a given sequence. The subject was asked to repeat the sequence in reverse order. There were four trials, with sequences of two, three, four and five cubes, respectively. Score was number of correctly completed sequences. Data were available for 15/21 patients;

(VII) *Proverbs (Hodges, 1994)*. In this task three proverbs were read to the subjects and they were asked to explain their meaning. For each proverb a score of 1 was given when the subject gave an adequate explanation, and a score of 0.5 for a correct example. Otherwise the score was 0. Data were available for 15/21 patients;

(VIII) *Hayling (Burgess and Shallice, 1997)*. This task consisted of a short version of the original test. Materials were six sentences, each missing the last word and constructed to strongly constrain what it should be. In the first part (three sentences), subjects were read each sentence and asked to complete it correctly, as quickly as possible. In the second part (remaining three sentences), subjects were asked for a completion unrelated to the sentence in meaning. Only the second part was scored. For each sentence, a score of 2 was given for a word unrelated to the sentence, a score of 1 for a word semantically related to the expected completion, and a score of 0 for the expected word itself. Data were available for 15/21 patients.

Hotel Task (Manly et al., 2002; Torralva et al., 2009a)

The task comprised five primary activities related to running a hotel (compiling bills, sorting coins for a charity collection, looking up telephone numbers, sorting conference labels, proofreading). The materials needed to perform these activities were arranged on a desk, along with a clock that could be consulted by removing and then replacing a cover. Subjects were told to try at least some of all five activities during a 15 min period, so that, at the end of this period, they would be able to give an estimate of how long each task would take to complete. It was explained that time was not available to actually complete the tasks; the goal instead was to ensure that every task was sampled. Subjects were also asked to remember to open and close the hotel garage doors at specified times (open at 6 min, close at 12 min), using an electronic button. Of the several scores possible for this task, we used time allocation: for each primary task we assumed an optimal allocation of 3 min, and measured the summed total deviation (in seconds) from this optimum. Total deviation was given a negative sign so that high scores meant better performance. Data were available for 20/21 patients.

Iowa Gambling Task (Bechara et al., 2000)

In the Iowa Gambling Task, subjects are required to pick cards from four decks and receive rewards and punishments (winning and losing abstract money) depending on the deck chosen. Two 'risky' decks yield greater immediate wins but very significant occasional losses. The other two 'conservative' decks yield smaller wins but negligible losses that result in net profit over time. Subjects make a series of selections from these four available options, from a starting point of complete uncertainty. Reward and punishment information acquired on a trial by trial basis must be used to guide behaviour towards a financially successful strategy. Normal subjects increasingly choose conservative decks over the 100 trials of the task. Our score was the total number of conservative minus risky choices. Data were available for 18/21 patients.

Faux Pas (Stone et al., 1998)

In each trial of this test, the subject was read a short, one paragraph story. To reduce working memory load, a written version of the story was also placed in front of the subject. In 10 stories there was a *faux pas*, involving one person unintentionally saying something hurtful or insulting to another. In the remaining 10 stories there were no *faux pas*. After each story, the subject was asked whether something inappropriate was said and if so, why it was inappropriate. If the answer was incorrect, an additional memory question was asked to check that basic facts of the story were retained; if they were not, the story was re-examined and all questions repeated. The score was 1 point for each *faux pas* correctly identified, or non-*faux pas* correctly rejected. Data were available for 20/21 patients.

Mind in the Eyes (Baron-Cohen et al., 1997)

This task consisted of 17 photographs of the eye region of different human faces. Participants were required to make a two alternative forced choice that best described what the individual was thinking or feeling (e.g. worried-calm). The score was total number correct. Data were available for 20/21 patients.

Results

Experiment 1

Results are shown in Table 2. For all three tasks, one-tailed *t*-tests were used to compare patients and controls. As expected, the frontal group was significantly impaired on all three tasks: Culture Fair,

Table 2 Patient and control scores, Culture Fair correlations and significance of group differences for each task

	Patients Mean (SD)	Controls Mean (SD)	Patients versus controls *P*	Correlations with Culture Fair IQ		Patients versus controls after adjustment for Culture Fair IQ	Differences between the four frontal subgroups
				r	*P*	*P*	*P*
Experiment 1							
Culture Fair IQ	91.32 (15.03)	104.30 (17.63)	**<0.01**	–	–	–	0.17
Wisconsin Card Sorting Test (total errors)	12.85 (9.88)	7.97 (8.27)	**0.02**	−0.61	**<0.01**	0.36	0.92
Verbal Fluency[a]	34.09 (11.16)	42.09 (11.20)	**<0.01**	0.56	**<0.01**	0.07	0.53
Experiment 2							
Motor Programming (max = 3)	2.81 (0.51)	2.92 (0.28)	0.18	0.15	0.16	0.24	0.82
Interference (max = 3)	2.90 (0.30)	3.00 (0.00)	0.06	0.21	0.08	0.10	0.78
Go–No go (max = 3)	2.52 (0.60)	2.88 (0.33)	**<0.01**	0.30	**0.02**	**0.02**	0.27
Digit Span (max = 6)	4.71 (1.10)	4.76 (1.05)	0.45	0.41	**<0.01**	0.31	0.44
Months (max = 2)	1.93 (0.26)	1.92 (0.28)	0.56	0.31	**0.02**	0.66	0.89
Spatial Working Memory (max = 4)	2.80 (0.68)	3.20 (0.76)	<0.06	0.22	0.09	0.07	0.38
Proverbs (max = 3)	1.80 (1.08)	2.74 (0.44)	**<0.01**	0.32	**0.02**	**<0.01**	0.86
Hayling (max = 6)	3.93 (1.58)	4.96 (0.89)	**<0.01**	0.32	**0.02**	**0.01**	0.19
Hotel Task[b]	−584.90 (292.47)	−319.32 (169.52)	**<0.01**	0.25	**<0.05**	**<0.01**	0.87
Iowa Gambling Task[c]	−1.22 (34.54)	13.80 (22.89)	**<0.05**	0.51	**<0.01**	0.29	0.32
Faux Pas (max = 20)	17.50 (2.28)	19.12 (1.36)	**<0.01**	0.31	**0.02**	**<0.01**	0.73
Mind in the Eyes (max = 17)	13.90 (1.55)	14.20 (1.22)	0.24	0.32	**0.02**	0.40	0.44

Significant P- values shown in bold.
a Total number of words generated.
b Deviation from optimum time per task.
c Conservative minus risky choices.

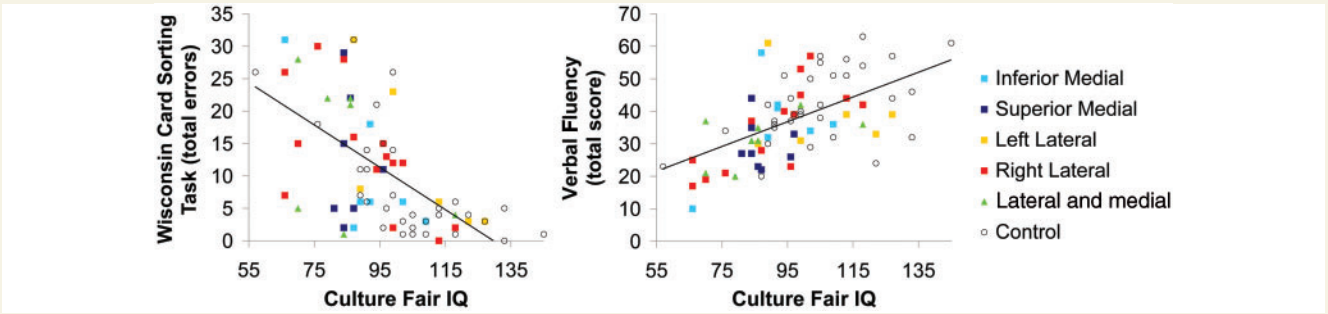

Figure 3 Experiment 1. Regressions of Wisconsin Card Sorting Test and verbal fluency on Culture Fair IQ. Points show data for single patients (coloured) and controls (empty); regression line is calculated on combined patient and control data.

$t(75) = 3.48$, $P < 0.001$; Wisconsin Card Sorting Test, $t(72) = 2.27$, $P < 0.02$; and Verbal Fluency, $t(74) = 3.09$, $P < 0.005$.

Also as expected, both Wisconsin Card Sorting Test and Verbal Fluency were correlated with Culture Fair. Combining data from patients and controls, Pearson's correlations and (one-tailed) significance levels were $r = -0.61$, $P < 0.001$ for Wisconsin Card Sorting Test, and $r = 0.56$, $P < 0.001$ for Verbal Fluency (Table 2). Scatterplots are shown in Fig. 3, showing that higher Culture Fair IQ was strongly associated with better performance in both executive tasks.

The scatterplots suggest that, for these two executive tasks, frontal deficits were entirely explained by fluid intelligence (*cf*. Fig. 1A). The effect of the frontal lesion was simply to shift the Culture Fair distribution downward, without changing its relation to executive task performance. To assess this conclusion, *t*-tests comparing patients and controls were repeated following adjustment for Culture Fair IQ as a covariate (equivalent to analysis of covariance with two-level factor patients versus controls). For both tasks, the difference between patients and controls was no longer significant; for the Wisconsin Card Sorting Test, $t(71) = 0.35$, $P = 0.36$, and for Verbal Fluency, $t(73) = 1.48$, $P = 0.07$, both tests again one-tailed (Table 2).

Figure 3 also suggests little difference between left lateral, right lateral, inferior medial and superior medial subgroups. In confirmation, ANOVA showed no significant difference between these groups, for Culture Fair IQ, $F(3, 32) = 1.76$, $P = 0.17$, for Wisconsin Card Sorting Test, $F(3, 30) = 0.16$, $P = 0.92$, or for Verbal Fluency, $F(3, 31) = 0.76$, $P = 0.53$ (Table 2, rightmost column; ANOVAs on raw scores unadjusted for Culture Fair).

As frontal lesions are sometimes specifically linked with perseverative errors on the Wisconsin Card Sorting Test (Milner, 1963), analyses were repeated using percentage perseverative errors (Nelson, 1976) instead of the total error score. For this measure, the group difference between patients and controls was not significant, $t(72) = 0.17$, $P = 0.43$, accompanied by a weaker correlation with Culture Fair, $r = -0.31$, $P < 0.005$. Again, ANOVA showed no significant difference between frontal subgroups, $F(3, 30) = 0.28$, $P = 0.84$.

In a further subsidiary analysis, numbers of problems correctly solved were examined for each of the four separate subtests of the Culture Fair. The correlation with Wisconsin Card Sorting Test total errors was negative for all four subtests (median −0.52), and with Verbal Fluency score positive for all four subtests (median 0.43), suggesting behaviour similar to that of total IQ scores from the full test.

Experiment 2

Again, one-tailed *t*-tests were used to compare patients ($n = 21$) and controls ($n = 25$). Results are shown in Table 2. The frontal group was significantly impaired on three subtests of the Ineco Frontal Screening: Go–No go, $t(44) = 2.54$, $P < 0.01$; Proverbs, $t(38) = 3.88$, $P < 0.001$; Hayling, $t(38) = 2.64$, $P < 0.01$. One other (Spatial Working Memory) was marginal, $t(38) = 1.67$, $P < 0.06$. Significant differences were also found for deviation from optimal time allocation on the Hotel Task $t(43) = 3.82$, $P < 0.001$, in the Faux Pas $t(43) = 2.95$, $P < 0.005$ and in the Iowa Gambling Task $t(41) = 1.69$, $P < 0.05$.

For all tasks, correlations with Culture Fair were positive, showing better performance associated with higher IQ (Table 2). The correlation was significant for 9/12 tasks, including the six with significant difference between patients and controls.

For these six tasks, scatterplots relating performance to Culture Fair score are shown in Fig. 4. Contrary to the results from Experiment 1, these scatterplots suggest some difference between patients and controls even when correcting for the difference in IQ (*cf*. Fig. 1B). As before, additional *t*-tests compared patients and controls after adjusting for IQ scores. For the Iowa Gambling Task, adjustment removed the significant patient–control difference, $t(40) = 1.07$, $P = 0.29$. For the remaining five tasks, however, significant differences remained even after such adjustment (Table 2).

Again, scatterplots in Fig. 4 suggest no evident differences between left lateral, right lateral, inferior medial and superior medial subgroups. Though the result is tempered by small subject numbers, in particular for inferior medial and superior medial, ANOVA showed no significant difference between subgroups in any of the 12 tasks of Experiment 2 (Table 2). Given previous suggestions that inferior medial damage may be especially important in social or emotional functions, supplementary tests compared all patients with any inferior medial damage ($n = 8$) to remaining patients ($n = 12$), separately for the Iowa Gambling Task, Mind in the Eyes and Faux Pas. In no case was the difference close to significant; for the Iowa Gambling Task $t(16) = -0.81$, $P = 0.79$ (data unavailable for two patients without

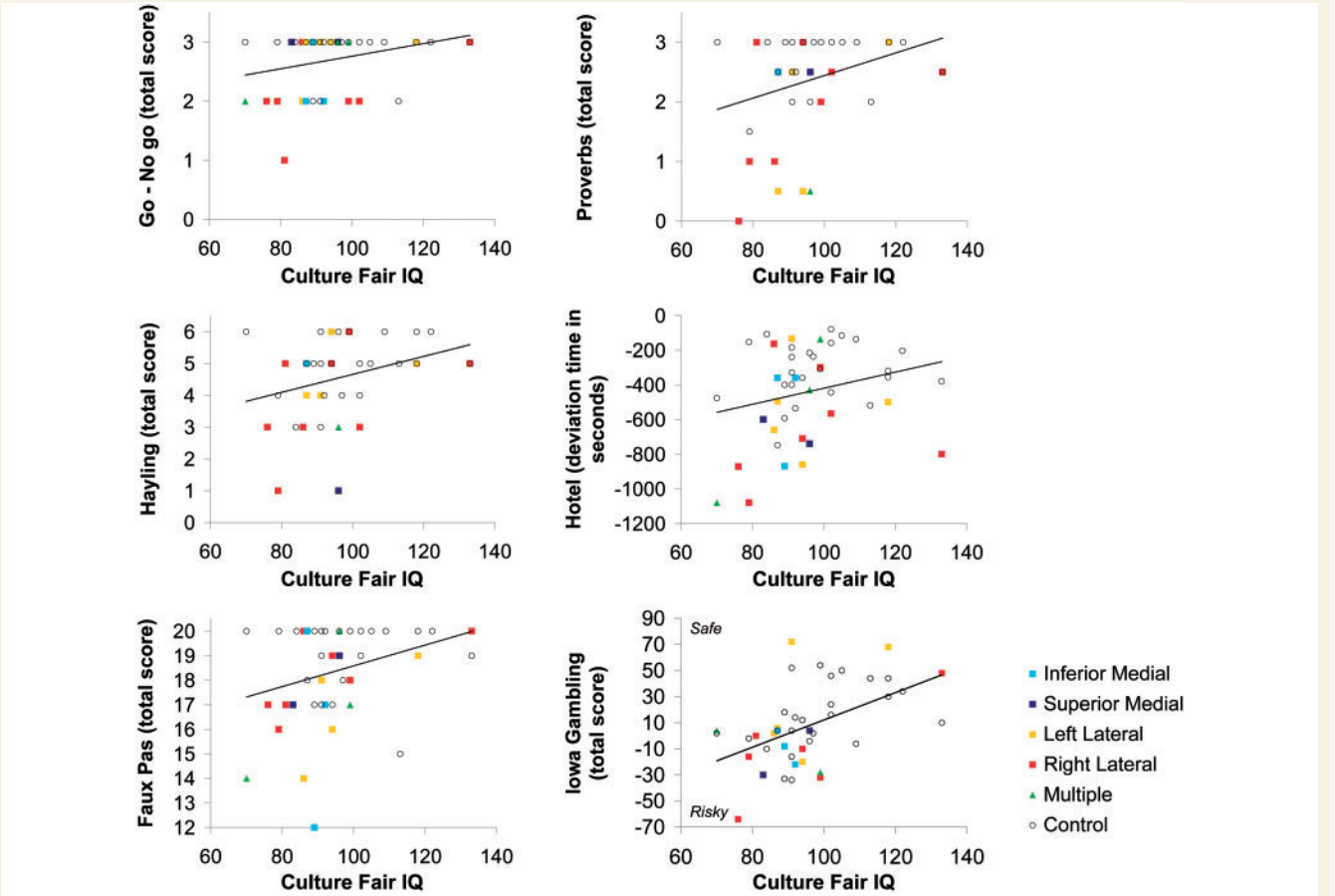

Figure 4 Experiment 2. Regressions on fluid intelligence for all tasks showing significant difference between patients and controls. Symbols and regressions as Fig. 3.

inferior medial damage), Mind in the Eyes $t(18) = -0.52$, $P = 0.70$, and Faux Pas $t(18) = 1.00$, $P = 0.33$.

In a further analysis we employed a lesion overlap method for more targeted examination of deficits beyond those explained by fluid intelligence. First, we examined the relationship between such deficits in the five tasks where they were found (Go–No go, Proverbs, Hayling, Hotel, Faux Pas). For each task, scores for each patient and control were converted to residuals after adjusting for fluid intelligence (Figs 3 and 4, vertical distances from the regression line). Residuals in the five tasks were then correlated, for a total of 10 correlations between all possible task pairs (see Supplementary Table). Combining the data for patients and controls, all 10 correlations were positive (median = 0.30, range = 0.03 to 0.52). For patients alone, 7/10 correlations were positive (median = 0.14, range = −0.36 to 0.45), while for controls alone 9/10 were positive (median = 0.28, range = −0.03 to 0.47). Together, these results suggest that, across the five tasks, deviations from the score predicted by fluid intelligence may be traced at least in part to some common factor. For each patient, accordingly, we obtained a mean residual across the five tasks (or fewer for patients with missing data), and examined lesion overlap for the six patients with the greatest negative value (i.e. greatest deficit beyond the prediction from fluid intelligence). The result (Fig. 5) provides a suggestion of selective association with anterior frontal lesions, especially in the right hemisphere.

To examine these results in the whole patient group, for each patient we measured volume of damage in four segments of the frontal lobe, anterior and posterior to $Y = 35$ in left and right hemispheres. Mean volume of damage, and variability across patients, were similar for left anterior, right anterior and left posterior regions, but somewhat greater for right posterior. For each region, volumes of damage were correlated with mean performance residuals (deficits beyond the prediction from fluid intelligence, averaged across the five critical tasks) as above. A more negative average residual (worse performance) was associated with larger lesion volume in the right anterior region ($r = -0.59$, $P < 0.005$, one-tailed). No significant correlations were found for left anterior($r = 0.24$, $P = 0.15$), right posterior ($r = -0.15$, $P = 0.25$), or left posterior ($r = 0.19$, $P = 0.20$). The significant correlation for right anterior damage remained even after covarying for total lesion volume, $r = -0.52$, $P < 0.01$.

Since scores were categorical, often with a small range, for the subtests of the Ineco Frontal Screening, data were re-examined as appropriate using non-parametric tests (Mann–Whitney U, Spearman rank correlation, Kruskal–Wallis H). Conclusions were essentially identical to those based on parametric tests. Differences between all combined frontal patients and controls

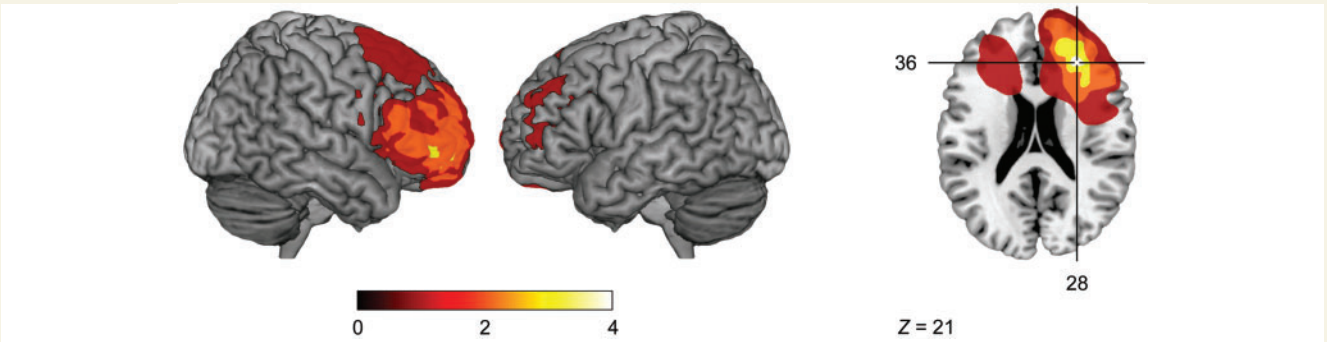

Figure 5 Experiment 2. Lesion overlap for 6 patients with worst average residual (performance adjusting for fluid intelligence) across Go–no go, Proverbs, Hayling, Hotel and *Faux Pas* tests. Left: overlap projected to brain surface; colour scale shows number of affected patients. Right: slice illustrating maximum overlap; coordinates in MNI space.

were significant for Go–No go, Proverbs, Hayling, and Spatial Working Memory; correlations with Culture Fair were significant for Go–No go, Digit Span, Months, and Hayling, $P<0.06$ for Proverbs; and no subtest showed significant differences between left lateral, right lateral, inferior medial and superior medial subgroups.

Discussion

In our data, the picture of relations between executive deficit and fluid intelligence is both simple and unanticipated. Certainly, the results show that fluid intelligence is a substantial contributor to frontal deficits. For one group of 'executive' tasks, including the Wisconsin Card Sorting Test, Verbal Fluency and Iowa Gambling, differences between patients and controls can be entirely explained by *g* (*cf*. Fig. 1A). When fluid intelligence is partialled out, however, a second set of tasks shows remaining deficits. This second set of tasks includes Go–No go, Proverbs, Hayling, Hotel and Faux Pas. The data give some suggestion that these additional, non-*g* deficits may be associated with the most anterior (especially right) frontal lesions. For these tests, results resemble those of Fig. 1B, implying deficits in some specific function largely separate from *g*.

For the first group of tasks—Wisconsin Card Sorting Test, Verbal Fuency and Iowa Gambling—we found no specific association with particular regions of prefrontal damage. As reviewed earlier, previous findings for the Wisconsin Card Sorting Test are contradictory, with some studies suggesting specific deficits after dorsolateral lesions (e.g. Milner, 1963; Rezai *et al*., 1993), but others not (e.g. Stuss *et al*., 1983, 2000). Verbal Fluency is also a widely used test in the assessment of frontal functions. Despite the fact that phonological fluency can be impaired in a wide range of conditions and in patients with different lesion localizations (Crawford *et al*., 1993; Brooks *et al*., 1999; Henry and Crawford, 2004), it has been extensively demonstrated that frontal patients are more impaired that non-frontal patients (Milner, 1964; Benton, 1968; Perret, 1974; Henry and Crawford, 2004). Deficits have been associated with a variety of frontal regions, including dorsolateral and superior medial (Stuss *et al*., 1998; Troyer *et al*., 1998). They occur with either left or right frontal lesions (e.g. Baldo and Shimamura, 1998; Davidson *et al*., 2007), though are commonly stronger on the left (e.g. Perret, 1974; Baldo and Shimamura, 1998). Further work would be needed to show why, in our patient sample, there was no specific association with left hemisphere lesions. One possibility is that, by comparison with many previous studies, our lesion sample was relatively anterior, with no lesions extending into the temporal lobe and lesions in only two of our left lateral patients incorporating more than 10% of Brodmann area 44. Previously, it has been suggested that frontal deficits in Verbal Fluency may be over and above those predicted by general intelligence as measured by the Wechsler Adult Intelligence Scale (Henry and Crawford, 2004). Our results suggest that fluid intelligence, with its emphasis on current problem solving, may be the more suitable measure of *g* in frontal patients (Duncan *et al*., 1995).

Our findings on the Iowa Gambling Task and *g* deserve special attention. Some prior studies show clear decision-making deficits in patients with ventromedial frontal deficits, manifest in consistent selection of risky decks (Bechara *et al*., 2000; Torralva *et al*., 2007). Decision-making deficits can exist in the absence of more general deficits, for example in working memory (Clark and Manes, 2004). At the same time, deficits in Iowa Gambling can be seen following other kinds of prefrontal lesion (e.g. Manes *et al*., 2002), and it has been suggested that this task depends on other cognitive functions besides reward coding and use, including learning, shifting and spatial working memory (Dunn *et al*., 2006). In our data, Iowa Gambling was positively correlated with *g*. Once *g* was removed, the deficit in frontal patients became non-significant, but was still borderline. We found no evidence of selective deficit in patients whose lesions included the inferior medial region. Certainly these data suggest that the task is influenced by factors in addition to a specific risky decision-making component, which may critically depend on ventromedial prefrontal cortex. This risky component is perhaps more salient in other patient groups, e.g. those with bilateral ventromedial damage (Bechara *et al*., 1994) or frontal variant frontotemporal dementia (Torralva *et al*., 2007).

For patients like ours, meanwhile, our data have strong implications for use and interpretation of tests such as the Wisconsin Card Sorting Test, Verbal Fluency and Iowa Gambling. To a large degree, the deficits measured in such tests may not be

specific to their particular cognitive content. Instead, they often reflect a much more general cognitive loss. It remains an open question how widely this may hold for other popular 'executive' tests in clinical and experimental neuropsychology.

Earlier we distinguished two plausible models of the relation between *g* and executive function. According to the first, *g* reflects a specific cognitive function, contributing to successful performance in many different cognitive contexts. Elsewhere, we have proposed that *g*, in large part, reflects the control of current behaviour by a flexible internal model of relevant facts, rules and task requirements (Duncan, 2001; Duncan *et al*., 2008; *cf*. the 'global workspace' of Dehaene *et al*., 1998, 2003). Central to such a model is the common pattern of frontal and parietal activity seen for a wide range of cognitive demands, including standard tests of fluid intelligence (Duncan *et al*., 2000; Duncan and Owen, 2000), incorporating posterior parts of the lateral frontal surface, the anterior insula/operculum, the anterior cingulate/pre-supplementary motor area and the intraparietal sulcus. According to the second model, in contrast, *g* reflects average efficiency in a number of separable executive functions, perhaps better measured by individual executive tests.

On the one hand, our data show little resembling the predictions from the average model illustrated in Fig. 1C and D. If a lesion selectively affects one executive function *X*, the regression line relating a test of *X* to *g* should lie below the line for control subjects, while regression lines for other, unaffected executive functions (*Y*, *Z*, . . .) should shift in the opposite direction. While results fitting this prediction would provide strong support for an average model, however, negative results do not rule it out. For one thing, the size of the upward shift for unaffected functions will depend on how many separate functions are included in the fluid intelligence score. The upward shift occurs because, if one function *X* is impaired, others must be correspondingly higher to achieve a given fluid intelligence level; the more functions are included in fluid intelligence, however, the smaller this upward shift needs to be in each individual one. Perhaps even more importantly, the predictions in Fig. 1C and D depend on the discovery of performance tests that reflect the separate components of fluid intelligence in a reasonably pure way, and on the sensitivity of these components to different regions of damage. As we have described, the activity pattern associated with tests of fluid intelligence encompasses a number of quite different structures in frontal and parietal cortex. Given this, it seems likely that the task modelling function we have linked to *g* can, in principle, be dissociated into components, and the functional imaging literature contains a number of proposals for such dissociations (see e.g. MacDonald *et al*., 2000). It is perhaps unlikely, however, that current neuropsychological tests successfully separate the different components of *g*; instead, the whole brain system comprising lateral frontal surface, anterior insula/operculum, anterior cingulate/pre-supplementary motor area, and intraparietal sulcus may work jointly to control many different kinds of cognitive activity. If this is so, then what appears now as a unified *g* may in future be dissociated into components with purer cognitive tests and/or better and larger patient groups.

In this article we have addressed relations between executive impairments and fluid intelligence in patients with frontal lesions. A separate question is which lesion characteristics are most predictive of fluid intelligence decrement itself. As described earlier, functional imaging shows a specific set of frontal and parietal activations during fluid intelligence test performance. Correspondingly, deficits in fluid intelligence can follow both frontal and posterior cortical lesions (e.g. Basso *et al*., 1973; Tranel *et al*., 2008). A plausible hypothesis is that fluid intelligence deficits will be most associated with lesions in the specific fronto-parietal network suggested by functional imaging; further data, incorporating patients with posterior as well as frontal lesions, would be needed to test this hypothesis.

Beyond *g*, our data suggest a separate set of impairments that may be specifically associated with anterior frontal lesions. Much recent attention has been paid to the function of this large and more recently evolved region, which is one of the latest to achieve myelination in the human brain. According to several accounts, anterior prefrontal cortex is at the top of a frontal processing hierarchy (Koechlin *et al*., 2003; Badre and D'Esposito, 2007). In agreement with our results, anterior functions have been previously linked to Six Element (a precursor to Hotel) (Burgess, 2005) and theory of mind (Frith and Frith, 2006) tasks. At least since the 1940s, it has frequently been observed that some aspects of frontal impairment are not well explained by conventional 'intelligence' (e.g. Hebb and Penfield, 1940; Teuber, 1972). Our data suggest that this may especially be so for aspects of anterior frontal function.

Anterior deficits in such a variety of tasks, from linguistic to social, might suggest linkage simply through anatomical proximity. Much functional imaging evidence, for example, suggests a degree of separation between detailed patterns of anterior activity for social versus non-social demands (Gilbert *et al*., 2006). A second possibility is that some common processing theme links these different deficits, implemented though they are in different cognitive domains. Anterior frontal activity has previously been linked to multi-tasking (Burgess *et al*., 2001; Braver and Bongiolatti, 2002; Gilbert *et al*., 2006) and the ability to switch between different cognitive contexts (Koechlin *et al*., 2003; Burgess, 2005; Badre and D'Esposito, 2007), and a change of context or perspective is certainly a feature of the tasks in which we find deficits beyond those explained by *g*. In Go–No go and Hayling, it may be significant that deficits follow a previous set of trials with a different instruction (*cf*. Koechlin *et al*., 2003; Badre and D'Esposito, 2007). In Hayling too, the normal process of hearing a sentence must be suspended in favour of searching for a new word generation strategy; just as, in Proverbs, the normal process of understanding and using a proverb must be suspended in favour of searching for a suitable abstract explanation. In Hotel, involvement in a sub-task must be periodically suspended in favour of the bigger picture of overall time management. *Faux Pas* stories require appreciation of two different perspectives, that of the speaker who is unaware of their blunder, and that of the listener who is hurt by it. Though, by comparison with multi-tasking, mentalizing capacity has been linked to more caudal aspects of anteromedial prefrontal cortex (Gilbert *et al*., 2006), at a broader level, they may share a requirement for multiple contexts or perspectives to be maintained. While such arguments provide little more than hints for future development,

it seems plausible that some common cognitive requirement does link the disparate set of deficits associated with anterior frontal lesions.

Further work may well reveal additional frontal deficits that are separate from *g*. For example, functional MRI studies have repeatedly suggested that, just anterior to the frontal eye fields in the dorsal premotor cortex, activity is especially strong during spatial working memory (e.g. Sala and Courtney, 2007). In anterior, ventral parts of the left prefrontal cortex, there is strong activity associated with a variety of semantic tasks (Wagner *et al*., 2001). For these cases, as for anterior frontal functions in our data, results with appropriate tasks and lesion groups might resemble the pattern of Fig. 1B. Indeed, establishing such relations might be greatly facilitated by our method for examining performance residuals after correcting for *g*. When tasks are affected both by specific executive processes and a common *g* component, associations between specific deficit and region of damage may be clarified when the *g* component is removed.

For a number of tasks in Experiment 2, the difference between frontal patients and controls was not significant. In every case but one (Months), however, the performance of patients was numerically inferior. As predicted by a deficit in *g*, it seems likely that, with sufficient experimental power, some degree of frontal impairment can ultimately be demonstrated for most or all cognitive tests.

Our data were negative with regard to dissociations between conventional left lateral, right lateral, inferior medial and superior medial regions. Especially in Experiment 2, these negative results must be interpreted in light of small patient numbers in the different subgroups, in particular inferior medial and superior medial. Perhaps most surprisingly, even a comparison of patients with and without inferior medial lesions suggested no hint of selective deficits, either in Iowa Gambling as discussed above, or in our two social functioning tests. Very likely, dissociations beyond those we saw here can be obtained with larger or different patient groups. Other tests, too, may be more successful in pinpointing specific functions associated with these different prefrontal regions (Stuss, 2006). Meanwhile, the broad picture from our data is of two main groups of deficits, one associated with *g*, and the other, manifest in a variety of tests, perhaps associated with anterior, context-switching functions.

From a clinical perspective, understanding executive deficits in patients with frontal lesions may greatly facilitate the design of appropriate assessment tools and rehabilitation strategies, with potential improvement in patients' daily living. Our results have clear implications for the clinical assessment of these functions in different neurological and neuropsychiatric diseases. In our view, an optimal frontal lobe assessment should include tests of fluid intelligence, in particular discrepancy from premorbid score, supplemented by one or more specific assessments of residual, putatively anterior frontal deficit. In many circumstances, these latter deficits—captured in several subtests of the Ineco Frontal Screening—may be of especial significance in impaired everyday activity. Clear separation from *g* may be an essential step in improved clinical assessment and management.

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Supplementary material

Supplementary material is available at *Brain* online.

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