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Frontal Lobe Functioning in Man: The Riddle Revisited

Sergio Della Sala and Colin Gray

University of Aberdeen, UK

Hans Spinnler

S. Paolo Hospital, University of Milan, Italy

Cristina Trivelli

University of Aberdeen, UK

Forty-eight patients, each with a single frontal lobe lesion, were tested with a battery of 10 of the most widely used neuropsychological tests, comprising five traditional "frontal" tests and five others, for which that claim is not generally made. All correlations among the tests in the group were positive and significant. Moreover, the average correlation between each frontal test and the other tests in the frontal group was found to be higher than the average correlation of the same frontal test with the tests in the other group. A factor analysis of the scores on the five frontal tests yielded a single factor accounting for 53% of the variance. A factor analysis on the entire battery of tests (frontal plus nonfrontal) also yielded a strong general factor; although this accounted for a smaller portion (43%) of the shared variance, and one test (Verbal Span) failed to show a substantial loading on the factor. Neither the results of the present study nor the findings of other researchers argue for the abandonment of the concept of "executive" functioning, mediated by the functioning of the frontal lobes, in favor of a variant of fractionation. © 1998 National Academy of Neuropsychology. Published by Elsevier Science Ltd

After a century and a quarter of research, the function of the frontal regions of the brain continues to be the subject of speculation, and of controversy. In the 1960s, Teuber, summing up the state of knowledge at the time, wrote of "the riddle of frontal lobe function in man" (Teuber, 1964, p. 410). Today, some 30 years later (and over 125 years after the publication of the puzzling case history of Phineas Gage [Harlow, 1868; see Damasio, Grabowski, Frank, Galaburda, & Damasio 1994]), the riddle has yet to be solved (review in Darling, Della Sala, Gray & Trivelli, in press).

Address correspondence to Sergio Della Sala, Department of Psychology, University of Aberdeen, Aberdeen AB24 2UB, UK.E-mail: sergio@abdn.ac.uk.

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The so-called "riddle of the frontal lobes" is, in fact, not one puzzle but a whole set of related questions, some theoretical, others methodological. The former are concerned with the nature of frontal lobe functioning, the latter with its measurement. In recent years, there has been much consideration of whether there is essentially one kind of prefrontal lobe activity that is brought into play whenever any of a wide category of tasks is undertaken or, on the contrary, there are many different frontal functions, each of which is required only for a relatively narrow range of tasks. It is this issue with which the present paper is primarily concerned.

The case histories of those who have sustained frontal damage are certainly perplexing. On the one hand, as with Harlow's famous patient Phineas Gage (Harlow, 1868), and with many similar cases described subsequently (e.g., Eslinger & Damasio, 1985), the cognitive effects of frontal damage are often by no means immediately apparent. The patient may appear to function much as before, with little or no obvious mental deterioration; in fact, some frontal patients show high levels of psychometric intelligence (Brazzelli, Colombo, Della Sala, & Spinnler, 1994; Shallice & Burgess, 1991). On the other hand, while a variety of other sequelae have been reported in frontal patients, each occurs in some patients but not in others, making it difficult to discern an underlying pattern. For example, some patients show personality change (Ackerly & Benton, 1948; Brickner, 1936; Penfield & Evans, 1935), but others may not (Hebb & Penfield, 1940). There are, however, certain recurring themes. Although one patient may show an uncharacteristic apathy, another may present a contrasting picture of puerile practical joking and disinhibited social behaviour, and a third may display both of these contrasting patterns at different times (Blumer & Benson, 1975), the occurrence of at least one of these presentations is so common in patients with damage to the frontal cortex that they are often referred to by clinicians as "frontal lobishness" (Benson, 1994).

In contrast with the frequency of the global patterns of frontal lobishness, the search for specific cognitive deficits peculiar to frontal lobe patients has generally been unrewarding. Following the discovery, in the 19th century, of Broca's area, and of evidence to suggest that the frontal lobes are involved in the coordination of the motor movements involved in voluntary actions (Bianchi, 1895; Jastrowitz, 1888), little else of interest was reported for several decades until, in the late 60s and 70s, Milner and her associates published some work suggesting that certain regions in the prefrontal lobes controlled specific functions (e.g., Jones-Gotman & Milner, 1977). Patients with frontal excisions involving the dorsolateral areas made more errors on the Wisconsin Card Sorting Test than did patients with lesions in the temporal areas (Milner, 1963, 1964). Further evidence of such specificity and localisation, however, has been slow in coming; in fact, Milner's interpretation of her own findings has been questioned (Anderson, Bigler, & Blatter, 1995; Reitan & Wolfson, 1994).

The diversity of changes reported in patients with frontal lobe injuries probably owes something to the fact that in the reported case histories, the patients had sustained their frontal damage in a variety of ways, including head injury, tumour, vascular disease and postepileptic surgery. In some cases, there were almost certainly injuries to other regions of the brain, as well as to the frontal lobes. Some of the discrepancies among the lists of frontal functions offered by different writers may reflect this varying etiology (see, e.g., Goldman-Rakic, 1993; Grafman, Sirigu, Spector, & Hendler, 1993; Hart & Jacobs, 1993; Lezak, 1993; Schwartz, Mayer, Fitzpatrick De Salme, & Montgomery, 1993; Shallice, 1988; Sohlberg, Mateer, & Stuss, 1993; Varney & Menefee, 1993).

Despite the discrepancies among the published lists of "frontal functions," however, a common core of features is clearly discernible. In all descriptions, pride of place is given to a set of activities comprising the deployment of attention, the initiation of nonhabitual action, and foresight and planning; although the authors differ in the emphases they place upon these common ingredients (e.g., Benton, 1994; Grafman et al., 1993; Lezak, 1993; Shallice, 1982; Stuss, Eskes, & Foster, 1994). For example, in the formulation of Grafman et al. (1993), there is an extensive consideration of the estimation of duration and the sense of temporal perspective, an emphasis that is much less apparent in the descriptions offered by Hart and Jacobs (1993) or by Benton (1994). In Shallice (1982), there is more emphasis upon the construction and execution of plans than there is in most other accounts. In the past 20 years or so, a considerable body of evidence has appeared to many neuropsychologists to converge upon the view that the frontal regions of the brain, rather than themselves implementing specific cognitive operations such as memorising, learning, or reasoning, are concerned instead with the deployment and coordination of such functions, which take place elsewhere in the brain. The frontal lobes have come to be regarded as having a supervisory, or "executive" function (Baddeley, 1986; Shallice, 1988; reviews in Tranel, Anderson, & Benton, 1994, and in Darling et al., in press).

A number of tests have been devised for the purpose of tapping the "executive dysfunction" believed to underlie the sequelae of frontal lobe damage. These tests are extensively used in neuropsychological examinations, and there is a considerable body of evidence to show that they are indeed sensitive to frontal damage. Since, however, the tests were constructed on the basis of clinicians' experiences with frontal patients, there is, to avoid circularity, the need for an independent line of evidence to confirm that the frontal lobes are indeed involved in (and crucial for) successful performance of "executive" tasks.

The traditional dependence on the study of the sequelae of frontal lesions, while establishing the existence of deficits, permits only indirect and negative inferences about the possible role of the prefrontal cortex. It is difficult or impossible to ascertain the loci of executive functions on the basis of such data. However, in support of the view that the frontal lobes have indeed a primarily executive function, recent PET-scan (Positron Emission Tomography) work has shown activation of the frontal cortex when subjects are engaged in mental tasks requiring foresight and planning (e.g., Corbetta, Miezin, Dobmeyer, Shulman, & Petersen, 1991; Frith, Friston, Liddle, & Frackowiak, 1991; Petersen, Fox, Posner, Mintun, & Raichle, 1988). Rezai and colleagues (1993) used single photon emission computed tomography (SPECT) with the xenon inhalation technique to monitor frontal cerebral blood flow during the performance of four widely used neuropsychological tests: The Tower of London (TL), the Porteus Mazes (PM), the Wisconsin Card Sorting Test (WCST) and the Continuous Performance test (CP). During performance on the CP, WSCT, and TL, there were increases in frontal blood flow; though no significant trend was found with the PM. Such *in vivo* monitoring of brain activity affords powerful independent corroboration of the claim that the frontal lobes play an important role in executive functioning.

The so-called "frontal" tests, however, appear also to be sensitive to damage in other areas of the brain; in fact, alcoholics and epileptics with seizures arising from the temporal lobes can have performance profiles suggestive of frontal lobe pathology (Hermann, Wyler, & Richey, 1988). Such findings have led some researchers (e.g., Reitan & Wolfson, 1994) to question whether these frontal tests are worthy of the name; in fact some authors (e.g., Baddeley & Della Sala, 1996; Baddeley & Wilson, 1988; Tranel et al., 1994) suggest that it may be helpful to retain the concept of "executive" in a purely functional sense, without commitment to the view that such functioning is the exclusive province of the frontal lobes. It is also possible to argue, however, (and this is the position taken here) that integrity of frontal lobe functioning is a necessary but not a sufficient condition for the performance of tasks that require attention, the initiation of nonhabitual action, or planning (cf. Grafman et al., 1993).

The assumption that the frontal tests all tap a single process has recently been called into question (e.g., McCarthy & Warrington, 1990; Shallice & Burgess, 1996). A major current issue is the question of whether there is just one executive, necessary for the performance of any task requiring planning and organisation, or many different executives, each concerned only with a particular type of problem or stimulus material (cf. Della Sala & Logie, 1993). For example, Shallice and Burgess (1993, 1996); Burgess and Shallice (1994); Baddeley (1996); Burgess (1997), and Duncan (personal communication) have argued for a "fractionation" of the executive into multiple components, suggesting that there may be distinct executives for verbal and spatial materials, and for the performance of abstract planning tasks, as opposed to those requiring the manipulation of visible objects.

Goldman-Rakic (1993), discussing her interpretation of working memory, has proposed that, corresponding to the areas in the posterior cortex concerned with such functions as spatial vision and object vision, are areas in the prefrontal lobes, the function of each of which is to retain and to organise the input from one posterior region. For example, in the frontal cortex a spatial memory area retains and organises the input from the spatial vision areas; and a feature memory area performs a similar function with the input from the object vision areas. According to Goldman-Rakic, each frontal area is but a single tessera in a veritable mosaic of such areas, each receiving input from a different posterior region. In Goldman-Rakic's view, however, the executive functioning that occurs in each of the myriad frontal areas is of the same nature. Her theory, therefore, replaces functional fractionation with anatomical segregation.

In support of functional fractionation, there have been reports of a number of dissociations and double dissociations among tests that are all supposed to be measures of executive functioning (for discussions, see Della Sala & Logie, 1993; McCarthy & Warrington, 1990). Patients with a lesion in one area of the frontal cortex can show impairment on one executive test and not on another, and this pattern may be reversed in patients with lesions in another area. For example, Jones-Gotman and Milner (1977) found that patients with damage to their right frontal lobes performed poorly on the Design Fluency test, whereas those with damage to their left frontal lobes performed adequately. Right frontal impairment, however, does not necessarily affect scores on other executive tests: Hécaen and Ruel (1981) report normal scores on the Weigl Sorting test in patients with right frontal damage, but poor scores in left frontal patients. Milner (1971) obtained a low level of scoring on the WCST in some of her patients with left frontal damage, who nevertheless performed adequately on Verbal Fluency. Other patients, however, showed just the opposite pattern: they were poor on Verbal Fluency, but performed adequately on the WSCT.

Duncan, Johnson, Swales, and Freer (personal communication, paper in preparation, 1997) gave a battery of nine widely used neuropsychological tests (four of them considered to be frontal, five nonfrontal) to 90 head-injured patients. They found that the correlations among the frontal tests were "uniformly low": The median correlation was .26. Moreover, the correlations between the frontal and nonfrontal tests turned out to be at least as high as the correlations among the tests within the frontal group: The median of the between-groups correlations was .29. Their data, therefore, do not appear to support the existence of a single general executive, accounting for a large part of the variability among test scores. As Duncan and colleagues (1997) themselves acknowledge, however, it is difficult to conceive of a neuropsychological test that does not involve executive functioning to at least some extent; on the other hand, this general executive factor (which is linked with concept of goal neglect, described in Duncan, 1990) has a very weak effect upon test variance. Duncan and colleagues (1997) therefore conclude that their study failed to find evidence for unity in the abilities tapped by the diverse set of tests that they used.

A multicomponential interpretation, however, while consistent with the findings of those such as Kopelman (1991) and Duncan et al. (1997), faces a number of difficulties. A near-zero correlation between two tests does not necessarily imply a dissociation between the abilities those tests are supposed to be measuring. The tests of executive functioning were constructed, sometimes rather intuitively, by selecting tasks because they *appeared* to require organisation and planning: their component items were not prepared on the basis of any detailed task analysis. As a result, performance on executive tests is probably contributed to by many other capacities (and deficits) also. These tests almost certainly place varying demands upon instrumental functions (Spinnler, 1991) subsumed by other regions of the brain. Empirically, therefore, it can be quite difficult to distinguish the effects of a genuinely multicomponential executive from those of using multicomponential tests. Some other difficulties with the fractionation of the executive will be considered later in this paper.

AIMS

The general motivation for the present study was the expectation that, since the frontal tests were developed from work with frontal patients and were all specially devised to tap executive functioning, a battery of such tests should show substantial positive correlations among them. We should also expect greater homogeneity within the tests in the frontal group than between the frontal and nonfrontal tests. On the other hand, since all neuropsychological tests require executive functioning to at least some extent, the difference between frontal and nonfrontal tests is one not of kind but of degree, and a sharp discontinuity between supposedly frontal tests and other neuropsychological instruments cannot be expected.

Kopelman (1991) obtained rather low correlations among the executive tests he used, a finding that would cast doubt upon the view that the tests are all tapping a strong and pervasive common core of executive functioning. A problem with that interpretation is that the subjects in his study were all sufferers from Korsakov syndrome and Alzheimer disease and therefore may also have sustained damage to other areas of the brain.

In view of the foregoing considerations, it was decided to investigate the pattern of correlations among some classic putative frontal tests with high face validity, and among tests not widely supposed to tap executive function to the same extent. Moreover, taking advantage of the norms available for all the tests we used, we also intended to ascertain whether double dissociations emerged among the frontal tests in a group of patients with focal frontal lesions.

METHOD

The Neuropsychological Tests

The test battery comprised 10 tests, which were divisible into two groups: (a) five instruments widely regarded as being sensitive to deficits in frontal lobe functioning; (b) five other neuropsychological tests not generally so regarded. In the first (frontal) group were the Digit Cancellation test, Gottschaldt's Hidden Figures test, Weigl's Sorting test, Elithorn's Perceptual Maze test, and Word Fluency; in the second (nonfrontal) group were Verbal Span, the Bushke-Fuld test, Verbal Judgement, Arithmetical Judgment, and the Token Test.

The reason for choosing these tests and not others was mainly the availability of normative data for the Italian population at the time of testing. For example, we excluded the WCST, not only because of the considerations recently raised against its claimed specificity to frontal damage (Anderson et al., 1995; Grafman, Jonas & Salazar, 1990; Reitan & Wolfson, 1994), but also because of the nonavailability of normative data. Other tests widely used in North America were omitted for the same reason.

For the reasons given in the introduction, the distinction between frontal and nonfrontal is regarded as somewhat arbitrary and conventional for many classic off-the-shelf tests, including the ones that we used in this study. A typical example is our decision to include the test of verbal judgements among the nonfrontal tests. Benton (1968) and Luria (1973), among others, have argued that items similar to some of those included in our test, such as evaluative judgements or explanations of proverbs, are sensitive to frontal damage. However, in a sample of 321 normal subjects it has been demonstrated that once the effects of education were partialled out, this test correlated highly with general intelligence, but poorly with executive measures or attentional tests (Spinnler & Tognoni, 1987). Therefore, we considered it not to be specifically frontal, bearing in mind that a misjudgement could only weight the balance against finding a difference between the two groups of tests.

The Frontal Tests

Digit Cancellation test (DC). This is a timed test of selective attention in visual search. The subject's task is to cross out target digits from three matrices (containing 1, 2, and 3 targets), the first (one-target) matrix being used for a practice run. Each subject can score within the range from 0 (no targets crossed out) to 50 (all targets crossed out) (Della Sala, Laiacona, Spinnler, & Ubezio, 1992). Digit Cancellation has been shown to be sensitive to frontal damage by Teuber, Battersby, and Bender (1951) and by Teuber (1972).

Gottschaldt's Hidden Figures test (HF) (Gottschaldt, 1926, 1929). This is a test of visual figure-ground discrimination. The subject is asked to discern a figure hidden within a complex pattern. Scores on this timed test range from 0 (no figures correctly detected) to 35 (all figures detected) (Capitani, Della Sala, Lucchelli, Soave, & Spinnler, 1988). Yacorynksy and Davies (1945) showed that patients with frontal lesions perform poorly on the Hidden Figures test. Capitani et al. (1988) demonstrated that Hidden Figures correlates highly with other attention-loaded tasks.

Weigl's Sorting test (WS) (Weigl, 1927). According to Goldstein (1944), this is an abstract thinking test in which subjects are required to categorise visual material. The subject is presented with 12 wooden blocks, and required to sort them into groups according to a specified criterion, which can be colour, shape, thickness, size or playing-card suits (De Renzi, Faglioni, Savoiardo, & Vignolo, 1966). The score can range from a minimum of 0 to a maximum of 15 (Spinnler & Tognoni, 1987). McFie and Piercy (1952) suggested that the Weigl's Sorting test might be sensitive to frontal damage; and indeed performance on sorting tests frequently shows impairment in patients with lesions in the frontal lobes (see Lezak, 1983, pp. 484–492).

Elithorn's Perceptual Maze test (EM) (Elithorn, 1955). This test of spatial planning consists of a network of paths, through which subjects are required to find an ascending route passing through specified numbers of superimposed black dots (3, 4, 5, or 6) without retracing their steps; nor must they switch from one path to another. The score of our version of Elithorn's test (Spinnler & Tognoni, 1987) ranges from a minimum of 0 to a maximum of 16. Benton, Elithorn, Fogel, and Kerr (1963) have suggested that this test is sensitive to frontal damage.

Word Fluency (WF) (Spinnler & Tognoni, 1987). This is a categorically cued test of access to the lexicon. The subject is asked to generate as many words as possible in each of four semantic categories (colours, animals, fruits, and cities), allowing 2 minutes for each category. The subject's score is the mean number of words produced over the four categories, and so has no upper limit. Ramier and Hécaen (1970) have shown the sensitivity of this type of Word Fluency test to frontal lobe damage.

The Nonfrontal Tests

Verbal Span (VS) (Spinnler & Tognoni, 1987). In this short-term verbal memory test, the subject is asked to repeat, in their order of presentation, lists of spoken disyllabic words. The score is the length of the longest sequence that is repeated correctly in two out of three trials. Of the many studies that have explored the impairment of short-term or working memory in frontal patients, the vast majority have failed to find span decrements in frontal patients (Luria, 1973; Owen, Downes, Sahakian, Polkey, & Robbins, 1990; Risse, Rubens, & Jordan, 1984; Stuss & Benson, 1986; Vilkki, 1985). Only one or two studies (e.g., Janowsky, Shimamura, Kritchevsky, & Squire, 1989) have found decrements in forward or backward digit span.

The Buschke-Fuld test (BF) (Buschke & Fuld, 1974). This is a traditional test of supra-span verbal learning, which is assumed to measure quality of episodic memory. First, a spoken string of 10 unrelated disyllabic words is presented, and the subject tries to recall as many words as possible. On the next trial, only the words that the subject failed to recall are presented and the subject is asked to produce the whole list of 10 words once again. The procedure is continued for 18 trials in total and the subject's score is the total number of words recalled, which can vary from 0 to 180. Since this test taps long-term memory, it is not thought to be particularly sensitive to frontal damage: "Frontal lobe damaged patients typically perform normally on many tests of long term memory" (Stuss et al., 1994, p. 166).

Verbal Judgement (VJ) (Spinnler & Tognoni, 1987). In this test, the subject is asked to discern the differences between pairs of items, to explain the meanings of some proverbs, to discern the absurdity of some phrases and to classify some items. The score can vary within the range from 0 to 60. Once educational level is partialled out, this test is highly correlated with intelligence tests such as the Raven's Progressive Matrices (Spinnler &Tognoni, 1987), performance on which is known to be largely unimpaired in frontal patients (Bigler, 1988; Shallice & Evans, 1978).

Arithmetical Judgement (AJ) (Spinnler & Tognoni, 1987). The subject is asked to perform a number of simple mental arithmetical operations, including calculations and counting forward and backward in twos and threes. The score can vary from 0 to 10. There is no report in the literature of frontal patients finding this test specially difficult.

The Token Test (TT) (De Renzi & Faglioni, 1978). This is a test of oral language comprehension. The subject is shown a set of counters (tokens) of different colours, sizes, and shapes. The experimenter then instructs the subject to select one of the counters, by

TABLE 1
Demographic and Clinical Characteristics of 48 Frontal Patients

Lesion Side	Age (Years)	Education (Years)	Gender F	Gender M	Length of Illness (Months)	Etiology V	Etiology HI	Etiology T
Left (n = 20)	49 (17.3)	9.5 (4.85)	11	9	13.7 (20.3)	7	5	8
Right (n = 17)	42.5 (17.2)	7.8 (3.1)	5	12	20.8 (26.7)	4	9	4
Bilateral (n = 11)	48.9 (16.3)	8.73 (4.3)	5	6	10.6 (12.8)	3	5	2[a]

Note. F = female; M = male; V = vascular; HI = head injury; T = tumour. Standard deviations are in parentheses.
[a]One patient suffered from the sequelae of bilateral encephalitis.

giving instructions such as: "Show me the small, red, square, then the large green triangle." The score ranges from 0 to a maximum of 36.

Test Norms

Normative data for all the tests used in this study had previously been gathered from previous investigations with large samples of healthy subjects (Capitani et al., 1988; Della Sala et al., 1992; Spinnler & Tognoni, 1987). When the norms were gathered, the effects of age, education, and sex were studied by means of a linear regression model. Age and education had significant effects upon the scores of every test considered. For each subject, therefore, an adjusted score was calculated by adding or subtracting the contributions made by age and education. Adjusted scores were ranked in ascending order and tolerance limits were calculated by means of a nonparametric procedure (Wilks, 1941). In the present study, the score that corresponds to the outer 5% tolerance limit drawn with 95% confidence, was chosen as the inferential cut-off score for every test. The outer tolerance limit (i.e., the worst score achieved by at least 95% of the population) defines the implicit risk involved in declaring that a subject is, in a statistical sense, "abnormal." The scores that fell below this point were considered to be indicative of pathology. The advantage of this standardisation procedure (Capitani, Della Sala, & Spinnler, 1986; Capitani & Laiacona, 1988) is that it permits meaningful comparisons among tests with varying scales and of varying intrinsic difficulty.

Characteristics of the Patients

Forty-eight patients with CT-demonstrated focal isolated frontal lesions were included in the study, although the possibility that among the head-injury patients some individuals may have sustained additional brain damage can never be confidently excluded. The mean age of the patients was 46.28 years (SD = 17.33), their mean number of years of education was 8.79 years (SD = 4.25) and the mean duration of their illness (the interval extending from diagnosis to testing) was 15.69 months (SD = 22.09). In 17 of the patients, the lesion was located in the right frontal lobe, in 20 others it lay in the left lobe, and in the remaining 11 patients the lesion involved both frontal lobes. The clinical and demographic characteristics of the patients are shown in Table 1. The patients with vascular lesions suffered mainly from strokes, though four had cerebral haemorrhages. The patients with tumours were mostly affected by meningiomas (in one

TABLE 2
Performance of the Frontal Patients on the 10 Neuropsychological Tests

Test	Patients' Performance *M*	Patients' Performance (*SD*)	Cut-Off Score[a]	Median Score for Healthy Controls	Percentage of Patients Below Cut-Off
Frontal					
DC	29.5	(10.7)	24.0	39.3	30.0
HF	21.2	(12.0)	16.7	34.0	31.0
WS	9.1	(3.6)	4.2	10.7	14.5
EM	9.8	(5.5)	7.5	14.2	27.5
WF	9.3	(4.9)	7.0	17.0	27.5
Nonfrontal					
VS	3.7	(0.7)	2.7	4.5	10.5
BF	61.0	(49.4)	36.0	111.0	37.5
VJ	43.4	(10.9)	32.0	50.0	17.0
AJ	9.2	(1.3)	6.5	9.7	9.0
TT	30.3	(5.3)	26.2	33.0	15.0

Note. DC = Digit Cancellation; HF = Hidden Figures; WS = Weigl Sorting; EM = Elithorn's Maze; WF = Word Fluency; VS = Verbal Span; BF = Buschke-Fuld; VJ = Verbal Judgement; AJ = Arithmetical Judgement; TT = Token Test.
[a]Estimated 5th percentile for healthy population.

case the tumour was medial frontobasal, encroaching upon both frontal lobes), three patients had a glioma, one an astrocytoma, one a glioblastoma. One patient was affected by the sequelae of a bilateral frontal encephalitis (details reported by Brazzelli et al., 1994).

Table 1 demonstrates that the patients with lesions in the three lesion sites (left, right, bilateral) had similar mean ages and levels of education.

RESULTS AND COMMENT

Performance of the Frontal Patients on the 10 Tests

Table 2 shows the mean performance levels of the frontal patients on the 10 neuropsychological tests compared with data from normal controls. On the whole, the tests classified as frontal are failed more often than the nonfrontal tests, the only exception being the supra-span learning test. These data replicate previous findings demonstrating the sensitivity of Buschke-Fuld's test to frontal damage, probably arising from the high level of controlled processing needed in a learning task (Della Sala, Laiacona, Spinnler, & Trivelli, 1993). It is noteworthy that none of the tests was failed by more than one third of the patients; although in all cases, the patients' mean level of performance was lower than the norms for healthy subjects.

The performance on the frontal and nonfrontal tests of the three subgroups of patients, subdivided according to the side of their lesion (left, right or bilateral, see Table 1), were analysed by means of one-way multivariate analyses of variance (MANOVA). The first MANOVA showed that there is no linear combination of the five frontal variables that reliably discriminates among the three lesion sites: Wilks' lambda = 0.658404; $df_1 = 10$, $df_2 = 72$; $p = 0.1038$. This negative result of the multivariate test indicates that there are no robust differences among the groups on any of the five variables, suggesting that the performance on the five frontal tests is unaffected by the locus of the frontal lesion. With the nonfrontal tests, however, the MANOVA indicated that there are differences among the left, right, and bilaterally lesioned patients: Wilks' lambda = 0.617889;

TABLE 3
Correlations Among the Tests in the Frontal Group

	DC	HF	WS	EM	WF	Row Median
DC		.53	.15	.55	.47	.50
HF	.53		.58	.77	.42	.56
WS	.15	.58		.52	.34	.43
EM	.55	.77	.52		.43	.54
SG	.47	.42	.34	.43		.43

M = .476
Median = .495
Minimum = .15
Maximum = .77
SD = .1625
Interquartile range = .16

Note. DC = Digit Cancellation; HF = Hidden Figures; WS = Weigl Sorting; EM = Elithorn's Maze; WF = Word Fluency.

$df_1 = 10$, $df_2 = 76$; $p = 0.0375$. Univariate ANOVAs on the individual variables show that the lesion site groups differ on Verbal Judgement, $F(2, 43) = 5.99$, $p = 0.0051$, and on the Token Test, $F(2, 43) = 4.11$, $p = 0.0232$, the left and bilateral groups having lower mean scores than the right-lesioned group.

Correlations among the Five Frontal Tests

Table 3 shows the correlations among the five tests in the frontal group. The correlations in Table 3 are, generally speaking, substantial ($M = 0.476$, median = 0.495), although they range from 0.15 to 0.77. The median correlation among all pairs of the five frontal tests used in the present study, therefore, is almost twice that reported by Duncan et al. (1997, manuscript in preparation) (0.26), in their study with a group of head-injured patients.

Table 4 shows the medians of the correlations of each test in the frontal group with the other four tests in the group and the five tests in the nonfrontal group. In all five cases, the intragroup correlation is higher. This result lends some empirical confirmation to the claim that tests regarded as frontal have rather more in common with one another than they do with those neuropychological tests that are not so regarded.

TABLE 4
Comparison Between the Average Correlation of Each Test in the Frontal Group with the Other Frontal Tests and the Average Correlation of the Same Test with Those in the Nonfrontal Group

	Median Correlation of Frontal Test with . . .	
Frontal Tests	Other Frontal Tests	Nonfrontal Tests
Digit Cancellation	.5	.33
Hidden Figures	.56	.45
Weigl Sorting	.43	.39
Elithorn's Maze	.54	.40
World Fluency	.43	.42

TABLE 5
Principal Axis Factor Analysis of Scores on the Frontal Group

Tests	Factor Loadings
Digit Cancellation	.616860
Hidden Figures	.893496
Weigl Sorting	.623114
Elithorn's Maze	.873554
Word Fluency	.559339
Variance Explained	2.653080
Percentage Explained	53%

Factor Analysis of the Correlations among the Tests in the Frontal Group

Table 5 shows the *F*-matrix resulting from a principal axis factor analysis of the correlations among the five frontal tests. A single factor was extracted, which accounted for 53% (eigenvalue 4.46) of the variance, a portion considerably larger than the 40 to 45% usually attributed to the g factor in classical research on intelligence. All the frontal tests load substantially and significantly on this general factor. No further factors need to be included in the solution, because the eigenvalues of the second and third factors extracted were 0.89 and 0.68, respectively, well below the Kaiser criterion of one and far into the factorial rubble on Cattell's scree test.

Table 6 shows the matrix that can be reproduced from the loadings of the tests on the first (and only) factor to be extracted from the analysis. It will be noticed that the reproduced correlations have quite similar values to those in the original *R*-matrix shown in Table 3. Also shown in Table 6 are the discrepancies between the reproduced and original correlations, arrayed in a residual matrix. The smallness of the values in the residual matrix indicates that the single factor gives a very good account of the correlations among the frontal tests.

Double Dissociation-Like Patterns Among the Five Frontal Tests

In recent years, in the context of single-subject research, neuropsychologists have placed heavy reliance upon a pattern of findings known as the *double dissociation*, which can be obtained by observations on as few as two patients. With readily observable

TABLE 6
The Reproduced and Residual Matrices

	Reproduced Matrix				Residual Matrix			
	HF	WS	EM	WF	HF	WS	EM	WF
DC	.55	.38	.54	.35	.03	−.16	.02	.10
HF		.56	.78	.50		.02	.02	−.08
WS			.54	.35			.02	.10
EM				.49				−.06

Note. DC = Digit Cancellation; HF = Hidden Figures; WS = Weigl Sorting; EM = Elithorn's Maze; WF = Word Fluency. The reproduced matrix was obtained by multiplying the loadings on the first principal factor of the tests involved in the correlation. The residual matrix was obtained by subtracting the products from the original correlations.

TABLE 7
Double Dissociation-Like Patterns of Scoring on Pairs of Executive Tests Among the 48 Frontal Patients

Patients	Abnormally Low on . . .	Above the Median on . . .
20, 29	Digit Cancellation	Hidden Figures
46, 47	Hidden Figures	Digit Cancellation
20	Digit Cancellation	Elithorn's Maze
47	Elithorn's Maze	Digit Cancellation
37	Digit Cancellation	Word Fluency
16, 44, 47	Word Fluency	Digit Cancellation
32, 46	Hidden Figures	Elithorn's Maze
29	Elithorn's Maze	Hidden Figures
29, 37, 41	Elithorn's Maze	Weigl Sorting test
21	Weigl Sorting test	Elithorn's Maze
37	Elithorn's Maze	Word Fluency
6, 16, 23	Word Fluency	Elithorn's Maze

symptoms or other phenomena, where each observation is a simple record of presence or absence, the proposition that *A* is a necessary condition for *B* is refuted by obtaining a case of *A* and no *B*, and another with *B* and no *A*: that is, the obtaining of a double dissociation refutes the claim that one qualitative variable is dependent upon another qualitative variable (Shallice, 1988).

In the present study, a double dissociation-like pattern was obtained on some pairs of tests: that is, some patients produced a very low score on test A, but an above-average one on B; and this inequality was reversed in the scores of other patients. Table 7 shows that some patients who scored below the 5% tolerance limit for the healthy subject sample on one frontal test scored above the median of the healthy distribution of scores on another test; whereas in other patients, the pattern is reversed.

It might be thought that the existence of such patterns lends support to those who argue for fractionation of the central executive. In fact, such findings by no means provide unequivocal support for the fractionation of the executive. The intrinsic limitations of the usual form of double dissociation have been much discussed in recent years (e.g., Caramazza, 1986; Dunn & Kirsner, 1988). Moreover, the problems of interpretation intensify with data in the form of correlations among neuropsychological tests, which are

TABLE 8
Correlations Among the 10 Neuropsychological Tests

	DC	HF	WS	EM	WF	VS	BF	VJ	AJ	TT
DC		.56	.18	.56	.51	.05	.32	.58	.45	.40
HF			.56	.82	.49	−.18	.21	.59	.45	.60
WS				.59	.50	−.24	.43	.48	.43	.68
EM					.45	−.11	.36	.56	.49	.62
WF						.13	.54	.64	.29	.50
VS							.08	.19	−.05	.15
BF								.50	.20	.33
VJ									.32	.66
AJ										.53

Note. DC = Digit Cancellation; HF = Hidden Figures; WS = Weigl Sorting; EM = Elithorn's Maze; WF = Word Fluency; VS = Verbal Span; BF = Buschke-Fuld; VJ = Verbal Judgement; AJ = Arithmetical Judgement; TT = Token Test.

TABLE 9
Factor Analysis of the Correlation Among All 10 Neuropsychological Tests (Principal Axis Method)

Tests	Factor Loadings
Digit Cancellation	.630963
Hidden Figures	.793344
Weigl Sorting	.692783
Elithorn's Maze	.819064
Word Fluency	.693000
Verbal Span	−.000482
Buschke-Fuld	.501296
Verbal Judgement	.785996
Arithmetical Judgement	.555689
Token Test	.791205
Percentage Explained	44.62%

usually aggregates of items and are measures of hypothetical constructs rather than observations of directly observable symptoms. Of the 48 patients in the present study, only 12 showed this degree of unevenness in their scoring on pairs of frontal tests. The obtaining of occasional dissociation-like patterns in no way refutes a high Pearson product-moment correlation as an index of positive linear association between the scores on two tests, and the occasional double dissociation-like pattern (which, in the scatterplot corresponds to points in adjacent, rather than opposite, quadrants) is what one would expect with scores on neuropsychological tests, each of which must tap many different abilities. What a double dissociation-like pattern does show is that the abilities tapped by two tests do not overlap completely.

Correlational and Factor Analysis of the 10 Neuropsychological Tests

Table 8 shows the correlation between each of the 10 neuropsychological tests and the 9 other tests in the battery. It can be seen not only that there are some very substantial correlations among both groups of tests, but also that there are some substantial correlations between the frontal and nonfrontal instruments. In fact, with the exception of Verbal Span, all the tests show several substantial correlations with other tests in the battery. The low correlations involving Verbal Span confirm that the substantial correlations among the tests in the frontal group and the very salient general factor emerging from the factor analysis cannot be dismissed as merely a matter of the severity of lesional damage: a general lowering of all scores does not thereby ensure a positive manifold of strongly correlated tests, as shown by the low correlations with Verbal Span.

Table 9 shows the *F*-matrix resulting from a principal axis factor analysis of the correlations among the 10 neuropsychological tests. A single factor was extracted, which accounted for 45% of the variance, a portion which, while lower than that accounted for by the first factor in the analysis of the frontal tests alone, is still comparable with the 40 to 45% usually attributed to the g factor in classical research on intelligence. Generally, the tests load substantially and significantly on this general factor, the single exception being Verbal Span.

The fact that a single general factor accounts for such a substantial proportion of the variance of all 10 neuropsychological tests is consistent with the view that all the tests require frontal involvement to at least some extent: the traditional distinction between frontal and nonfrontal tests is one of degree, not of kind. The only result here that might, perhaps, be thought surprising, is the dissociation between Verbal Span and the other neuropsychological tests. Verbal Span, however, while requiring the deployment of attention, would appear to place little emphasis upon the initiation of nonhabitual action, strategy, or planning. This hypothesis is supported by observations from both neuropsychology and cognitive psychology. Neuropsychological reports on the effects of brain lesions on verbal span performance have almost invariably shown that patients with frontal damage are unimpaired on verbal span tasks (e.g., Luria, 1973; Owen et al., 1990; Risse et al., 1984; Stuss & Benson, 1986; Vilkki, 1985). Indeed, the association between poor Verbal Span and lesions to the language areas of the left inferior parietal lobe has long been known (Warrington, 1979; Zangwill, 1946), and it has been confirmed by recent meta-analyses (e.g., Vallar & Papagno, 1995) and PET studies (e.g., Paulesu, Frith, & Frackowiak, 1993). Further evidence that verbal span is independent of the executive functions of the frontal lobes comes from the findings of cognitive studies, which have shown that auditory-verbal memory span is supported by the functioning of the passive short-term phonological store, rather than the central executive component of working memory (for a discussion, see Vallar & Papagno, 1995). Taken together with the findings of the present study, these reports in the literature confirm the hypothesis that verbal span taps frontal functioning to a lesser extent than do many other neuropsychological tests.

As a methodological strategy, the correlational, factor analytic approach, although useful in the early stages of the development of knowledge in a field, has certain inherent limitations that render it incapable of resolving the more technical and specific issues that arise in a more advanced field of study.

Even within the factor analytic paradigm, it would be difficult to infer that performance on executive tests in general can be accounted for entirely in terms of a single general factor; indeed, in view of the varied nature of the activities required in neuropsychological tests, that is highly unlikely. The use of a small and varied battery of tests, as in the present study, creates a situation in which group factors (those accounting for common factor variance on only some of the tests) are unlikely to emerge. Group factors tend to be reliable only where test batteries (and subject samples) are very large.

The use of factor analytic methodology, however, raises questions of a more fundamental nature. Factors were defined by Thomson, one of the pioneers of factor analytic research, as "fluid descriptive mathematical coefficients" (Thomson, 1939, p. 299), which reflect both the manner in which the subjects in the study were selected and the composition of the test battery. On this basis, it can be argued that factor analysis is unsuited to the testing of hypotheses in general and those about the cognitive architecture in particular: Hypotheses are tested by gathering data whose interpretation is not in doubt; whereas the factors emerging from factor analysis, being "fluid" and "descriptive," can only be given interpretations that are themselves theoretical. A theory must be tested by data, not more theory.

The limitations of factor analysis for the purpose of refining a theory are well illustrated by a feature of Spearman's own data, some of which comprised schoolchildren's scores on school subjects such as Mathematics, Classics, and French. According to Spearman (1927), the g factor involves (a) "The apprehension of one's own experience" (p. 164), (b) "the eduction of relations" (p. 165), and (3) "the eduction of correlates" (p. 166). The variable with the highest loading on g was Classics; but it is difficult to sustain the argument that Classics requires education of relations and correlates any more than do, say, French, or Mathematics. Right from the inception of the factor analytic approach, therefore, there is an evident tension between theory and empirics, and variables are selected for their statistical qualities, rather than from conceptual analysis of the functions they measure.

The problems with the correlational and factor analytic approach, however, are by no means confined to the search for a single central executive; in fact, arguably, the fractionation hypothesis is, from a methodological point of view, even more problematic. Shallice and Burgess (1991) interpreted the performance of three head-injured patients who, while achieving very satisfactory scores on intelligence quotient (IQ) tests and performing adequately on some of the most commonly used frontal tests, nevertheless had very low scores on the Six Element and Multiple Errands tests, which are designed to measure the patient's ability to formulate (and modify) plans, by suggesting the need for the "fractionation of component processes undertaken by the Supervisory System" (p. 739). The difficulty with the fractionation approach is that, while it motivates the construction of tests of the patient's ability to cope with specified situations requiring the construction and execution of plans, there remains a potentially infinite set of other situations that might be considered which, if analysed, might lead to the construction of tests whose content is very different from the present tests. The assertion, therefore, that the posited abilities of, say, marker creation and triggering and goal articulation were still being tapped by the tests would require the collateral of supporting evidence. There is also the question of how fine-grained the fractionation should be: Is there, for example, a single planning function, or several? Does the triggering of markers always work in the same way?

In this area can be heard clear echoes of the issues that have bedevilled the psychology of intelligence for the past hundred years. While Spearman (1927) had argued that there was a single factor of general intelligence, the "g-factor," other psychometricians, especially in the US, eschewed the g-factor, preferring to divide human intellect into group factors. The difficulty with group factor solutions is that factors tend to proliferate alarmingly. Thurstone, in the 1930s and 1940s, identified eight primary mental abilities (Thurstone, 1938); and Guilford, in this Structure of Intellect model, described no fewer than 120 distinct abilities, of which he claimed to have demonstrated the existence of over ninety (Guilford, 1959). The parallel with the potential proliferation of fractions of executive functioning is obvious.

The notion of the central executive is, from a theoretical point of view, very attractive, because it makes sense of what would otherwise be puzzling phenomena (see, e.g., Baddeley, 1996). Even some of the most bizarre presentations of "frontal lobishness" (Benson, 1994) can readily be viewed as aspects of dysexecutive function.

Some theories, however, though cogent, explain too much—ex post facto. A term such as *executive functions* can so easily become a handy portmanteau, which can be enlarged indefinitely to accommodate any manner of task that could be thought of as having an "executive" element, a label, posing as an explanation. The consequences can be uncomfortable: for example, Duncan (1995) has suggested that g may largely reflect the functions of the frontal lobes, particularly goal-directed thought and action (see also Duncan, Burgess, & Emslie, 1995). Yet this interpretation, though entirely compatible with the meaning of "executive," seems to subsume the fractions of the executive described by Shallice and his colleagues under the single aegis of g, an implication that is not borne out by the good performance on general intelligence tests of patients who have great difficulty with the planning and execution of goal-directed behavior. The difficulty arises not only from the empirical underspecification of executive functioning, but also from the essentially fluid and descriptive nature of factors and the consequent inability of factor analytic research to adjudicate between competing alternatives.

It might be argued that the idea of a single executive is preferable to fractionation, because the former is the more parsimonious view. Reber (1985), however, questions the applicability of the parsimony principle to psychology, suggesting (pace Hamlet) that it is a heuristic more honoured in the breach than in the observance.

Philosophers warn against explanations that, in effect, place tiny human beings, or homunculi, inside the systems they are trying to explain. Kenny (1991) defines the homunculus fallacy as the taking of predicates whose normal application is to complete human beings or animals and wrongly applying them to parts of their bodies, thus evading the burden of proper explanation, and incurring the penalty of infinite regress. He illustrates his argument with Descartes' claim that the mind views the images of objects and deduces what must be "out there" in the environment, which begs the question of how the homunculus itself sees the image. Extending Kenny's argument to the concept of executive functioning, it could be argued that to say that the frontal lobes control other brain functions is to attach the human being predicates of choice and decision-making to a part of the body, without casting any real light on how these acts are achieved.

To most neuropsychologists, Kenny's arguments are less convincing when applied to the brain than were they to be applied to, say, the finger, or the foot, particularly since much more is known about the brain than in Descartes' time. As Lezak (1993) notes, it is reasonable, in seeking the manner in which human beings achieve the consciousness and self-awareness that seems to elude nonhuman primates, to turn for an explanation to that part of the brain which, in humans shows such a relatively marked increase in development. Kenny's point about circularity and infinite regress is well taken, however: it is necessary to unpack the concept of executive functioning to produce independent specifications of what it involves. It is certainly insufficient to say, by analogy with Edwin Boring's (1923) notorious circular definition of intelligence, that executive functioning is what executive tests measure: for the question at issue is what, precisely, do executive tests measure? In any potentially homuncular theory, it is necessary to preempt the potential problem of circularity by operationising each hypothetical function, giving each an empirical trademark.

In recent years, there have been several attempts to clarify the various supposed aspects of executive functijoning, so that they can be put to the empiricat test (e.g., Baddeley, 1996; Shallice & Burgess, 1991). There are still many pressing questions to be answered, however, not least of which is how the frontal lobes effect decision-making. There is certainly the need to replace the homunculus with a clear mechanism, whose properties can be demonstrated. To effect such a translation of decision-making, for example, one may speculate that the frontal lobes function as a perpetually live network, the state of which at any time depends upon many factors, including the activation set up by the experiential history of the individual. In such a network, there may be tensions arising from rivalry among competing routes. Perhaps, when certain critical thresholds are reached by a process of summation, there occurs a sudden change of state, or "coagulation" of functions, whereby certain routes and patterns take over and others are blocked. Such a view has at least the merit of accounting for the marked individual differences in the sequelae of frontal lobe damage that have been reported in the literature.

On many occasions, philosophers have rightly warned empirical scientists against drawing unwarranted conclusions from their findings. On the other hand, what is needed are concepts that generate, rather than stifle, enquiry. In our view, the concept of a single central executive has already stimulated many productive lines of research, and will continue to do so in the foreseeable future. What is required now is refinement, not abandonment.

CONCLUSION

This study has shown that some of the most common neuropsychological tests of executive functioning do appear to tap a common core of abilities. Nevertheless, the limitations of the correlational, factor-analytic approach point to the need to find the empirical fingerprints of the hypothetical processes involved in executive functioning. There are different ways of achieving this, motivated by different theoretical perspectives. The data from the present study suggest that the concept of a single executive will continue to be useful until displaced by a better conceptualisation (Baddeley, 1996; Baddeley & Della Sala, 1996; Della Sala & Logie, 1998).

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