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Performance on tests of frontal lobe function reflect general intellectual ability

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Abstract

Recent studies have indicated that performance on tests of frontal lobe function are highly associated with general intellectual ability (*g*). Some authors have even claimed that the available evidence does not support a more specific account of frontal lobe function than to provide a general intellectual function for the performance of goal directed tasks. We examined the relationship between performance on the WAIS-R (as a measure of *g*) and performance on standard tests of frontal lobe function in 123 healthy individuals. Our results demonstrate that in healthy individuals (i) performance on the most popular tests of frontal lobe function shares significant variance, and (ii) a large proportion of that shared variance is highly associated with performance on the Wechsler Adult Intelligence Scales-Revised (WAIS-R), so that the tests are similar to the extent that they measure *g*. Performance on the Modified Card Sorting Test (MCST), however, is not related to *g*. The results support the claim that many tests of frontal lobe function measure primarily a non-specific intellectual function but also indicate that some tests, like the MCST, may be assessing more specific cognitive operations.

Keywords: General intellectual ability (*g*); Intelligence; Frontal lobe function

1. Introduction

Although there are many neuropsychological tests currently in clinical use that appear to be sensitive to frontal lobe dysfunction, there is no consensus as to the psychological functions these tests are measuring. Neuropsychological tests of frontal lobe function are said to measure many apparently different functions, including inhibition of automatic responses, spontaneity, perseveration, planning, attention, monitoring, fluency, and abstract reasoning. A number of investigators have attempted to make sense of the wide range of behavioural disturbances following damage to the frontal lobes, and each investigator appears to have emphasised discrete aspects of these disturbances. Many authors have suggested that the frontal lobes carry out the functions associated with working memory, and allow behaviour to be regulated by internal representations of the external world. Goldman-Rakic [19], Passingham [46], and Petrides [48], e.g. have all suggested different mechanisms for ways in which the frontal lobes could mediate the functions of working memory. The inability of individuals with lesions to the frontal lobes to use internal representation to guide behaviour was vividly described by Lhermite [31]. Fuster [17] emphasised the role of the frontal lobes in the control of sequential behaviours over time. Other investigators have suggested that the role of the frontal lobes is to select the response that is most appropriate for the current context, but the basis on which the frontal lobes makes the selection appears unclear. Passingham [45], e.g. has suggested that the frontal lobes select behaviours during the performance of a novel task, but contribute to behaviour much less when the task is well rehearsed. Nauta [38] wrote that frontal systems selected the appropriate response by assessing the information from the external and internal environments. More recently, Damasio [9] has stressed the importance of cues from the internal environment, by suggesting that the emotional response to a situation guides the selection of appropriate behaviours. Individuals who, for some reason, do not produce an emotional response to what is usually considered an emotional situation, often select an inappropriate behaviour. According to Damasio, the ventromedial frontal lobe is necessary to guide behaviour selection on the basis of an emotional response [9].

Some investigators have suggested roles that appear to be less precisely defined than the roles mentioned above. Luria [32] wrote that the frontal lobes were responsible for

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the planning, coordination and monitoring of behaviour. The notion of the frontal lobes having an "executive" function has grown steadily over the past few years, but this notion remains poorly defined. Shallice [52] has proposed that the frontal lobes control and supervise the allocation of attention, and thus, control the production of behaviour.

Many of these theories of frontal lobe function are not mutually incompatible, and it is not unlikely that all these theories emphasise different functions, or component operations, carried out by the frontal lobes. Despite the variety of opinions on the role of the frontal lobes in the regulation of behaviour, there is some agreement that the different areas of the frontal lobes carry out separate component operations. There have been many attempts to parse and define these component operations. Some investigators have used correlations to parse out the shared cognitive components of different tasks. The rationale underlying the use of correlations is that if two or more tasks are correlated, the shared variance could be due to shared cognitive operations that is required to successfully complete the tasks. Perret [47] used this method to investigate the shared cognitive operations in the Stroop test and the verbal fluency task. On the basis of a modest correlation between the scores on the two tests, he concluded that both tests shared at least one cognitive operation. He suggested that both tasks required the inhibition of automatic responses. However, Perret's results are difficult to interpret. It is not uncommon for scores on different tests to correlate and Spearman [55] showed that to some extent, performance on all tasks correlate, and an individual who performs well on one task will likely perform well on another task, whether they share a cognitive operation or not. Spearman went on to claim that tasks that intercorrelate do so because they measure a non-specific general intellectual ability or *g* [55]. Intellectual ability is not a cognitive operation, but a non-specific factor that affects the performance of most tasks. There is strong evidence that performance on many neuropsychological tests of frontal lobe function intercorrelate [5,8,14,29,44,54]. These intercorrelations could indicate shared cognitive operations, or they could indicate that tests of frontal lobe function are similar to the extent that they measure *g*.

The relationship between frontal lobe function and intellectual ability has puzzled investigators for many years. The influential work of Hebb and Penfield [23] and Teuber [58] appeared to make it quite clear that frontal lobe functions like planning and monitoring of behaviours could be severely impaired despite preserved intellectual ability. However, these conclusions were drawn on the basis of performance on the Wechsler intelligences scales. One approach to the measurement of intellectual ability that has received considerable attention distinguishes between the extent of accumulated knowledge (crystallised intelligence), and current ability (fluid intelligence) [24,25]. The Wechsler scales contain many subtests that assess crystallised over fluid intelligence, and tests of crystallised intelligence may not measure current intellectual ability in individuals with lesions of the frontal lobes. Indeed, Warrington et al. [60] reported that the scores on the Wechsler adult intelligence scale (WAIS) of individuals with unilateral parietal, temporal, occipital or frontal lobe damage were similar. Tests of fluid intelligence, however, may be more sensitive to frontal lobe dysfunction. Duncan et al. [12] demonstrated that individuals with lesions to the frontal lobes perform well on the Wechsler Adult Intelligence Scales-Revised (WAIS-R), yet present with lower *g* scores when *g* is measured by a test of fluid intelligence. According to Duncan et al. [12], not only is general intellectual ability an important factor influencing the performance on tests of frontal lobe function, but these tests measure frontal lobe function to the extent that they measure *g*. Consequently, neuropsychological tests of frontal lobe function should provide extremely good measures of *g*. Duncan [11] has argued that tests of frontal lobe function, and tests of general intellectual ability for healthy people, essentially test the ability to formulate the appropriate goal-directed behaviours in novel situations. In fact, Duncan et al. [13] have demonstrated that individuals with lesions to the frontal lobes are significantly impaired on a goal neglect task, that performance on the task is highly correlated with *g*, and that the performance of healthy individuals at the low end of the *g* distribution on the goal neglect task is similar to the performance of individuals with lesions to the frontal lobes.

The WAIS-R remains the most clinically popular test of intellectual ability. Lezak [30] has described it as the "workhorse of neuropsychological assessment". Unlike individuals with lesions to the frontal lobes, healthy individuals show no discrepancy between scores on tests of crystallised and fluid intelligence, and scores on the WAIS-R provide an extremely good measure of *g* in the healthy population [28]. The relationship between the performance on the WAIS-R and performance on tasks of frontal lobe function remains to be explored in healthy individuals. We administered a battery of neuropsychological tests sensitive to frontal lobe dysfunction, along with the WAIS-R, to 123 healthy individuals. The neuropsychological tests chosen were tests that are often used to assess frontal lobe function. It is unlikely that performance on any of these tests is selectively sensitive to frontal lobe function [51], but it is likely that frontal lobe activity contributes substantially to the successful performance on these tests. On the basis of Duncan's hypothesis that general intellectual ability consists mostly of those psychological functions that are usually associated with frontal lobe function [11], we predicted that performance on all tests of frontal function would share significant variance, and that a large proportion of that shared variance would be highly associated with performance on the WAIS-R.

2. Methods

2.1. Participants

Participants ($n = 123$) were recruited from the community and received an honorarium for their participation.

Table 1
Percentage of participants in our sample ($n = 123$) and of Great Britain (according to the 1981 Census) in each of the five socio-economic classes

	Social class				
	1	2	3	4	5
Sample	5	30	43	12	10
Great Britain	4	22	48	19	7

Table 2
Percentage of participants in our sample ($n = 123$) and of Great Britain (according to the 1981 Census) according to age and sex

	Age			Sex	
	16–34	35–59	>60	Male	Female
Sample	44	46	10	53	47
Great Britain	37	45	18	48	52

Potential participants were excluded if they had ever been hospitalised for a mental illness, had ever had alcoholism, a serious head injury, a stroke or a neurological condition, or if they were currently receiving medical treatment for anxiety or depression. The demographic characteristics of the sample are shown in Tables 1–3, and are compared to the demographic characteristics of the population of Great Britain at the 1981 Census. The mean (±S.D.) age of the participants was 40.3 (±14.0) years, and ranged from 16 to 75 years. The definition of social class was based on occupation, as defined by the Office of Population Censuses and Surveys [42]. The social classes were: I (professional), II (managerial), III (skilled, non-manual and manual), IV (partly skilled) and V (unskilled). The number of years of education was calculated by adding the total number of years of full-time education, and allowing 0.25 year for each year of part-time education.

2.2. Procedure

Each participant was administered the full version of the WAIS-R [61]. In all the correlations carried out, performance on the WAIS-R is not the full scale IQ, but the sum of the non-age graded scores. In that way, the contributions of intellectual ability can be examined independently from the contributions of age. In addition, each participant was administered a battery of neuropsychological tests that are often used to measure frontal lobe function. Each one of these tests is described briefly.

Table 3
Performance on WAIS-R and years of education of participants

	Mean (S.D.)	Range
FSIQ	105.35 (13.71)	70–141
VIQ	105.72 (13.40)	72–143
PIQ	104.00 (14.06)	68–140
Education	12.84 (2.77)	8–20

2.2.1. Verbal fluency

The controlled oral word association test (COWAT), or verbal fluency task, was administered as described by Benton and Hamsher [2,3] and Goodglass and Kaplan [20] to assess word generation (language and executive functions). The letters F, A and S were used, and participants were asked to generate as many words as possible for each letter. A duration of 60 s were allowed for each letter. The score is the total number of words correctly produced over the 3 min period. This task is thought by many to be very sensitive to frontal lobe dysfunction [43,58]. Performance on verbal fluency is thought to reflect behavioural spontaneity, the ability to guide behaviour over the period of 1 min by a command, and strategy formation for retrieval [49]. Impairment on the task is associated with the lateral, or the inferior prefrontal region, especially of the left hemisphere [56].

2.2.2. Modified Card Sorting Test

The Modified Card Sorting Test (MCST) is thought to measure the ability to form concepts and to shift cognitive set. Like the COWAT, it is thought to assess the integrity of frontal lobe function [43]. Participants are required to sort cards according to specific dimensions (colour, number and shape), and to change the sorting rule on a cue provided by the examiner. It was administered and scored according to the method described by Nelson [39]. We chose the percent perseverative error score, which appears to be the score that is most sensitive to frontal lobe dysfunction. The test is said to assess behavioural flexibility, the ability to respond to environmental cues and feedback, and conceptual and abstract function. The locus of impairment is still unresolved, but the superior dorsolateral frontal cortex, perhaps Brodman's area 9, especially in the left hemisphere, has been suggested for the Wisconsin Card Sorting Test [33–35,57].

2.2.3. The Stroop test

For the Stroop test, we used the interference score, because it is this score that is thought to be sensitive to frontal lobe dysfunction. The Stroop test is thought to measure impaired response inhibition and attention. Whereas there is general agreement that lesions to the frontal lobes impair performance on this task, there is no agreement as to whether lesions to the left [47] or right [59] hemispheres cause greater impairment.

2.2.4. Tower of London

The Tower of London (TOL) is a modification by Shallice [52] of the Tower of Hanoi. The total score was calculated in the manner suggested by Shallice. The TOL is thought to measure strategy generation, planning and anticipatory processing (lookahead). It is thought to be sensitive to lesions of the left frontal lobe.

2.2.5. Cognitive estimation

The cognitive estimates test, thought to measure strategy planning, requires that the participant verbally answer 10 questions. More than likely, the participant will not know the exact answer to the question, but has to provide the best guess possible. The scoring system attempts to quantify the extent to which the participant's score deviates from the norm. For example, they could be asked what is the height of a double decker bus. We used a 10 question version described by Shoqeirat et al. [54] and investigated more intensively by O'Carroll et al. [41]. This version was adapted from the original version by Shallice and Evans [53]. The test is said to be sensitive to lesions in the right and left frontal lobes [53].

2.2.6. Paced auditory serial addition task (PASAT)

Although not usually considered as strictly a test of frontal lobe function, PASAT is sensitive to problems with attention and working memory, functions usually associated with the frontal lobes. It was, therefore, included in the test battery. We used the original four-trial version of Gronwall and Wrightson [21], which has digits that are recorded at a rate of one every 2.4, 2.0, 1.6 and 1.2 s. The score used is the number of correct responses on all four trials. Performance on this task is known to be highly associated with the attention/concentration factor of the WAIS-R [7].

2.2.7. Uses for common objects

In the uses for common objects task, the participants are required to give as many uses as possible for two items: a bottle and a brick. They are given 3 min for each item. The score is the total number of correct items that they report. Repetitions, or uses that are thought to be too similar to a previous response, are not counted. Like the verbal fluency task, this task is thought to measure behavioural spontaneity and strategy planning. There is evidence that individuals with lesions to the frontal lobes are impaired on this task [6,62].

3. Results

The score chosen to summarise performance on the WAIS-R was the sum of the non-age graded subtests of the WAIS-R. The interference score of the Stroop test and the percent perseverative score on the MCST, both ratio scores, were transformed to their arcsin square root to build the Pearson correlation matrix. Many correlations were carried out, but no Bonferroni-type corrections to the significance level were applied, because the issue of interest was the number of significant correlations in the presence or absence of certain covariates. We did not dwell on nor emphasise any particular correlation.

Performance on all neuropsychological tests of frontal lobe function correlated significantly with performance on the WAIS-R. Although many of the tests are significantly correlated with one another, the correlations are not very high (Table 4). If correlations with scores on the WAIS-R are omitted, and only correlations involving the neuropsychological tests of frontal function are considered, we find 13 significant correlations, ranging between 0.2 to about 0.5.

When the same correlation matrix is covaried with performance on the WAIS-R, most correlations decrease and in fact, only four remain statistically significant (Table 5). Although scores on these neuropsychological tests are similar

Table 4
Pearson r correlations between performances on tests of frontal lobe function in healthy participants ($n = 123$)[a]

	WAIS-R	Tower	Estimates	Objects	Stroop	MCST	Fluency
Tower	**+0.3770**						
Estimates	**−0.5764**	**−0.2129**					
Objects	**+0.4816**	**+0.2455**	**−0.3621**				
Stroop[b]	**+0.3816**	+0.1758	**−0.2324**	+0.1402			
MCST[c]	**−0.2396**	−0.0156	+0.1350	−0.1490	−0.0704		
Fluency	**+0.5313**	**+0.2958**	**−0.4134**	**+0.4751**	**+0.3274**	−0.0622	
PASAT	**+0.6258**	**+0.3846**	**−0.4739**	**+0.4027**	**+0.3529**	−0.1102	**+0.4652**

[a] Pearson r correlations in bold typeface are all significant at the 0.05 level.
[b] Interference score, arcsin square root transformation.
[c] Percent perseverative errors, arcsin square root transformation.

Table 5
Pearson r correlations between performances on tests of frontal lobe function, covaried with performance on the WAIS-R, in healthy participants ($n = 123$)[a]

	Tower	Estimates	Objects	Stroop	MCST	Fluency
Estimates	−0.0302					
Objects	+0.1541	−0.0875				
Stroop[b]	+0.0970	−0.1250	−0.0535			
MCST[c]	+0.0952	+0.0471	−0.0977	+0.0028		
Fluency	+0.0701	−0.0701	**+0.2650**	+0.1732	−0.0058	
PASAT	**+0.3144**	**−0.1864**	+0.1483	+0.1591	+0.0303	**+0.2167**

[a] Pearson r correlations in bold typeface are all significant at the 0.05 level.
[b] Interference score, arcsin square root transformation.
[c] Percent perseverative errors, arcsin square root transformation.

Table 6
Pearson r correlations between performances on tests of frontal lobe function, covaried with age, in healthy participants ($n = 123$)[a]

	Tower	Estimates	Objects	Stroop	MCST	Fluency
Estimates	**−0.1982**					
Objects	**+0.2822**	**−0.2998**				
Stroop[b]	+0.1773	**−0.2790**	+0.1050			
MCST[c]	+0.0260	+0.1579	−0.1946	−0.0383		
Fluency	**+0.2391**	**−0.2315**	**+0.4519**	**+0.3265**	−0.1398	
PASAT	**+0.4293**	**−0.4459**	**+0.3835**	**+0.2999**	−0.1023	**+0.4768**

[a] Pearson r correlations in bold typeface are all significant at the 0.05 level.
[b] Interference score, arcsin square root transformation.
[c] Percent perseverative errors, arcsin square root transformation.

Table 7
Rotated factor matrix (Varimax rotation) from principal component analysis[a]

	Factor 1	Factor 2
Tower	**0.61**	0.20
Estimates	**−0.60**	0.30
Objects	**0.63**	−0.31
Stroop[b]	**0.54**	0.03
MCST[c]	−0.01	**0.92**
Fluency	**0.75**	−0.06
PASAT	**0.78**	−0.09

[a] Pearson r correlations in bold typeface are all significant at the 0.05 level.
[b] Interference score, arcsin square root transformation.
[c] Percent perseverative errors, arcsin square root transformation.

to the extent that they measure general intellectual ability, the shared variance could be due to age. When the correlation matrix is covaried with age, and not performance on the WAIS-R, there is very little change from the original correlation matrix (Table 6). The shared variance on the scores for these neuropsychological tests is not accounted for by age, but is mostly accounted for by performance on the WAIS-R.

A principal components analysis was carried out with the scores from all tests of frontal function (Table 7). Varimax rotation yielded 2 factors (eigenvalue > 1.0), that accounted for 52.8% of the total variance. Scores from most tests loaded highly on the first factor, and not on the second. The only measure to load highly on the second factor was the percent perseverative errors in the MCST. Performance on both the PASAT and fluency tests correlated most highly with scores on factor 1. As displayed in Table 8, the score for factor 1 correlated very highly with performance on the WAIS-R (0.73, $P < 0.001$), and equally well with performance on the verbal and performance scales. The score for factor 2 correlated significantly, but much less than did factor 1, with performance on the WAIS-R. Whereas factor 2 was significantly associated with performance on the verbal scale, it was not significantly associated with performance on the performance scale. Both correlations of factor 2 with the WAIS-R and the verbal scale are negative, reflecting the fact that the main component of factor 2 is the percent perseverative error score on the WCST, whereas the sums of the WAIS-R scales reflect the number of correct responses.

Table 8
Pearson r correlations between performances on the WAIS-R (sum of scaled scores, before age-grading) and the factor scores for tests of frontal lobe function, in healthy participants ($n = 123$)[a]

	Factor 1	Factor 2
FSIQ	**0.73** ($P < 0.001$)	**−0.26** ($P < 0.005$)
VIQ	**0.66** ($P < 0.001$)	**−0.31** ($P < 0.001$)
PIQ	**0.66** ($P < 0.001$)	−0.14 ($P = 0.111$)

[a] The significance value is provided below the r value. Pearson r correlations in bold typeface are all significant at the 0.05 level.

4. Discussion

Our results demonstrate that in the healthy population, general intellectual ability accounts for a large proportion of the shared variance between neuropsychological tests of frontal lobe function. General intellectual ability, therefore, contributes substantially to the performance on neuropsychological tests sensitive to frontal lobe dysfunction. The results also show that within the healthy population, there may be some variance, independent of general intellectual ability, in the more specific abilities required to complete some tests of frontal function. These results resemble those previously obtained by Duncan et al. [14], but the two studies are different in three main ways. The present study examined the performance of healthy individuals and not individuals with head injury, the sample size was much larger (123 as opposed to 24), and the test of intellectual function was the full WAIS-R. Many factors are likely to contribute to the performance of these neuropsychological tests of frontal lobe function. Successful performance on these tests will require the recruitment of specific cognitive operations. It is likely that some cognitive operations will be required for the successful performance of more than one test, so that variance in the ability to carry out that cognitive operation will contribute to the variance of more than one test, and would contribute to the shared variance between tests. It would, therefore, be expected that the performance on many of these tests would show correlations with one another. As expected, our results demonstrate clearly that all tests do display some shared variance, but this shared variance was low. Not more than 25% of the variance was shared by these popular neuropsychological tests of frontal lobe function. These correlations found in healthy individuals are similar to correlations reported in studies examining individuals with lesions to the frontal lobes [5,8,29,54], or individuals with head injury [14], and the healthy elderly [44].

One explanation for the low correlations between the tests is that these tests have low specificity for frontal lobe functions, and that the contribution of frontal lobe activity to the performance of these tests is low. The shared variance between these tests could represent the variance due to the shared frontal functions. However, not only does the performance on most neuropsychological tests intercorrelate, but performance on all neuropsychological tests also correlate with performance on the WAIS-R. At least some of the variance in the performance of these tests can be accounted for by *g*. This result is not surprising, given that individuals who perform well on one test will also tend to perform well on other tests [55]. The more important issue to be resolved is whether the shared variance between individuals tests of frontal lobe function is the same variance that appears to be shared with *g*. Does *g* account for the shared variance between neuropsychological tests of frontal lobe function? The results of our study indicate that it might. When the correlation matrix of tests of neuropsychological function is covaried with performance on the WAIS-R, but not age, most of the significant correlations between test scores disappear.

Our results demonstrate clearly that general intellectual ability, and not age, is a major contributor to the shared variance between these tests. These results are similar to those previously reported by Duncan et al. [14], who found that partialling out the scores on a measure of fluid intelligence (the Culture Fair Test) reduced the correlations between performance scores on tests of frontal lobe function in 24 individuals with head injury.

In addition, six of the seven neuropsychological tests load highly on one factor. The score for this factor correlates extremely highly with performance on the WAIS-R. These results have two clear implications: (i) in healthy individuals, many of the most popular neuropsychological tests of frontal lobe function are similar to the extent that they measure *g*, and (ii) a battery of these tests provides a very good measure of *g*. These results are consistent with recent neuroimaging studies demonstrating the activation of restricted areas of the frontal lobes during the performance of tests of frontal lobe function [15], and tests of fluid intelligence [16,50].

These results emphasise the importance of considering more than two tests of neuropsychological function when using the correlational method to parse out shared cognitive components. Perret [47], for example concluded that the shared variance between performance on the Stroop test and on verbal fluency was likely a shared specific cognitive component, which he hypothesised to be the inhibition of an automatic response. However, our results indicate that the shared variance between scores on verbal fluency and the Stroop test is also shared with scores on the Tower of London, PASAT, cognitive estimates, and uses for common objects, and with performance on the WAIS-R, so that it may be premature to speculate on the specific shared cognitive components that may be recruited to perform these tasks on the basis of shared variance. Intellectual ability is a non-specific and unsatisfactory explanation for the shared variation between tasks, but it does have the advantage of being a single, simple explanation for a considerable proportion of the variance, and any future attempt to account for intercorrelations between tasks of frontal lobe function by proposing more specific processes should first demonstrate that *g* alone does not account for the entire variance.

According to Duncan, it is precisely because these tests are related to general intellectual ability that they are sensitive to frontal lobe dysfunction. Duncan has argued that those skills long thought to be components of *g* (problem-solving, planning, control of behaviour under conditions of novelty) are also skills that are thought to be mediated by the frontal lobes. Duncan found that individuals with lesions to the frontal lobes showed a large discrepancy between scores on tests of crystallised intelligence (the WAIS-R) and scores on a test of fluid intelligence (Cattell's Culture Fair Test). These individuals had high, and perhaps unaltered scores on the WAIS-R, but scores on the Culture Fair Test were much lower than predicted by their performance on the WAIS-R. Duncan argues that tests of frontal lobe function provide good measures of intellectual ability. Our results support Duncan's interpretation. Six of the seven tests of frontal lobe function were similar to the extent that they measured general intellectual ability. Because the participants in our study were all healthy, there should be no discrepancy between scores on tests of crystallised and fluid intelligence, and scores on the WAIS-R should provide a good estimate of general intelligence.

In their brief historical review, Reitan and Wolfson [51] clearly demonstrate that the association between frontal lobe functions and general intelligence has a long history (relative to the history of neuropsychology). Early reports by Gelb and Goldstein [18] and Ackerly [1] had suggested that frontal lobe lesions impaired intellectual function, as assessed by problem-solving tasks, and Brickner [4], Jefferson [26,27] and Halstead [22] later argued that the frontal lobes were the brain regions underlying intellectual function. Indeed, the wish to prevent emotional arousal interfering with intellectual function was part of the rationale for the prefrontal leucotomies performed by Moniz [36,37]. Reitan and Wolfson [51] argue that individuals with damage to the frontal lobes usually present with generalised impairment on tasks, in contrast to individuals with non-frontal pathology, who present with much more specific impairments. These authors argue that in the absence of better evidence, it is difficult to suggest more precise functions for the frontal lobes [51]. Our results provide some support for their argument by demonstrating that the shared variance in the performance on tests of frontal lobe function can be largely accounted for by a non-specific factor like *g*. However, two parts of our results also demonstrate that *g* does not account for the entire shared variance. First, performance on the MCST is not accounted for by *g*, and may indicate a more specific cognitive operation. Second, performance on some tests remained significantly correlated even after covarying with performance on the WAIS-R. It is possible that this common variance indicates shared specific cognitive operations.

A few points should be borne in mind when interpreting these results. First, the extent to which the neuropsychological tests chosen for this study are tests of frontal lobe function is still not clearly resolved. Not one of these tests is specifically sensitive to frontal lobe dysfunction. At best, frontal lobe activity makes a larger contribution to the successful performance on these tests than on other types of tasks. Second, the current study only involved healthy individuals. Specific cognitive components may become more apparent if neurologically impaired individuals were tested in the same way. Third, general intellectual ability accounted for only a tiny proportion of the variance in the percent perseverative errors on the MCST (see also Obonsawin et al. [40]), and this score did not share any variance with other scores. According to Nelson [39], this measure is a very good indicator of frontal lobe dysfunction, but there has been very little investigation of this issue [10]. The extent to which perseveration on the MCST reflects frontal lobe dysfunction requires urgent investigation.

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References

[1] Ackerly SS. Instinctive, emotional and medical changes following prefrontal lobe extirpation. American Journal of Psychiatry 1935;92:717–29.

[2] Benton AL, Hamsher K. Multilingual aphasia examination. Iowa City: University of Iowa, 1976.

[3] Benton AL, Hamsher K. Manual for multilingual aphasia examination. Iowa City: University of Iowa, 1978.

[4] Brickner RM. Bilateral frontal lobectomy: follow-up report of a case. Archives of Neurology and Psychiatry 1936;41:580–5.

[5] Burgess PW, Shallice T. Fractionnement du syndrome frontal. Revue de Neuropsychologie 1994;4:345–70.

[6] Butler RW, Rorsman II, Hill JM, Tuma R. The effects of frontal brain impairment on fluency: simple and complex paradigms. Neuropsychology 1993;7:519–29.

[7] Crawford JR, Obonsawin MC, Allan KM. PASAT and components of WAIS-R performance: convergent and discriminant validity. Neuropsychological Rehabilitation 1998;8:255–72.

[8] Crockett D, Bilsker D, Hurwitz T, Kozak J. Clinical utility of three measures of frontal dysfunction in neuropsychiatric samples. International Journal of Neuroscience 1986;30:241–8.

[9] Damasio AR. On some functions of the human prefrontal cortex. In: Grafman J, Holyoak KJ, Boller F, editors. Structure and functions of the human prefrontal cortex. New York: The New York Academy of Sciences, 1995. p. 241–51.

[10] de Zubicaray G, Ashton R. Nelson's (1976) modified card sorting test: a review. The Clinical Neuropsychologist 1996;10:245–54.

[11] Duncan J. Attention, intelligence, and the frontal lobes. In: Gazzaniga MS, editor. The Cognitive neurosciences. Cambridge: MIT Press, 1995. p. 721–33.

[12] Duncan J, Burgess P, Emslie H. Fluid intelligence after frontal lobe lesions. Neuropsychologia 1995;33:261–8.

[13] Duncan J, Emslie H, Williams P, Johnson R, Freer C. Intelligence and the frontal lobe: the organization of goal-directed behavior. Cognitive Psychology 1996;30:257–303.

[14] Duncan J, Johnson R, Swales M, Freer C. Frontal lobe deficits after head injury: unity and diversity of function. Cognitive Neuropsychology 1997;14:713–41.

[15] Duncan J, Owen AM. Common regions of the human frontal lobe recruited by diverse cognitive demands. Trends in Neurosciences 2000;23:475–83.

[16] Duncan J, Seitz RJ, Kolodny J, Bor D, Herzog H, Ahmed A, et al. A neural basis for general intelligence. Science 2000;289:457–60.

[17] Fuster JM. The prefrontal cortex. New York: Raven Press, 1980.

[18] Gelb A, Goldstein K. Ueber Farbennamenamnesie. Psychologie Forschrift 1925;6:127–86.

[19] Goldman-Rakic PS. Circuitry of primate prefrontal cortex and regulation of behavior by representational memory. In: Plum F, editor. Handbook of physiology. The nervous system, higher functions of the brain. Bethesda: American Physiological Society, 1987. p. 373–417.

[20] Goodglass H, Kaplan E. An assessment of aphasia and related disorders. Philadelphia: Lea and Fibiger, 1972.

[21] Gronwall DM, Wrightson P. Delayed recovery of intellectual function after minor head injury. Lancet 1974;9:605–9.

[22] Halstead WC. Brain and intelligence: a quantitative study of the frontal lobes. Chicago: University of Chicago Press, 1947.

[23] Hebb DO, Penfield W. Human behavior after extensive removal from the frontal lobes. Archives of Neurology and Psychiatry 1940;44: 421–38.

[24] Horn JL. Remodelling old model of intelligence. In: Wolman BB, editor. Handbook of intelligence. New York: Wiley, 1985. p. 267–300.

[25] Horn JL, Cattell RB. Refinement and test of the theory of fluid and crystallized intelligence. Journal of Educational Psychology 1966;57:253–70.

[26] Jefferson G. Left frontal lobectomy. Proceedings of the Royal Society of Medicine 1937a;30:851–3.

[27] Jefferson G. Removal of right or left frontal lobes in man. Medical Journal 1937;2:199–206.

[28] Kaufman AS. Assessing adolescent and adult intelligence. Boston: Allyn and Bacon, 1990.

[29] Kopelman MD. Frontal dysfunction and memory deficits in the alcoholic Korsakoff syndrome and Alzheimer-type dementia. Brain 1991;114:117–37.

[30] Lezak MD. Neuropsychological tests and assessment techniques. In: Boller F, Grafman J, editors. Handbook of neuropsychology, vol. 1. Amsterdam: Elsevier, 1988. p. 47–68.

[31] Lhermite F. Human autonomy and the frontal lobes. Part II. Patient behavior in complex and social situations: the "environmental dependency" syndrome. Annals of Neurology 1986;19:335–43.

[32] Luria AR. The working brain. Harmondsworth, Middlesex: Penguin, 1973.

[33] Marenco S, Coppola R, Daniel DG, Zigun JR, Weinberger DR. Regional cerebral blood flow during the Wisconsin card sorting test in normal subjects studied by xenon-133 dynamic SPECT: comparison of absolute values, percent distribution values, and covariance analysis. Psychiatry Research 1993;50:177–92.
[34] Milner B. Effects of different brain lesions on card sorting: the role of the frontal lobes. Archives of Neurology 1963;9:100–10.
[35] Mountain MA, Snow WG. Wisconsin card sorting test as a measure of frontal pathology: a review. The Clinical Neuropsychologist 1993;7:108–18.
[36] Moniz E. Les premières tentatives opératoires dans le traitement de certaines psychoses. Encéphale 1936;91:1–29.
[37] Moniz E. Prefrontal leukotomy in treatment of mental disorders. American Journal of Psychiatry 1937;93:1379–85.
[38] Nauta WJH. The problem of the frontal lobe: a reinterpretation. Journal of Psychiatric Research 1971;8:167–87.
[39] Nelson HE. A modified card sorting test sensitive to frontal lobe defects. Cortex 1976;12:313–24.
[40] Obonsawin MC, Crawford JR, Page J, Chalmers P, Low G, Marsh P. Performance on the modified card sorting test by normal, healthy individuals: relationship to general intellectual ability and demographic variables. British Journal of Clinical Psychology 1999;38:27–41.
[41] O'Carroll R, Egan V, MacKenzie DM. Assessing cognitive estimation. British Journal of Clinical Psychology 1994;33:193–7.
[42] Office of Population Censuses and Surveys. Standard Occupational Classification, Vol. 3. Social Classifications and Coding Methodology. London: HMSO, 1991.
[43] Parker DM, Crawford JR. Assessment of frontal lobe dysfunction. In: Crawford JR, Parker DM, McKinlay WW, editors. A handbook of neuropsychological assessment. Hove: Lawrence Erlbaum Associates, 1992. p. 267–91.
[44] Parkin AJ, Lawrence A. A dissociation in the relation between memory tasks and frontal lobe tests in the normal elderly. Neuropsychologia 1994;32:1523–32.
[45] Passingham RE. The frontal lobes and voluntary action. Oxford: Oxford University Press, 1993.
[46] Passingham RE. Attention to action. In: Roberts AC, Robbins TW, Weiskrantz L, editors. Executive and cognitive functions in the prefrontal cortex. London: Royal Society of London, 1996. p. 1473–9.
[47] Perret E. The left frontal lobe of man and the suppression of habitual responses in verbal categorical behaviour. Neuropsychologia 1974;12:323–30.
[48] Petrides M. Lateral frontal cortical contribution to memory. Seminars in the Neurosciences 1996;8:57–63.
[49] Phillips LH, Della Salla S, Trivelli C. Fluency deficits in patients with Alzheimer's disease and frontal lobe lesions. European Journal of Neurology 1996;3:102–8.
[50] Prabhakaran V, Smith JAL, Desmond JE, Glover GH, Gabrieli JDE. Neural substrates of fluid reasoning: an fMRI study of neocortical activation during performance of the Raven's progressive matrices test. Cognitive Psychology 1997;33:43–63.
[51] Reitan RM, Wolfson D. A selective and critical review of neuropsychological deficits and the frontal lobes. Neuropsychology Review 1994;4:161–98.
[52] Shallice T. Specific impairments of planning. Philosophical Transactions of the Royal Society of London B 1982;298:199–209.
[53] Shallice T, Evans M. The involvement of the frontal lobes in cognitive estimation. Cortex 1978;14:294–303.
[54] Shoqeirat MA, Mayes A, MacDonald C, Meudell P, Pickering A. Performance on tests sensitive to frontal lobe lesions by patients with organic amnesia: Leng, performance on tests sensitive to frontal lobe lesions by patients with organic amnesia: Leng & Parkin revisited. British Journal of Clinical Psychology 1990;29:401–8.
[55] Spearman C. The abilities of man. New York: Macmillan, 1927.
[56] Stuss DT, Alexander MP, Hamer L, Palumbo C, Dempster R, Binns M, et al. The effects of focal anterior and posterior brain lesions on verbal fluency. Journal of the International Neuropsychological Society 1998;4:265–78.
[57] Stuss DT, Levine B, Alexander MP, Hong J, Palumbo C, Hamer L, et al. Wisconsin card sorting test performance in patients with focal frontal and posterior brain damage: effects of lesion location and test structure on separable cognitive processes. Neuropsychologia 2000;38:388–402.
[58] Teuber HL. Unity and diversity of frontal lobe functions. Acta Neurobiologica Experimentalis (Warszaw) 1972;32:615–56.
[59] Vendrell P, Junque C, Pujol J, Jurado MA, Molet J, Grafman J. The role of prefrontal regions in the Stroop task. Neuropsychologia 1993;33:341–52.
[60] Warrington EK, James M, Maciejewski C. The WAIS as a lateralizing and localizing diagnostic instrument: a study of 656 patients with unilateral cerebral lesions. Neuropsychologia 1986;24:223–39.
[61] Wechsler D. Manual for the Wechsler adult intelligence scale-revised. New York: Psychological Corporation, 1981.
[62] Zangwill O. Psychological deficits associated with frontal lobe lesions. International Journal of Neurology 1966;5:395–402.