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Research paper

Separate contributions of general intelligence and right prefrontal neurocognitive functions to academic achievement at university level

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ABSTRACT

It is hypothesized that performance on frontal-lobe neuropsychological tests and intelligence tests may independently contribute to variation in academic achievement in higher education. We examined the ability of an IQ test (the WAIS-IV) to predict grade point averages (GPA) in a sample of 64 undergraduate students. We also included a battery of five neuropsychological assessments of frontal-lobe functions, all known to be unrelated to general intelligence and linked to right-prefrontal function. Regression analysis with stepwise entry of variables revealed separate contributions to the variation in GPA scores explained by general intelligence and two different measures of response inhibition (Stop-signal and Hayling). The addition of the inhibition measures more than doubled the amount of variance in GPA explained by general intelligence alone, from adjusted R^2=.115 to adjusted R^2=.239, suggesting an important role of right prefrontal-mediated response inhibition in high-level academic achievement. This contrasts with the mainly left-hemisphere contribution from general intelligence.

1. . Introduction

There has long been an interest in predicting academic achievement through cognitive testing. This is one of the primary reasons that intelligence tests were first developed [1,2]. Indeed, intelligence testing can predict academic performance very well in some contexts. A study of 70,000 British school children found that a psychometrically derived measure of general intelligence correlated very highly (r=.81) with a measure of school leaving qualifications [3].

However, other studies have shown much less impressive associations, particularly when adult learners are considered, such as in higher education contexts. For example a study in India found no relationship between intelligence tests scores and academic achievement in a sample of 120 postgraduate students [4]. Similarly a study of 93 undergraduate students in London, the UK, found very low and not statistically significant correlations between academic performance (as measured by end of year exam grades) and IQ [5]. In fact, a recent meta-analysis found a mean observed effect size (r^+) between intelligence test performance and academic achievement at university level of only about .2 [6] which therefore only accounts for a tiny proportion of the variance.

There may be many reasons why IQ is only weakly predictive of university level performance. For example, students are often selected based on their performance in challenging entrance examinations. Consequently this limits the range of intellectual ability observed in student samples [5]. Furthermore, non-intellective factors such as effort regulation and self-efficacy have been found to be important predictors of university level grades [6]. Another reason may be that IQ tests are not specifically designed based on neuroscientific principles and are in fact failing to focus on how cognition drives adaptive goal-directed behavior. In fact, the rationale behind intelligence test development is psychometric, to develop tests that measure well. One feature of this psychometric approach has been the focus of assessments that measure the same basic underlying concept – *general intelligence*. This has been motivated by the observation that scores on cognitive tests correlate positively with each other, suggesting they are measuring some fundamental neural property [7]. Indeed, the development of intelligence tests has been driven by the need to best measure this general intelligence, or the *g-factor*.

Although, there is certainly something of great interest to

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cognitive- and neuroscientists in the concept of *g*, as it is also known, there is no direct theoretical link to adaptive goal-directed behavior. The concept of *g* is statistically related to abstract problem solving in a range of tasks, but not obviously to behavior regulation mechanisms. On the other hand, neuropsychologists have developed approaches to measure and explain where goal-directed behavior fails, or at least fails to lead to the most adaptive outcome for the individual. In particular, studies of frontal lobe and basal ganglia damaged patients have revealed a range of behavioral dysregulations such as the apathetic, disinhibited and dysexecutive syndromes, linked to damage to the medial, orbitofrontal and dorsolateral prefrontal cortices respectively [8]. These neurobehavioral syndromes appear to show the breakdown of effective goal-directed behavior [9]. Furthermore, neuropsychologists have developed a range of assessments to measure impairments associated with damage to the prefrontal-subcortical circuits. Such tests cover a wide-range of abilities, but the majority tend to measure 'executive functions' such as response inhibition, task shifting and planning.

From a neuropsychological perspective, such tests may also be useful in the measurement of effective goal-directed behavior in non-clinical contexts. Indeed, a recent study of self-report executive functions in a large sample of students starting university found that better executive functions predicted better attainment at the end of their first year [10]. Furthermore, it has been shown that clinical executive function tests linked to the efficiency of the prefrontal cortices are at least as good as traditional tests of intelligence in the prediction of academic achievement of university students [11]. These better executive skills may allow students to generally prosper in university environments, rather than resolve specific cognitive problems. Support for this comes from a study in which it was shown that those university students with the best working memory scores more readily developed information literacy skills [12].

Furthermore, there is a wealth of evidence linking executive functions to educational achievement in children. For example, measurements of executive functions including working memory in pre-school age children have been shown to predict later school performance. In particular, visuospatial short-term memory skills (measured at age 4) predict better math, and general executive function scores predict better attainment in general at age 7 [13]. A separate study of 11-year-old children observed another prefrontally-mediated executive function, inhibition, was predictive of general school attainment and also confirmed that working memory scores predict math scores. Furthermore, these two broad executive functions (working memory and inhibition) appear to make independent contributions to attainment, although the magnitude of the relationship appears to be much greater for working memory [14]. Indeed, in children, working memory ability is superior to general intelligence in prediction of academic achievement in general [15].

Therefore a focus on frontal lobe functions, and assessments developed to measure those functions, may ultimately be a more productive approach in understanding complex behavior than the concept of general intelligence. However, it has become clear that many but not all executive function tests are highly correlated with general intelligence and in fact may be measuring the *g*-factor rather than any specific, modular, cognitive ability [16]. A recent modeling study for example found that in a combined clinical and non-clinical sample, general intelligence including crystallized but particularly fluid intelligence, was highly correlated with several supposed executive functions, most strikingly with working memory [17]. Furthermore, frontal lobe lesions tend to lead to very large impairments in general intelligence, suggesting that frontal lobe function may in fact be the biological basis of the *g*-factor [18].

Nevertheless, there appear to be some frontal-lobe neuropsychological functions which are not, or only weakly, related to the *g*-factor. One study by Roca et al. [19] compared the performance of a group of frontal lobe damaged patients with a healthy control sample on a range of common neuropsychological tests of frontal lobe function. They also used a test of 'fluid intelligence', thought to be a strong measure of general intelligence. As expected, the frontal lobe patients performed significantly below the levels of the controls on all assessments. The researchers then examined the between-group differences while covarying the effects of reduced general intelligence. This revealed that frontal damage related impairments on most of the supposed executive function tests could be fully accounted for by reduced general intelligence. However, this analysis also revealed five tests where performance was impaired by frontal lobe damage, but the impairments could not be explained by general intelligence reductions [19]. These five tests, the Hotel Task [20], Proverbs [21], Faux Pas Test [22], Go/No-go [23] and the Hayling Response Suppression Test [24] therefore appear to be non-*g* related measures of frontal lobe function. Despite being conceptually linked by their independence from *g*, they appear to measure a diverse range of abilities including multi-tasking (Hotel Task), abstract reasoning (Proverb Test), theory of mind (Faux Pas), psychomotor response inhibition (Go/No-go/Stop-signal) and verbal response suppression (Hayling). They are therefore ideal candidate tests for understanding goal-directed behavior functions of the frontal lobes in contrast to the concept of *g* or general intelligence.

Interestingly, a lesion analysis linked impairments on these five different non-*g* neuropsychological tests to damage of the right prefrontal region, specifically the right frontal pole (BA10) [19,25]. This contrasts sharply with lesion studies that have demonstrated that tasks that are known to load highly on *g* are specifically linked to left-hemisphere damage of the parietal and frontal cortices and white matter tracts linking them [26,27]. This therefore suggests that general intelligence and the five neuropsychological tests described are not only functionally independent, but may have separate neurological bases. They consequently may make independent contributions to the high-level goal directed behavior such as needed for success in higher education.

In the current research we attempted to explore the relative contributions of general intelligence and the five non-*g* frontal lobe tests identified by Roca et al. [19] to academic achievement at university level. In addition we included a measure of working memory capacity, considering that this is closely linked to general intelligence and may, in some cases, be a better predictor of academic achievement than IQ. It was hypothesized that non-*g* related neuropsychological functions and traditional general intelligence/working memory may both be independently contributing to achievement as measured by grade-point average data (GPA).

2. Methods

2.1. Design and analysis

The aim of this research was to examine the ability of general intelligence and specific tests of frontal lobe function to predict GPA scores of undergraduate students. Thus a single sample of 64 students was recruited and all were individually assessed with a range of neuropsychological tests as well as with a standard IQ assessment known to load highly on the construct of psychometric *g*. Data on these assessments were then compared via correlations and regression analysis to examine the relative contributions to variance in GPA. For reporting descriptive statistics, numbers less than 10 are given to 2 decimal places, numbers over 100 to

0 decimal places and numbers in-between to 1 decimal place. Details of inferential statistics are given in the results section. All analyses were two-tailed.

2.2. Participants

A group of 64 undergraduate students of Universidad San Francisco de Quito (Ecuador) were recruited from introductory psychology courses. These courses are open to all students of the University and so the sample includes mainly non-psychology majors, e.g. business, engineering, medicine, sciences (41/64, 64.1%). All were Spanish speakers. The majority (47/64, 73.4%) were female and the mean age was 19.8 (SD=2.27). Participants were asked about diagnosed neurodevelopmental disorders, but these were not used as exclusion criteria. One participant reported a diagnosis of dyslexia and another a diagnosis of attention deficit hyperactivity disorder. All individuals participated in return for course credits.

2.3. Assessments

2.3.1. General intelligence

The Wechsler Adult Intelligence Scale Fourth-edition: Spanish (WAIS-IV) [28] was used to measure general intelligence. We used a validated seven test short-form administration based on the subtests of Block Design, Similarities, Digit-span, Arithmetic, Information, Picture Completion and Symbol Coding [29]. This WAIS IQ score loads highly on the concept of psychometric *g* and is therefore considered to be a strong measure of general intelligence [30].

2.3.2. Frontal lobe function

As described earlier, the frontal lobe tests used in this research were based on the five identified by Roca et al. [19], all of which appear to be impaired by frontal lobe lesions independent of changes to general intelligence. In general, the research by Roca et al. with brain-lesioned patients used reduced length versions of tasks and simple clinical grading of responses. However, we have opted to use the full versions of the neuropsychological tasks with standardized grading criteria to gain greater precision and ranges of scores in our non-neurological sample. The five tests are detailed below.

2.3.2.1. Hotel Task

The Hotel Task was developed as a laboratory measure of the dysexecutive syndrome seen after frontal lobe damage in man [20]. It is an adaption of the Six Elements Test, developed by Shallice and Burgess, which was used to demonstrate disordered strategy application following frontal lobe lesions [31]. The Hotel Task involves participants performing six different procedures that might reasonably be expected from somebody working in a hotel: sorting coins, compiling customer accounts, searching a telephone directory, alphabetizing conference name badges and proofreading a document. The participant has 15 min and is told to divide their time equally between the five tasks, and additionally open and close garage doors by pressing buttons at set times. Administration in the current research followed the set procedure and instructions of the task developers, as did the derivation of the main index of performance – the total time deviation (from the optimal performance of spending exactly three minutes on each subtask) [20]. This is the exact same administration and performance index as used by Roca et al. The Hotel Task measures goal management, a feature of executive functioning, and multi-tasking in a complex situation; poor performance is considered to indicate ‘goal-neglect’ [32]. Performance on this task and similar tasks has been linked to function of the right frontal-polar and rostrolateral prefrontal cortex – BA10 in neuropsychological studies [19,25] as well as with fMRI of healthy participants [32].

2.3.2.2. Proverb Test

Proverb interpretation involves extracting the abstract meaning behind common figurative phrases. It is often considered as an executive function, as impaired performance is manifest in the tendency to neglect analogical figurative meaning, instead being drawn to concrete interpretations [33]. We followed the administration and scoring procedures of the Proverb Test in the Delis-Kaplan Executive Function System (D-KEFS) [34]. This involves eliciting free verbal responses describing the meaning of eight proverbs and then scoring them on i) accuracy and ii) level of abstraction, before calculating an overall performance score. However, we used proverbs used in the local context (Ecuador) and in Spanish in place of the English language proverbs in the original D-KEFS. We displayed each proverb on the screen of a 10 in. tablet computer and also read them aloud to minimize memory load. A neuropsychological study using the same basic protocol has linked impaired Proverb Test performance to frontal lobe damage, particularly the medial regions [21].

2.3.2.3. Faux Pas Test

The Faux Pas Test was developed to measure ‘theory of mind’ ability, i.e. the ability to infer mental states in others [22]. Participants are read stories in which some social awkwardness may or may not be present (for example a story of a person talking to a mother and referring to her little girl with a male pronoun). Individuals on the autistic spectrum tend to perform poorly on this task. This is often because they cannot detect the faux pas at all, others fail to understand the emotional impact or fail to recognize that the acts causing the social embarrassment were not intentional [22,35]. Although developed for studying autistic spectrum individuals, later neuropsychological studies have linked impaired Faux Pas Test performance to acquired damage to the amygdala [36] and to the medial frontal cortex [37]. The Spanish language adult version was available from the original test developers at http://www.autismresearchcentre.com. We followed the administration and scoring system of Roca et al. [19,25], awarding one point for each correct categorization (faux pas/not faux pas) of 20 different scenarios. The scenarios were read aloud and also displayed in written form on a tablet computer to reduce memory load.

2.3.2.4. Hayling Test

The Hayling Test was developed to measure difficulties with verbal response suppression in patients with frontal lobe lesions [24]. Disinhibition in general, including lack of verbal suppression, is one of the most common features of frontal lobe damage, and is generally distinguished from the dysexecutive and apathetic syndromes [9]. In the test, patients are read 30 sentences in which the last word is missing and they are required to complete each sentence as quickly as possible either with a congruent word (15 sentences, Condition A) or a completely incongruent word (15 sentences, Condition B). The sentences constrict the possible responses and frontal lobe impairment is associated with poor accuracy on Condition B, i.e. producing words which are related to the overall meaning of the sentence (when the instruction was to produce unrelated words). Neuropsychological studies have confirmed that frontal lobe damaged patients perform worse than patients with posterior lesions [24], and that impairment is particularly linked to right hemisphere lateral frontal cortex lesions [38]. Analyses of error types have indicated that in addition to poor response suppression *per se*, right frontal lobe damaged patients perform poorly because they fail to develop effective strategies [38]. This suggests that the Hayling Test measures both response suppression and strategy application efficiency. It has been further argued that this may reflect a general goal-maintenance system in the right prefrontal cortex that is necessary for successful response suppression [39]. We used a Spanish language version of the Hayling Test [40] and followed Roca et al. [19] by examining accuracy on Condition B as the variable of interest. In addition, this accuracy measure is that most sensitive 2.3.2.5 to frontal lobe impairment [38]. Responses are scored as two points for a completely unrelated word (indicating good suppression), one point for a semantically-related word and zero points for the sentence-primed word [40]. Scores therefore range from 0 to 30 with higher scores indicating better performance.

2.3.2.5. Stop-signal Task

The fifth test used by Roca et al. was a Go/No-go procedure [19,23]. However, the version that they used was a clinical bedside version in which one tap on the desk was the 'go' signal and two consecutive taps was the 'no-go' signal [19]. From an experimental neuropsychology perspective this is actually a Stop-signal Task in which a 'go' signal is given and then (on some trials) a stop-signal tells the participant to cancel the already triggered response [41]. For this reason, and also to make the test more challenging for healthy participants, we used a computerized Stop-signal procedure in which participants performed a two-option choice reaction time task to visually presented stimuli (a square or a circle), but with 25% of trials involving a stop-signal (beeping sound) delivered after the visual go-stimuli [41]. There were 16 practice trials followed by data acquisition 64 trials. The stop-signal delay was adjusted based on performance. This task was administered on a 15 in. Windows laptop computer, with responses made to the keyboard with the two fingers of the dominant hand. We recorded the overall performance accuracy on suppression of responses (PRS), as that measure is equivalent to that of the original research of Roca et al. The Stop-signal Task is a response cancelation task, meaning that it measures the ability of individuals to inhibit a response once triggered. It therefore provides an index of response inhibition, one of the basic features of executive control processes supporting goal-directed behavior [42]. Impaired performance on Stop-signal Tasks has been linked in neuropsychological studies to damage to the right inferior frontal gyrus (BA44, BA45, BA47) [43].

2.3.3. Working memory

2.3.3.1. Counting Span Task

The Counting Span Task is considered a measure of verbal working memory capacity [44]. This was included in the test battery as working memory is often identified as a cognitive skill linked to both general intelligence [16], academic performance [15] and prefrontal function [45]. We followed a standard Counting Span test administration involving the counting of dark-blue circles in displays of light-blue circles and dark-blue squares [46]. The task itself involves conjunctive visual search [47], however, the working memory component is that participants must count aloud and remember the totals from different trials and report them together at a later time point. It is therefore similar to a simple digit-span task, but also includes distraction elements (simultaneous conjunctive visual search and counting aloud). We used a version administered on a 10 in. tablet computer in which span increases from 2 items to a maximum of 9. Similar to standard digit span, two attempts of each length were given and the task was discontinued if participants completely failed two sequences of the same length. We used unit-weighted partial credit scoring system, i.e. giving fractional points for the number of elements in a string correctly recalled, even if the string contained some errors, as this has been recommended on psychometric grounds [44]. Such verbal working memory span tasks are thought to invoke several frontal cortical regions, including short-term storage of verbal material in Broca's and left hemisphere premotor areas with executive control from dorsolateral prefrontal and anterior cingulate cortices [45].

2.4. Procedure

Participants were recruited from various introductory psychology classes. All provided written informed consent in accordance with the research protocol (approved by the local research ethics committee). Each participant was given the neuropsychological and intelligence assessment by one of three researchers (all qualified psychologists), under the supervision of a neuropsychologist (Dr Pluck). First, basic demographic information was collected, including the study major and number of semesters already completed at the university. Next the tests described above were all administered as well as some lexical cognitive tasks, not reported here. The entire interview took around two and half hours, including a ten minute break. On completion the participant was verbally debriefed about the research and thanked for their cooperation. All individuals participated in return for course credits. Data collection continued over one complete semester plus some additional participants were recruited from a summer course. GPA data of individuals was extracted from the university systems on average six months after participation (range 3–9 months). The potential range for GPA is 0 (worst, 100% fail grades) to 4 (best, 100% A grades). The mean GPA for the whole time that each student had studied at the university to the point of systems access was calculated. This would have therefore have included grades awarded both prior to and after this research participation.

3. Results

The mean GPA score for the sample was 3.11 (range = 1.84–4.00, SD = .534). Students had completed between 1 and 10 semesters of study, the mean number was 3.27 (SD = 2.05). The mean average IQ and raw neuropsychological test scores are shown in Table 1.

Bivariate correlation analyses were used to identify which IQ and neuropsychological variables were associated with GPA scores. Shapiro-Wilk tests were used to assess the normality of the distributions of each variable prior to correlation analyses. For those that were found to have non-normal distributions various data transformations were attempted (x^2, x^3, square root, reciprocal and log10). Although this normalized distributions for some variables, others continued to have abnormal distributions (i.e. number of semesters studied, Hayling, Stop-signal, and Faux Pas). For variable pairs with normal data distributions we used parametric Pearson correlations (r), when either variable was abnormally distributed we used non-parametric Spearman correlations (r_s). The results of these analyses are also shown in Table 1. Both IQ ($r = .298$, $p = .017$), and Hayling task performance ($r_s = .367$, $p = .003$) were significantly positively correlated with GPA, indicating better task performance linked to higher GPA scores. None of the other cognitive tests were significantly correlated with GPA (at $p < .05$).

The primary aim of the correlation analyses was to identify candidate predictors of GPA for modeling with multiple linear regression. We therefore selected any cognitive variable that correlated with GPA at $p <= .1$, in addition to IQ and Hayling, this included the Stop-signal Task ($r_s = -.217$, $p = .085$).

Prior to multiple regression analyses we used Mahalanobis distance analysis to identify multivariate outliers based on the three candidate variables for all 64 cases. Each distance based on the three candidate variables (IQ, Hayling and Stop-signal) was then compared to the Chi^2 distribution and any case in which the Mahalanobis distance differed significantly at $p < .001$ was

Table 1
Correlations between the various cognitive assessments and GPA, number of semesters studied and IQ data.

Assessment	Mean (SD)	Correlations with GPA		Correlations with Semesters		Correlations with IQ	
		Coefficient	Sig.	Coefficient	Sig.	Coefficient	Sig.
GPA	3.11 (.534)			r_s=.005	.970	r=.298	.017
IQ	90.2 (15.0)	r=.298	.017	r_s=−.116	.360		
Counting Span	8.94 (1.83)	r=−.068	.594	r_s=.074	.561	r=.305	.014
Faux Pas	17.4 (2.23)	r_s=.032	.803	r_s=−.224	.075	r_s=.086	.500
Proverbs	21.7 (5.93)	r=.112	.377	r_s=−.104	.412	r=.216	.086
Hotel Task	508 (292)	r=−.009	.945	r_s=−.067	.599	r=−.102	.423
Hayling	28.0 (2.50)	r_s=.367	.003	r_s=.059	.646	r_s=.006	.963
Stop-signal	35.0 (14.1)	r_s=−.217	.085	r_s=−.008	.950	r_s=.163	.199

removed. This resulted in two cases being excluded. The linear regression modeling was performed on the remaining 62 cases.

In order to address our primary question of whether frontal lobe tests can add to our prediction of GPA we performed a multiple linear regression with GPA as the dependent variable and as the independent variables, IQ, Hayling and Stop-signal scores were entered stepwise with a probability to enter of $p < .05$ and to remove of $p > .1$. The linear regression produced a final model which included all three independent variables (R=.526, R^2=.276, $F(3,58)$=7.376, $p < .001$). Details of the model are shown in Table 2 where we can also see details of the change in R with the entry of each variable. With only IQ as the independent variable the adjusted R^2 value was.115, the addition of Hayling and Stop-signal data more than doubled the this to adjusted R^2=.239. In each step, the change to R^2 was statistically significant at $p < .05$. This analysis confirms that each of the three cognitive variables explains an independent part of the variance and that the inclusion of all three variables provides the best overall explanation of the variance in GPA.

Following the linear regression analysis we assessed how well the statistical assumptions of multiple linear regression (normality of distribution, multicollinearity) were satisfied. The unstandardized residuals of the model regressing IQ, Hayling and Stop-signal performance on GPA were found to be normally distributed (Shapiro-Wilk=.974, DF=62, p=.207). This confirms the normality of distribution assumption. To examine multicollinearity we examined the variance inflation factor (*VIF*) for each independent variable in the model. These were all low confirming no multicollinearity within the model (IQ *VIF*=1.036, Hayling *VIF*=1.004, Stop-signal *VIF*=1.032).

In addition to the associations between cognitive test scores and GPA, we examined how length of higher education study associated with cognitive test performance and GPA. These correlations are shown in Table 1. There was no statistical correlation between number of semesters completed and GPA scores (r_s=.005, p=.970). There were only low and non-significant correlations between the cognitive variables and number of semesters studied at university.

Finally, as the five main neuropsychological tests were selected for inclusion in this research based on their supposed functional independence from general intelligence, we examined their bivariate correlations with the WAIS full-scale IQ scores. This confirmed that the five tests are relatively independent of IQ, all correlations were found to be non-significant. However, the additional working memory task that we included (Counting Span) was significantly correlated with full-scale IQ scores, r=.305, p=.014).

4. Discussion

We found that IQ significantly explains some of the variation in university level academic performance, as measured by student GPA. In fact, considered alone, it explains about 12% of the variance in GPA scores (based on the adjusted R^2 score of .115). However, we also found that two neuropsychological measures also explain some of the variance. When performance on the Hayling and Stop-signal Tasks are included with IQ, about 24% of the variance in GPA is explained (based on the adjusted R^2 score of .239). Furthermore, the inclusion of all three variables in the linear regression model suggests that the three are relatively independent in their associations with GPA and that the inclusion of each variable significantly increased the amount of GPA variance explained.

The two frontal lobe tests, Hayling and Stop-signal, were both included in the present study along with three others, because they are considered to be relatively independent of the concept of general intelligence, *g*. Although in theory all cognitive tests are related to some extent to the concept of *g*, we are considering those five tests as being practically non-*g* due to their neuropsychological dissociations [19]. In fact, our data confirms this independence, none of the five tests correlated significantly with IQ scores in our non-clinical sample. Although, we additionally included a working memory capacity measure (Counting Span) which did correlate significantly with IQ. This was anticipated. Of the various supposed executive functions, those that appear to tap working memory are generally found to be most strongly linked to general intelligence [16].

That performance on the Hayling and Stop-signal Tasks is relatively independent of general intelligence was also revealed in the regression analyses which showed that each variable independently predicted part of the variance in student GPA scores. This suggests that general intelligence, or more simply *g*-related

Table 2
Details of the stepwise linear regression of GPA on IQ, Hayling and Stop-signal test scores.

	Final Model			Stepwise entry of variables		
Variable	*b*	*t*	*Sig.*	*R* when variable entered	Adjusted R^2 when entered	*Sig.* of change
Constant	.150					
IQ	.015	3.696	< .001	.360	.115	$F(1,60)$=8.922, p=.004
Hayling	.070	2.740	.008	.473	.198	$F(1,59)$=7.201, p=.009
Stop-signal	−.011	−2.042	.046	.526	.239	$F(1,58)$=4.169, p=.046

cognitive ability, plays only a small part in academic achievement in higher education. Furthermore, there is an equal or perhaps even greater contribution from non-*g*-related cognitive functions. We have demonstrated that additional contribution with two well-known 'frontal lobe' tests, the Hayling and the Stop-signal Tasks. In fact, in our comparison with IQ as a predictor, we focused only on frontal lobe tests. This was because the neurobehavioral functions of the frontal lobes are closely linked to goal-directed behavior [8], they are therefore obvious candidates when attempting to explain high-level achievements such as success in higher education.

Of the five neuropsychological tests examined in predication of GPA, we found no association with three. Those tests particularly involved multi-tasking (Hotel Task), mentalizing/theory of mind (Faux Pas Test) and abstract reasoning (Proverb Test). It is perhaps interesting to note which abilities had no statistical link to academic achievement. *A priori* one could see possible links between multi-tasking, abstract reasoning and even theory of mind ability in educational success; however, the fact is that the current evidence negates such theorizing.

On the other hand, it is notable the two non-*g*-related tests that were predictive of GPA, the Hayling and Stop-signal tests are both primarily measures of response inhibition, albeit verbal response suppression in the case of the Hayling Test and psychomotor inhibition in the Stop-signal Task. Interestingly, a study using fMRI and a Stroop paradigm found that the academic performance of medical students was positively related to inhibition related activity in the dorsal anterior cingulate cortex (BA32) [48].

The reason why inhibition should be particularly linked to better academic performance at university level is not clear. Good inhibition ability has also been shown to predict academic performance in school-age children, however, it is usually observed that both inhibition and working memory are predictive, and that of the two, working memory is the better predictor [49]. In fact in primary school age children, working memory ability is an even stronger predictor of academic attainment than IQ [15]. In the current data, despite finding significant links between GPA and inhibition task performance, we found no link between working memory capacity and GPA scores.

One possible explanation for the link between inhibition and GPA in our sample is that response inhibition was acting as a proxy for maturation of the frontal lobes. Structural brain imaging studies suggest that, unlike the other lobes, the frontal lobes continue to develop in the post-adolescence period [50]. Furthermore, non-human primate work suggests that response inhibition continues to improve post-puberty and this occurs in tandem with developmental maturation of the prefrontal cortex [51]. Interestingly, the same researchers also demonstrated, via single cell recordings in monkey prefrontal cortex at different developmental stages, that optimal inhibition task performance was achieved not when inhibition ability *per se* matured, but rather with maturation of stronger goal representations of alternative actions [51]. This supports our suggestion that rather than strong inhibition being behind the better academic performance, it may be that it indexes a more general maturing of prefrontal processes.

If the, Hayling and Stop-signal Tasks are simply indexing physiological maturity of the prefrontal cortices, this raises the question of why the other measures related to prefrontal function, such as working memory ability, were not similarly predictive of GPA scores. One possibility may be that, as with younger learners, working memory ability primarily predicts mathematics and language development, while inhibition has a more general relationship with academic achievement [13,14]. As our sample contained students studying for a range of different majors, specific influences on numerical and linguistic ability may have not affected achievement of all members of the sample equally. In contrast, the effect of inhibitory control on achievement may have been more readily detected due to its generalized impact. If correct, this suggests that different results could be found comparing different student samples. For example, working memory may be more important for university students studying for technical subjects such as mathematics, or those studying foreign languages. Further research with more narrowly defined undergraduate student populations could clarify this issue.

It is also worth considering whether cognitive inhibitory control is actually the underlying process that associated with academic achievement in the current research. Although the two tests, Stop-signal and Hayling, are both said to be measures of inhibition, the later of these has also been linked to spontaneous strategy application. This is because participants being tested can potentially use strategies such as naming objects in the room that they are in. Indeed, the impairment of such strategy use is thought to partly explain why patients with frontal lobe damage perform poorly on this task [24,38]. Interestingly, it has recently been suggested that the impaired performance on both the Hayling and Stop-signal Tasks associated with right lateral prefrontal damage might indicate impairment of a more general goal-maintenance system that is needed for amongst other things, response inhibition [39]. This would also suggest that response inhibition *per se* is not the factor influencing academic achievement, but perhaps a more general goal-representation system based in the right lateral prefrontal cortex.

Alternatively, the mechanism linking successful "inhibition" task performance to academic achievement may simply operate on the behavioral level and directly influence achievement. Those students with stronger inhibition ability may be able to better focus on task and ignore irrelevant distractions, potentially enhancing learning, task completion etc. Some support for this interpretation comes from studies that show that various characteristics labeled 'self-regulation' predict academic achievement of adolescents. For example a study of eighth-graders in the USA found that a composite measure of self-discipline was a better predictor of achievement than IQ and it also predicted hours spent doing homework, school attendance, and inversely, hours spent watching television [52].

As we have demonstrated two relatively independent individual difference factors that contribute to academic achievement, IQ, or *g*-related cognition and non-*g*-related cognition, it is also of interest to consider their neurobiological bases. Both of the non-*g*-related tasks are strongly linked to the right-hemisphere prefrontal cortex. Based on performance of frontal damaged patients, Roca et al. located performance on both tasks to the right frontal pole (BA10) [19]. However, others have suggested that damage to the right lateral prefrontal cortex is more important. A comparison of patients with either frontal lobe or posterior damage confirmed that the frontal lobes are essential for suppression of responses in the Hayling task, and that this was most clear in patients in with damage to the right lateral prefrontal region [38]. Similarly, poor performance on the Stop-signal Task has been observed in patients with damage to the right lateral prefrontal cortex, specifically, the right inferior frontal gyrus (BA44 and BA45), but not in left hemisphere damaged patients [43].

On the other hand, general intelligence has been shown in neuropsychological studies to have a very lateralized representation in the brain, to the left hemisphere. In one analysis of 241 patients with brain lesions, general intelligence, *g*, was clearly linked to functioning of the left-hemisphere fronto-parietal systems, in particular white matter tracts linking the two lobes and the left fronto-polar cortex (BA10) [27]. The crucial role of left hemisphere fronto-parietal cortex and white matter tracts in general intelligence was confirmed in a separate study of 182 brain injured patients, a study which also revealed that many 'executive functions' share this same network [26].

This leads us to suggest that there may be two broad neurocognitive factors independently contributing to academic achievement. There is clearly a left hemisphere system which mediates 'intelligent' processes, involving a range of cognitive abilities all linked by the fact that they draw on general intelligence, the *g* factor. Our data suggests a parallel right hemisphere system which although cognitive in nature, is mainly unrelated to general intelligence. The two systems are therefore anatomically and functionally distinct. Working independently, these left- and right-hemisphere neurocognitive systems contribute to successful goal-directed behavior, and in the current context, to high-level academic achievement.

A related issue is the extent to which exposure to higher education improves these neurocognitive systems. This would be expected as various studies have shown experimentally that cognitive training can improve neuropsychological performance [53]. However, we found no statistical associations between number of semesters studied in higher education and intelligence or neuropsychological variables. This tends to suggest that in the current sample exposure to higher education is not improving GPA or neurocognitive performance, and that the true relationship may be that variation in neurocognitive abilities leads to better academic performance as reflected in GPA scores. This is consistent with a study of children which showed that IQ predicts school achievement over time, but not vice versa [54].

Some limitations of the current research should be acknowledged. The sample size is somewhat limited ($N=64$), particularly in the context of regression analyses. However, as only 3 variables were modeled, the ratio of cases to variables is at a generally acceptable level. Furthermore, it is possible that other low correlations between neuropsychological performance and GPA would have reached significance and consequently been included in the regression model if a larger sample had been recruited. A further limitation is that we included a mixed sample of undergraduate students. It is quite possible that different results may be found within samples of students studying for specific majors. The role of general intelligence may be more or less important to achievement in some academic fields, for example in engineering or humanities. Finally, it should be acknowledged that together our cognitive measures (IQ, Hayling and Stop-signal) only accounted for about 24% of the variance in GPA scores. Thus more than three-quarters of the variance remained unexplained. Clearly other factors make a significant impact; many of these will be non-cognitive individual differences factors. As described in the Introduction, various personality factors such as measures effort regulation and self-efficacy have been shown to be generally better predictors of university level performance than cognitive measures [6]. Other factors contributing to variation in GPA may be external to the students, such as inconsistency in grading practices by professors.

Nevertheless, we have demonstrated that both general intelligence (*g*) and non-*g* related cognitive tasks independently predict a reasonable amount of the total variation in academic performance of a general undergraduate sample. This distinction between *g* and non-*g* related cognition may constitute a productive vein of investigation in formal education. Furthermore, it may be applicable to other areas where prediction of achievement is desirable such as management training, and indeed the psychological and neurobiological understanding on high-level goal-direct behavior in general.

Conflicts of interest

None.

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