Big-Brained People are Smarter:

A Meta-Analysis of the Relationship Between *In Vivo* Brain Volume and Intelligence

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Revise and resubmit paper for *Intelligence*

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Abstract

The relationship between brain volume and intelligence has been a topic of a scientific debate since at least the 1830's. To address the debate, a meta-analysis of the relationship between *in vivo* brain volume and intelligence was conducted. Based on 37 samples across 1,530 people, the population correlation was estimated at .33. The correlation is higher for females than males. It is also higher for adults than children. For all age and sex groups, it is clear that brain volume is positively correlated with intelligence.

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A Meta-Analysis of the Relationship Between

***In Vivo* Brain Volume and Intelligence**

Introduction

In 1836, Frederick Tiedmann wrote that there exists "an indisputable connection between the size of the brain and the mental energy displayed by the individual man" (as cited in (Hamilton, 1935). Since that time, the quest for the biological basis of intelligence has been pursued by many. Various narrative reviews (Rushton & Ankney, 1996; Rushton & Ankney, 2000; Vernon, Wickett, Bazana, & Stelmack, 2000) and a meta-analysis (Nguyen & McDaniel, 2000) have documented a non-trivial positive relationship between brain volume and intelligence in non-clinical samples. In the brain volume literature, there are two general categories of brain volume measures. The first category consists of measures of the external size of the head, such as the circumference of the head. The second category consists of measures of the *in vivo* brain volume, typically assessed through an MRI scan. For external head measures, Vernon *et al*. (Vernon et al., 2000) reported the population correlation between head size and intelligence to be .19. Nguyen and McDaniel (2000) reported population correlations from .17 to .26 for three different sub-categories of external head size measures. Studies assessing the correlation between *in vivo* brain volume and intelligence are more rare. Vernon et al. (Vernon et al., 2000) reported data on 15 such correlations and obtained a population correlation of .33. Nguyen and McDaniel (2000) reported the same population correlation based on 14 correlations. Gignac, Vernon, and Wickett (2003), reported data published in 2000 or earlier with a mean correlation of .37. Since 2000, much more data relating brain volume and intelligence have become available due to the increased use of MRI-based brain assessments. The purpose of this meta-analysis is to cumulate our

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knowledge concerning the magnitude of the correlation between *in vivo* brain volume and intelligence in order to answer the long-standing question on this topic. In addition, potential sex and age moderators of the relationship are evaluated.

Methods

Literature review. A review of all known past literature was conducted using PsychInfo and Medline as well as citation index searches of popular past reviews. Studies containing relevant data were reviewed to identify citations to other relevant research. Often, studies were found in which the authors collected MRI-assessed brain volume and intelligence data but did not report the correlation between these measures because the correlation between brain volume and intelligence was not the focus of the study, and/or because the publication standards for the journal did not require a correlation matrix among all variables. For such studies, the correlations were requested from the authors.

After preliminary findings were obtained, over 50 authors were contacted who: 1) had published in the area of brain volume and intelligence, 2) had provided commentaries on such literature, or 3) were known to have an interest in the relation between brain volume and intelligence. These researchers were provided with the preliminary findings and were asked to scan the references to determine if any relevant research had been omitted. These researchers were also asked if they knew of any data sets containing both MRI-assessed brain volume and intelligence that might be relevant to the study.

Decision rules. The analysis included all correlations between *in vivo* measures of full brain volume and intelligence that met the decision rules. It did not include studies if they only measured partial brain volume, for example only frontal gray matter volume (Thompson et al., 2001). All intelligence measures were standardized tests of general cognitive ability and primarily were full-scale IQ measures or the *Ravens Progressive*

Matrices Test. We did not include data from studies that estimated full-scale IQ from other measures such as the New Adult Reading Test. Some studies reported data on more than one sample. Only one correlation between brain volume and intelligence for a given sample was reported, but whenever possible, data were coded separately by age (children vs. adults) and by sex. Thus, if a sample recorded a correlation for all members of the sample and correlations separately by sex, the correlation for each sex group was included, but the correlation for all members in the sample was not included. Thus, all correlations contributing to the meta-analysis are from independent samples. All sample members were non-clinical. Often the sample was the non-clinical control group in a clinical study.

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Whereas the Gignac et al. (Gignac et al., 2003) paper is the most recently published review on this topic, it is useful to compare that data set with the data set used in the this study. This paper incorporates 23 additional samples raising the total number of coefficients available for analysis from 14 to 37. Some of the 23 sample difference is due to differing decision rules. For this paper, correlations are reported separately by sex for six studies (Andreasen et al., 1993; Gur et al., 1999; Ivanovic et al., 2004; Reiss, Abrams, Singer, Ross, & Denckla, 1996; Tan et al., 1999; Willerman, 1991) while Gignac et al. reported a single correlation for males and females combined for five of the studies and did not include data from Ivanovic et al. (2004). This reduced the number of different samples to 18. Gignac et al. included data from 96 individuals (Pennington et al., 2000) of whom at least half had reading disabilities. This sample was excluded from

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the present study because it did not meet this paper's decision rule for clinically normal subjects. Also, Gignac et al. had included a study by Tramo (1998). That study was excluded from the present analysis because it lacked a measure of full brain volume. This increased the number of unique samples in this study to 20. These 20 coefficients from independent samples were drawn from 11 sources (Aylward, Minshew, Field, Sparks, & Singh, 2002; Castellanos et al., 1994; Frangou, Chitins, & Williams, 2004; Garde, Mortensen, Krabbe, Rostrup, & Larsson, 2000; Giedd, 2003; Ivanovic et al., 2004; Kareken et al., 1995; MacLullich et al., 2002; Nosarti et al., 2002; Shapleske et al., 2002; Staff, 2002) not included in the Gignac et al. review. The increased number of samples over the Gignac et al. review and the decision rule to record data separately by age and sex, permitted the evaluation of both age and sex moderators.

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Analysis Approach. The psychometric meta-analysis approach (Hunter & Schmidt, 1990, 2004) was used. This approach estimates the population correlation by correcting the observed correlations for downward bias due to various artifacts including measurement error and range restriction. Whereas both intelligence measures and MRI-based measures of *in vivo* brain volume have reliabilities in the .90s, correlations were not corrected for measurement error in either variable. However, 16 of the 37 samples reported standard deviation for the intelligence measure. Of these 16 samples, 13 reported the standard deviation of the intelligence measures to be below the population standard deviation of 15. The average (median) of the standard deviations was 12.9 indicating that the observed correlations were, on average, underestimates of the population correlation due to restriction of range on the intelligence measures.

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The analyses are presented in two ways. First, the observed correlations were cumulated without any corrections for range restriction/enhancement. The resulting

mean correlation would likely be an underestimate of the population parameter due to range restriction. Next, the observed correlations were corrected individually for range restriction (three correlations were corrected for range enhancement because the standard deviation of the intelligence measure was larger than the population standard deviation of 15). For those coefficients where the degree of range restriction was not known, the value of 12.9 (the median of the known values) was used. The resulting mean correlation corrected for range restriction is offered as the best estimate of the population parameter. Those who are not comfortable with the interpolation of the range restriction data and/or the range restriction corrections may interpret the mean observed correlation with knowledge that it is likely an underestimate of the population parameter. Those who are comfortable with the range restriction corrections may interpret the mean of the corrected correlations as a reasonable estimate of the population parameter. The pattern of the reported moderators is evident in both the observed and corrected means.

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Results

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The results of the analysis based on 37 correlations that met the decision criteria (Andreasen et al., 1993; Aylward et al., 2002; Castellanos et al., 1994; Egan, Wickett, & Vernon, 1995; Flashman, Andreasen, Flaum, & Swayze, 1998; Frangou, Chitins, & Williams, 2004; Garde et al., 2000; Giedd, 2003; Gur et al., 1999; Ivanovic et al., 2004; Kareken et al., 1995; MacLullich et al., 2002; Nosarti et al., 2002; Pennington et al., 2000; Raz et al., 1993; Reiss et al., 1996; Schoenemann, Budinger, Sarich, & Wang, 2000; Shapleske et al., 2002; Staff, 2002; Tan et al., 1999; Wickett, Vernon, & Lee, 1994; Willerman, Rutledge, & Bigler, 1991) are reported in Table 1. The results for the correlations corrected for the downward bias of range restriction will be discussed in this paper, although results for uncorrected correlations are also shown in the table. The best

unbiased estimate of the population correlation between brain volume and intelligence is .33.

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It is possible that the correlation between brain volume and intelligence in studies that provided standard deviations of intelligence is systematically higher or lower than the studies that did not report standard deviations of intelligence. If this were the case, the interpolation of the standard deviations for those studies that did not report standard deviations might lead to biased estimates of the unattenuated correlation between brain volume and intelligence. To assess this potential problem, the author analyzed the data partitioned by whether the standard deviation was reported in the study or whether it was interpolated. The similarity of the observed correlations (.29 and .30) suggested that the studies that reported standard deviations for intelligence were not systematically different in their average observed correlation. Thus, it is reasonable to interpolate the missing standard deviations from the known standard deviations.

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When the data were subdivided by sex, one obtains three sub-distributions: samples of males, samples of females, and samples that contained both males and females. The relationship between brain volume and intelligence shows a clear sex moderator with the correlation being larger for females than males (.40 vs. .34). For studies in which both males and females were combined in the same sample, the correlation is .25. Assuming this correlation is not an anomaly due to sampling error, it argues for separate reporting of results by sex.

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The data were then subdivided by age into adult and child samples. The analyses restricted to age alone showed no evidence of a moderating effect, however, the mixed sex samples and the uneven distribution of age across sex clouded an effect that is evident when the data were divided hierarchically by sex and then by age. Female adult samples showed a

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somewhat larger population correlation than female children samples (.41 vs .37). Male adult samples showed a larger population correlation than male children samples (.38 vs .22). The hierarchical sex/age results also confirms the sex moderator. Female adult samples showed a higher population correlation than male adult samples (.41 vs .38). Female children samples showed a higher population correlation than male children samples (.37 vs. .22

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An anonymous reviewer requested a significance test on the sex difference. Most applications of psychometric meta-analysis (Hunter & Schmidt, 2004) do not incorporate statistical significance tests. This is in part because the meta-analysis seeks to estimate population parameters and statistical tests are designed for sample data. This is also in part due to the fact that statistical tests do not answer the questions that most users think they answer (Cohen, 1994; Hunter & Schmidt, 2004). However, in deference to the reviewer, statistical significance tests are reported here. Statistical tests in meta-analysis focus on whether the observed variance in the distribution of effect sizes is different from the variance one would expect from sampling error alone. A chi-square significance test on the distribution of 37 effect sizes was statistically significant ($p < .0003$) indicating that some of the variance in the distribution is not due to sampling error and thus might be due to moderators. Thus, on the basis of the statistical significance test, the moderator analyses for interpolation, age and sex were warranted. With respect to the sex moderator analysis, the significance test was not statistically significant for females ($p < .065$) but was significant for males ($p < .014$) and for the mixed sex samples ($p < .017$). One interpretation of these significance tests is that there are no moderators within the effect size distribution for females but there are moderators with the distribution of males and within the distribution of mixed-sex samples. Based on this interpretation, the age within sex analyses for females

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was not warranted while the age within sex analysis was warranted for the males and the mixed-sex samples. However, the significance of the chi-square analyses is a function of the sample size. At least by meta-analysis standards, all these sample sizes are small. Thus, a second interpretation, and the one favored by the author, is that the distribution of effect sizes from female samples needs more data to reach significance. Based on this interpretation, the search for age within sex analyses for females is reasonable and should be replicated as more data cumulate.

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Discussion

This study's best estimate of the correlation between brain volume and intelligence is .33. The correlation is higher for females than males. It is higher for adults than children. Regardless of the subgroups examined, the correlation between brain volume and intelligence is always positive. It is very clear that brain volume and intelligence are related.

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<u>Data Reporting and Availability Issues</u>

There is much cause for concern regarding the reporting practices of research in this area. Few studies reported means and standard deviations and a zero-order correlation matrix among the variables. The lack of reported standard deviations makes it impossible to estimate precisely the effect of range restriction in these data. The lack of a correlation matrix results in excluding data from this analysis and thus increases publication bias concerns. Publication bias analyses for these data were not conducted because some procedures assume that the results are homogeneous (i.e., lacking moderators) (Terrin, Schmid, Lau, & Olkin, 2003). These data clearly show evidence of both sex and age moderators. The data distributions subdivided by both sex and age may be homogeneous but the number of correlations in these distributions were judged too few to conduct meaningful

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publication bias analyses. As future data accumulate, these analyses should be re-conducted and publication bias analyses should be pursued.

Given the evidence of age and sex moderators in these data, more research reporting results separately by age and sex is warranted. Potential race moderators were not examined due to the relative lack of non-Caucasians in the samples and the failure to report correlations separately by race.

Additional research

In addition to more research with better reporting, two additional areas deserve greater research attention. The first area is an examination of the brain volume and intelligence relationship at a more refined level of analysis than total brain volume. For example, although Staff's (2002) results indicated a small negative correlation between brain volume and intelligence, the fraction of brain volume that was gray matter was correlated .35 with intelligence. Likewise MacLullich et al., (2002) examined the relationship between regional brain volumes (e.g., left and right hippocampus, left and right frontal lobe, left and right temporal lobe) with intelligence. The author had considered including in this meta-analysis an analysis of regional brain volumes with intelligence but there were too few studies to analyze. The second area worthy of increased attention is the genetic contribution to the brain volume and intelligence relationship. The research in this area is both recent and rapidly growing (Molloy, Rapoport, & Giedd, 2002; Pennington et al., 2000; Posthuma et al., 2002; Posthuma et al., 2003; Schoenemann et al., 2000; Thompson et al., 2001). These two research areas will help us to better understand the causal relationship between brain volume and intelligence.

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Conclusion

This paper contributes to the literature in three ways. First, the study more than doubles the number of unique samples that address the *in vivo* brain volume and intelligence relationship. Second, it also contributes by testing age and sex moderators of the relationship. The relationship is stronger for females than males and is stronger for adults than children. Finally, it resolves a 169 year-old debate. Tiedmann (1836) was correct to conclude that intelligence and brain volume are meaningfully related.

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Table 1. Comparison of the data reported by Gignac et al. (2003) and the current study

	Included in Gignac, Vernon & Wickett (2003)	Included in Current Study	*N*	*r*	Sex/race/age information
Aylward et al. (2002)	No	Yes[1]	46	-.13	Male, white, children
Aylward et al. (2002)	No	Yes[1]	30	.08	Mixed sex, white, adults
Andreasen et al. (1993)	Yes, data based on sample containing both males and females	Yes, data reported separately by sex	37	.40	Male, unknown race, adults
			30	.44	Female, unknown race, adults
Castellanos et al. (1994)	No	Yes	46	.33	Male, unknown race, children
Egan et al. (1994,1995)	Yes, used 1994 data[2]	Yes, used 1995 data[2]	40	.31	Mostly male[2], unknown race, adults
Flashman et al. (1998)	Yes	Yes	90	.25	Mixed sex, unknown race, adults
Frangou et al. (2004)	No	Yes	40	.41	Mixed sex, unknown race, mostly children[6]
Garde et al. (2000)	No	Yes[1]	46	.07	Male, white, adults
			22	.22	Female, white, adults
Giedd (2003)	No	Yes	7	-.67	Female, not white and not black, children
			8	.46	Female, black, children
			39	.34	Female, white, children
			7	.17	Male, black, children
			63	.27	Male, white, children
			7	.67	Male, not white and not black, children
Gur et al. (1999)	Yes, data based on sample containing both males and females	Yes, data reported separately by sex	40	.39	Male, unknown race, adults
			40	.40	Female, unknown race, adults
Ivanovic et al. (2004)	No	Yes	47	.55	Male, unknown race, adults
			49	.37	Female, unknown race, adults
Kareken et al. (1995)	No	Yes[1]	68	.30	Mixed sex, unknown race, adults

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	Included in Gignac, Vernon & Wickett (2003)	Included in Current Study	*N*	*r*	Sex/race/age information
MacLullich et al. (2002)	No	Yes	97	.39	Male, white, adults
Nosarti et al. (2002)	No	Yes[1]	42	.37	Mixed sex, white, children
Pennington et al. (2000)	Yes[3]	Yes	36	.31	Mixed sex, mixed race, children
Raz et al. (1993)	Yes	Yes	29	.43	Mixed sex, unknown race, adults
Reiss et al. (1996)	Yes, data based on sample containing both males and females	Yes,[1] data reported separately by sex	12	.52	Male, white[4], children
			57	.37	Female, white[4], children
Schoenemann et al. (2000)	Yes[5]	Yes[5]	72	.21	Female, unknown race, adults
Shapleske et al. (2002)	No	Yes[1]	23	.13	Male, white, adults
			3	-.86	Male, black, adults
Staff (2002)	No	Yes	106	-.08	Mixed sex, white, adults
Tan et al. (1999)	Yes, data based on sample containing both males and females	Yes, data reported separately by sex	49	.28	Male, white, adults
			54	.62	Female, white, adults
Tramo et al. (1998)	Yes, the authors used a forebrain volume measure.	No, There is no full brain volume measure in this study	-	-	-
Wickett et al. (1994)	Yes	Yes	40	.40	Female, unknown race, adults
Wickett et al. (2000)	Yes	Yes	68	.35	Male, unknown race, adults
Willerman et al. (1991)	Yes, data based on sample containing both males and females	Yes, data reported separately by sex	20	.51	Male, unknown race, adults
			20	.33	Female unknown race adults

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1. Data from this study were supplemented by communication with the author(s). This communication resulted in correlations that were not reported in the original study.
2. In Egan et al. (1994), the sample was described as 48 males and two females. Egan et al. (1995) reported corrected analyses using a sample of 40. This sample of 40, being a subset of the 48 could have had no more than 2 females and was classified as a male sample in the analysis.
3. Gignac et al. (2003) also included a correlation from a sample of twins where at least one of each twin pair had a learning disability. The current study excluded the sample because it was not consider clinically normal.
4. In personal communication to the author (10/17/2002), Dr. Reiss described the race of the sample as being “great majority white”.

5. Gignac et al. (2003) reported a correlation of .45 which was the partial correlation between the first principal component of a battery of test and brain volume controlling for age and simple reaction time. The author used the correlation between brain volume and the Ravens which was provided to us by Dr. Schoenemann on November 14, 2002.
6. The sample used by Frangou, Chitins, & Williams (2004) had an age range of 12 to 21. Based on the mean and standard deviation of age, it appeared that most of the sample was under 18. We classified the sample as "children."

Note: Correlation coefficients in this table were rounded to two decimal places. The statistical analysis did not use rounded correlation coefficients.

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Table 2. Meta-Analytic Results for *In Vivo* Brain Volume and Intelligence

Distribution	Number of Studies	Sample Size	Observed Mean Correlation	Mean Correlation Corrected for Range Restriction
All Correlations	37	1,530	.29	.33
Analyses by Whether the Degree of Range Restriction Was Interpolated				
Interpolation	21	963	.29	.32
No Interpolation	16	567	.30	.34
Analyses by Sex				
Females	12	438	.36	.40
Males	17	651	.30	.34
Mixed sex	8	441	.21	.25
Analyses by Age				
Adults	24	1,120	.30	.33
Children	13	410	.28	.33
Analyses by Age and Sex				
Female Adults	8	327	.38	.41
Female Children	4	111	.30	.37
Male Adults	11	470	.34	.38
Male Children	6	181	.21	.22

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