

## Gray matter heritability in family-based and population-based studies using voxel-based morphometry

van der Lee, Sven J.; Roshchupkin, Gennady V.; Adams, Hieab H.; Schmidt, Helena; Hofer, Edith; Saba, Yasaman; Schmidt, Reinhold; Hofman, Albert; Amin, Najaf; van Duijn, Cornelia M.

**DOI**

[10.1002/hbm.23528](https://doi.org/10.1002/hbm.23528)

**Publication date**

2017

**Document Version**

Accepted author manuscript

**Published in**

Human Brain Mapping

**Citation (APA)**

van der Lee, S. J., Roshchupkin, G. V., Adams, H. H., Schmidt, H., Hofer, E., Saba, Y., Schmidt, R., Hofman, A., Amin, N., van Duijn, C. M., Vernooij, M. W., Ikram, M. A., & Niessen, W. J. (2017). Gray matter heritability in family-based and population-based studies using voxel-based morphometry. *Human Brain Mapping, 38*(5), 2408-2423. <https://doi.org/10.1002/hbm.23528>

**Important note**

To cite this publication, please use the final published version (if applicable). Please check the document version above.

**Copyright**

Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

**Takedown policy**

Please contact us and provide details if you believe this document breaches copyrights. We will remove access to the work immediately and investigate your claim.

# Grey matter heritability in family-based and population-based studies using voxel-based morphometry

Sven J. van der Lee\*<sup>1</sup>, Gennady V. Roshchupkin \*<sup>2,4</sup>, Hieab H.H. Adams\*<sup>1,2</sup>,

Helena Schmidt<sup>6,7</sup>, Edith Hofer<sup>8,9</sup>, Yasaman Saba<sup>6</sup>, Reinhold Schmidt<sup>8</sup>,

Albert Hofman<sup>1</sup>, Najaf Amin<sup>1</sup>, Cornelia M. van Duijn<sup>1</sup>, Meike W. Vernooij<sup>1,2</sup>, M. Arfan Ikram<sup>1,2,5</sup>,

Wiro J. Niessen<sup>2,3,4</sup>

\*Authors contributed equally

<sup>1</sup> Department of Epidemiology, Erasmus Medical Center, Rotterdam, Netherlands,

<sup>2</sup> Department of Radiology and Nuclear Medicine, Erasmus Medical Center, Rotterdam, Netherlands

<sup>3</sup> Faculty of Applied Sciences, Delft University of Technology, Delft, Netherlands

<sup>4</sup> Department of Medical Informatics, Erasmus Medical Center, Rotterdam, Netherlands

<sup>5</sup> Department of Neurology, Erasmus Medical Center, Rotterdam, Netherlands

<sup>6</sup> Institute of Molecular Biology and Biochemistry, Centre for Molecular Medicine, Medical University of Graz, Austria

<sup>7</sup> Department of Neurology, Medical University Graz, Austria

<sup>8</sup> Clinical Division of Neurogeriatrics, Department of Neurology, Medical University Graz, Austria

<sup>9</sup> Institute of Medical Informatics, Statistics and Documentation, Medical University Graz, Austria

**Word count manuscript: 10037**

**References: 58**

**Figures: 3**

**Tables: 2**

**Supplementary figures: 1**

**Website:** [www.imagene.nl/heritability](http://www.imagene.nl/heritability)

**Short title: Grey matter heritability map of the brain**

**Keywords:** brain structure heritability; genetics; magnetic resonance imaging; grey matter; family-based study; population-based study; voxel-based morphometry

## Correspondence:

W. J. Niessen, PhD, Department of Medical Informatics, Erasmus Medical Center,  
Dr. Molewaterplein 50, 3015 GE, Rotterdam, the Netherlands.

**Phone nr.:** +31 10 70 43050 / **Fax nr.:** +31 10 70 44722 / **E-mail:** [w.niessen@erasmusmc.nl](mailto:w.niessen@erasmusmc.nl)

**Abstract** (250 words)

**Background:** The combination of genetics and imaging has improved our understanding of the brain through studies of aggregate measures obtained from high-resolution structural imaging. Voxel-wise analyses have the potential to provide more detailed information of genetic influences on the brain. Here we report a large-scale study of the heritability of grey matter at voxel resolution (1×1×1mm).

**Methods:** Validated voxel-based morphometry (VBM) protocols were applied to process magnetic resonance imaging data of 3239 unrelated subjects from a population-based study and 491 subjects from two family-based studies. Genome-wide genetic data was used to estimate voxel-wise gray matter heritability of the unrelated subjects and pedigree-structure was used to estimate heritability in families. We subsequently associated two genetic variants, known to be linked with subcortical brain volume, with most heritable voxels to determine if this would enhance their association signals. **Results:** Voxels significantly heritable in both estimates mapped to subcortical structures, but also voxels in the language areas of the left hemisphere were found significantly heritable. When comparing regional patterns of heritability, family-based estimates were higher than population-based estimates. However, regional consistency of the heritability measures across study designs was high (Pearson's correlation coefficient=0.73,  $p=2.6\times 10^{-13}$ ). We further show enhancement of the association signal of two previously discovered genetic loci with subcortical volume by using only the most heritable voxels. **Conclusion:** Grey matter voxel-wise heritability can be reliably estimated with different methods. Combining heritability estimates from multiple studies is feasible to construct reliable heritability maps of grey matter voxels.

## 1. Introduction

1 The human brain shows large inter-individual variation, which could be explained by genetic and  
2 environmental influences. Studying these influences is essential in better understanding brain  
3 structure and function. The degree to which genetics explains phenotypic variation, in other words  
4 heritability, depends on many factors: the actual genetic contribution to the trait, environmental  
5 effects, measurement error, study design and sample characteristics [Visscher, et al., 2008; Visscher,  
6 et al., 2006; Yang, et al., 2010]. Recently an overview was published of fifty years of worldwide  
7 heritability research in twins encompassing thousands of traits, showing heritability studies are  
8 highly informative on how large the genetic contribution to a trait is [Polderman, et al., 2015].  
9 Heritability studies could aid future genetic research to focus on particular regions of interest in the  
10 brain. For example, large scale genetic studies of brain structures with the highest heritability  
11 typically yield the most findings [Hibar, et al., 2015]. When studying the multitude of measures of  
12 voxel based magnetic resonance imaging (MRI), limiting genetic studies to the most heritable traits  
13 could be feasible in light of multiple testing. Recent studies have focused on heritability of detailed  
14 MRI measures at a voxel level [Brouwer, et al., 2010; Ganjgahi, et al., 2015; Jahanshad, et al., 2013;  
15 Jahanshad, et al., 2010; Kochunov, et al., 2016; Kochunov, et al., 2010; Kochunov, et al., 2015].  
16 Different study designs showed comparably high estimates for white matter tract heritability in twin  
17 pairs [Brouwer, et al., 2010; Kochunov, et al., 2010], sib-pairs [Jahanshad, et al., 2010] and extended  
18 pedigrees (heritability = 50-90%) [Ganjgahi, et al., 2015]. The heritability of grey matter was studied  
19 by voxel-based morphometry (VBM) previously [Hulshoff Pol, et al., 2006; Peper, et al., 2009;  
20 Thompson, et al., 2001], but the studies were relatively small and relatively large voxels were  
21 studied. Moreover, heritability of grey matter VBM has not been estimated in population-based  
22 studies.  
23  
24 Here, we perform a large multi-site study to estimate the voxel-wise heritability of grey matter. We  
25 calculate pedigree-based heritability in two family-based studies and heritability based on genome-

26 wide genetic data in a large population-based study of unrelated subjects. Using these approaches,  
27 we created two grey matter heritability maps and described which regions contain significantly  
28 heritable voxels in both designs. We furthermore estimated overall regional consistency of the  
29 heritability measures across study designs and explored if usage of our heritability maps could  
30 potentially enhance association signals of two genetic variations, previously discovered by genome-  
31 wide association studies [Bis, et al., 2012; Hibar, et al., 2015; Stein, et al., 2012].

32

## 33 **2. Methods**

### 34 **Study subjects and imaging protocol**

35 Rotterdam Study – The Rotterdam Study is a population-based cohort study among inhabitants of a  
36 district of Rotterdam (Ommoord), The Netherlands, and aims to examine the determinants of  
37 disease and health in the elderly with a focus on neurogeriatric, cardiovascular, bone, and eye  
38 disease [Hofman, et al., 2015]. In 1990 to 1993, 7983 persons participated and were re-examined  
39 every 3 to 4 years (RS-I). In 2000 to 2001 the cohort was expanded by 3011 persons who had not yet  
40 been part of the Rotterdam Study (RS-II). All participants had DNA extracted from blood at their first  
41 visit. In 2006-2008 a second expansion (RS-III) of 3,932 persons aged 45 and over was realized.

42 Genotyping was performed at the Human Genotyping Facility, Genetic Laboratory Department of  
43 Internal Medicine, Erasmus MC, Rotterdam. Genotypes were imputed to the 1000 genomes phase I  
44 version 3 reference panel, using standard methods and software [Willer, et al., 2008]. From 2005  
45 onwards MRI is part of the core protocol of the Rotterdam study [Ikram, et al., 2015]. For this study  
46 a total of 4071 unique study participants had both MRI and genetic data and were available for  
47 analysis. The Rotterdam Study has been approved by the Medical Ethics Committee of the Erasmus  
48 MC and by the Ministry of Health, Welfare and Sport of the Netherlands, implementing the Wet  
49 Bevolkingsonderzoek: ERGO (Population Studies Act: Rotterdam Study). All participants provided  
50 written informed consent to participate in the study and to obtain information from their treating  
51 physicians.

52 Erasmus Rucphen Family (ERF) – The ERF study is a family-based cohort study in a genetically  
53 isolated population from a community in the South-West of the Netherlands (Rucphen municipality)  
54 including 3000 participants. Participants are all descendants of a limited number of founders living in  
55 the 19th century, and all of Caucasian European descent. Extensive genealogical data is available for  
56 this population. The study population is described in detail elsewhere [Sayed-Tabatabaei, et al.,  
57 2005]. In a follow-up analysis, non-demented hypertensive (systolic blood pressure  $\geq 160$ , diastolic  
58 blood pressure  $\geq 100$  or use of antihypertensive medication) subjects aged 55-75 years were  
59 included for a new battery of tests, including MRI scanning [Ibrahim-Verbaas, et al., 2012]. These  
60 122 participants from the ERF were related to each other in one large pedigree. This large pedigree  
61 was split into multiple small pedigrees for heritability calculations (pedcut version 1.19  
62 <http://mga.bionet.nsc.ru/soft/>). Participants related to each other in 27 families with in total 880  
63 relatives. The average size of the pedigrees was 32.6 relatives (range 20-44) with on average 4.5  
64 participants with MRI per family. All participants gave informed consent to participate in the study  
65 and to obtain information from their treating physicians. The study was approved by the medical  
66 ethics committee at Erasmus MC University Medical Center, Rotterdam, The Netherlands.

67

68 MRI scanning for ERF and the Rotterdam Study was done on the same 1.5 T MRI unit (GE Healthcare,  
69 Milwaukee, USA, Signa Excite software version 11x) fitted with a dedicated 8-channel head coil. The  
70 T1-weighted, proton density-weighted (PDw) and fluid-attenuated inversion recovery (FLAIR)  
71 sequences were used [Ikram, et al., 2015]. For the purpose of segmentation, the T1w scan is  
72 acquired in 3D at high in-plane resolution and with thin slices (voxel size  $< 1 \text{ mm}^3$  [Ikram, et al.,  
73 2015].

74

75 Austrian Stroke Prevention Study (ASPS) – The ASPS study is a single-center, prospective follow-up  
76 study on the effects of vascular risk factors on brain structure and function in the normal elderly  
77 population of the city of Graz, Austria. The procedure of recruitment and diagnostic work-up of

78 study participants has been described previously [Schmidt, et al., 1999; Schmidt, et al., 1994].  
79 Between 2006 and 2013 the study was extended for the Austrian Stroke Prevention Family Study  
80 (ASPS-Fam) [Seiler, et al., 2014]. Study participants of the ASPS and their first grade relatives were  
81 invited to enter ASPS-Fam. Inclusion criteria were no history of previous stroke or dementia and a  
82 normal neurological examination. In total 176 families connecting a total of 719 relatives, among  
83 which 369 were study participants with brain-MRI. The average size of the pedigrees was 4 (range 1-  
84 10) relatives with on average 2.4 participants with MRI per family. The diagnostic work-up was  
85 identical to the original study. The study protocol was approved by the ethics committee of the  
86 Medical University of Graz, Austria, and written and informed consent was obtained from all  
87 subjects. MRI scanning of the ASPS-Fam was done on a 3.0 T Tim Trio (Siemens, Erlangen). T1-  
88 MPAGE 1×1×1mm was used for image processing [Seiler, et al., 2014].

89

## 90 **Image processing**

91 Prior to analysis, a number of pre-processing steps were performed. For multispectral image  
92 analysis, the different scans were spatially registered using rigid registration [Ikram, et al., 2015].  
93 Subsequently, the brain was extracted from the scan. Hereto a manually segmented brain mask,  
94 which excludes cerebellum, eyes and skull, was non-rigidly registered to the T1-weighted image  
95 using Elastix [Ikram, et al., 2015]. Finally, scans were corrected for intensity non-uniformity using the  
96 N3 method; non-uniformity correction was carried out within the brain mask [Ikram, et al., 2015]. All  
97 T1-weighted images were segmented into supra-tentorial grey matter (GM), white matter (WM) and  
98 cerebrospinal fluid (CSF). For the Rotterdam Study and ERF, we used a previously described  
99 k-Nearest-Neighbor (kNN) algorithm, which was trained on six manually labeled atlases [Vrooman, et  
100 al., 2007]. For the ASPS-Fam study a Quantib BV tissue segmentation tool was applied  
101 ([www.quantib.org](http://www.quantib.org)). Quantib® software implements the same algorithm, which we then used for  
102 tissue segmentation in the Rotterdam Study and ERF. There are thus no methodological differences

103 between the methods, both of them based on kNN-based segmentation training on manually  
104 labeled subjects for segmenting GM, WM and CSF.  
105  
106 Voxel-based morphometry (VBM) was performed by the same optimized VBM protocol in all three  
107 studies [Good, et al., 2001] and previously described [Roshchupkin, et al., 2016a]. FSL software  
108 [Smith, et al., 2004] was used for VBM data processing. First, all GM density maps were non-linearly  
109 registered to the standard GM probability template. For this study we chose the MNI152 GM  
110 template (Montreal Neurological Institute) with a 1×1×1 mm voxel resolution [Fonov, et al., 2011].  
111 The MNI152 standard-space T1-weighted average structural template image is derived from 152  
112 structural images, which have been warped and averaged into the common MNI152 coordinate  
113 system after high-dimensional nonlinear registration. A spatial modulation procedure was used to  
114 avoid differences in absolute grey matter volume due to the registration. This involved multiplying  
115 voxel density values by the Jacobian determinants estimated during spatial normalization. To  
116 decrease signal to noise ratio, all images were smoothed using a 3 mm (FWHM 8 mm) isotropic  
117 Gaussian kernel. Thus all results are in MNI space. Brain regions were segmented using atlas-based  
118 segmentation based on the Hammer atlas [Hammers, et al., 2003]. The modulation step in the VBM  
119 pipeline preserves the volume of a particular tissue within a voxel. The multiplication of the voxel  
120 values in the segmented images by the Jacobian determinants derived from the spatial  
121 normalization step allows us to calculate volumes by aggregating voxels. In total we estimated  
122 heritability for 1,405,508 grey matter voxels in all three studies.

123

#### 124 **Reproducibility VBM measures**

125 **We investigated the test-retest reliability of the VBM measures in a subset of 83 persons who**  
126 **were scanned twice within 1-9 weeks. We quantified the reproducibility by calculating the**  
127 **intraclass correlation (ICC) of the gray matter density measures for every voxel (Online viewer,**  
128 **Supplementary Figure 1)[Shrout and Fleiss, 1979]**



129

## 130 **Heritability analysis**

131 Population-based heritability estimates were calculated using Genome-wide Complex Trait Analysis  
132 (GCTA v1.24) [Yang, et al., 2011] (<http://cnsgenomics.com/software/gcta/>) in the population-based  
133 Rotterdam Study. GCTA implements REML (restricted maximum likelihood) analysis, this method  
134 compares genotypic similarity between individuals to their phenotypic similarity. **Formula's**  
135 **underlying the GCTA method to determine heritability estimates are described elsewhere [Yang,**  
136 **et al., 2010] and thoroughly explained in a commentary by the authors [Visscher, et al., 2010].** The  
137 1000 Genomes imputed genotypes (Imputation quality (Rsq) > 0.5 and minor allele frequency (MAF)  
138 > 0.01) were used to create a genetic relationship matrix (GRM) in GCTA [Adams, et al., 2016]. **The**  
139 **power of GCTA analysis is determined by pair-wise genetic relationships in the studied population**  
140 **[Visscher, et al., 2010; Yang, et al., 2010]. Therefore the three cohorts of the Rotterdam study**  
141 **were combined and analyzed as one in the voxel-wise heritability analysis.** Pairwise genetic  
142 relatedness between all individuals (N=4071) was calculated and for pairs with more than 0.02  
143 genotype similarity [Adams, et al., 2016] one person was removed (N<sub>removed</sub> = 832). REML analysis  
144 was then performed in the remaining 3239 unrelated subjects using the GRM correcting for age and  
145 sex. All grey matter heritability was estimated once.

146 Family-based heritability was estimated using maximum-likelihood variance components methods  
147 implemented in the SOLAR (version 6.6.2) [Almasy and Blangero, 1998] software. Formulas for the  
148 calculation of heritability estimates are described in detail elsewhere [Almasy and Blangero, 1998].  
149 Briefly, the algorithms in SOLAR employ maximum likelihood variance decomposition methods. The  
150 covariance matrix  $\Omega$  for a pedigree of individuals is given by:

151

$$\Omega = 2 \cdot \Phi \cdot \sigma_g^2 + I \cdot \sigma_e^2$$

152

153 where  $\sigma_g^2$  is the genetic variance due to the additive genetic factors,  $\Phi$  is the kinship matrix  
154 representing the pair-wise kinship coefficients among all individuals,  $\sigma_e^2$  is the variance due to  
155 individual-specific environmental effects, and  $I$  is an identity matrix (under the assumption that all  
156 environmental effects are uncorrelated among family members). Narrow sense heritability is defined  
157 as the fraction of phenotypic variance  $\sigma_p^2$  attributable to additive genetic factors:

$$h^2 = \frac{\sigma_g^2}{\sigma_p^2}.$$

159  
160 The variance parameters are estimated by comparing the observed phenotypic covariance matrix  
161 with the covariance matrix predicted by kinship (Almasy and Blangero, 1998). Significance of  
162 heritability is tested by comparing the likelihood of the model in which  $\sigma_g^2$  is constrained to zero  
163 with that of a model in which  $\sigma_g^2$  is estimated. Twice the difference between the  $\log_e$  likelihoods of  
164 these models yields a test statistic, which is asymptotically distributed as a ½:½ mixture of a  $\chi^2$   
165 variable with 1 degree-of-freedom and a point mass at zero. If the algorithm converges SOLAR  
166 outputs the heritability value, the significance value (p), and the standard error for each voxel  
167 [Almasy and Blangero, 1998; Kochunov, et al., 2015].

168 ERF study and ASPS-Fam were not jointly analysed because ERF subjects were scanned on a 1.5T MRI  
169 and ASPS-Fam subjects on a 3.0T MRI. Instead inverse variance meta-analysis using heritability and  
170 heritability standard errors was performed in METAL [Willer, et al., 2010] to boost power and  
171 improve stability of heritability estimates [Jahanshad, et al., 2013]. Heritability estimates were  
172 calculated in both studies with age and sex as covariates. Variance component methods  
173 implemented in SOLAR are vulnerable for inflation if phenotypes have a leptokurtic to distribution.  
174 Therefore we applied inverse normal transformations in SOLAR to all voxels, but some voxels still  
175 violated the distribution of too high residual kurtosis (kurtosis >0.9) and were therefore excluded  
176 [Blangero, et al., 2001]. Non converging heritability estimates of 0 without standard errors were also

177 excluded from the meta-analysis. **In the family-based studies some voxels had valid p-values and a**  
178 **heritability of 1, but missing standard errors. These voxels were located in the middle of voxel-**  
179 **clusters with high heritability (online viewer reference) (close to 1). Therefore standard errors for**  
180 **such voxels were imputed to retain these voxels for meta-analysis. This resulted in imputation of**  
181 **the standard error for 6.4% of voxels in the ERF study and a negligible percentage of voxels in**  
182 **ASPS-Fam (<0.001%).**

183

#### 184 **Enhancement of association signal**

185 We explored whether voxel heritability information could enhance the association of genetic  
186 variants with brain structures. The genetic variants most significantly associated with hippocampal  
187 volume (rs77956314 on 12q24.22, near the gene *HRK*) and putamen volume (rs945270 on 14q22.3,  
188 downstream of the gene *KTN1*) were selected from a recently published genome-wide association  
189 study on subcortical structures [Hibar, et al., 2015]. To select the most heritable voxels in the  
190 hippocampus and putamen, we ordered them using three approaches. First, we ranked the voxels  
191 from low to high family-based heritability estimates. Second, we ranked them from low to high  
192 population-based heritability estimates. In the third approach we summed the ranks obtained from  
193 both the family- and population-based estimates and used the sum of the ranks to prioritize the  
194 voxels. Using these three approaches we excluded the voxels in a step-wise manner by removing the  
195 5% least heritable voxels. For each step we computed the volume by summing the values of the  
196 remaining voxels. As a voxel represents grey matter density in  $1 \text{ mm}^3$ , the sum of voxels gives the  
197 volume of grey matter. We determined the association of the two genetic variants in an additive  
198 model with the volumes in linear regression analyses (adjusted for age, sex, and the first three  
199 principal components) and compared this to association of the volume derived from all voxels  
200 mapped to the structure (i.e. the total VBM-volume of the hippocampus or putamen). The p-value of  
201 the association of the genetic variants with the subsets of voxels divided by the p-value of the  
202 association of the genetic variants with the total VBM-volume was calculated to measure change in

203 the strength of the association. Genetic effects were calculated in the three cohorts of the  
204 Rotterdam study separately (RS-I = 844, RS-II = 1003, RS-III = 2190) and were combined using an  
205 inverse variance weighted meta-analysis in METAL [Willer, et al., 2010].  
206

### 207 **Statistical analysis**

208 Descriptive statistics were compared using one-way ANOVA and chi-squared tests. **To correct for**  
209 **multiple comparisons we applied FDR p-value thresholds [Benjamini and Hochberg, 1995] for both**  
210 **population and family heritability separately to declare which voxels are significantly heritable.**

## 211 **3. Results**

### 212 **Population characteristics**

213 Characteristics of the study population are shown in **Table 1**. The spread of the age of subjects in the  
214 ERF study (age range 55-76) was smaller compared to ASPS-Fam (38-86) and the Rotterdam Study  
215 (46-98) due to the fact that inclusion criteria for scanning was restricted to midlife (**Table 1**).

216 However, the average age at the time of MRI-scanning of the cohorts was very similar, ranging from  
217 64.3 ( $\pm 4.5$ ) years in the ERF study, 64.9 ( $\pm 10.7$ ) years in ASPS and 64.9 ( $\pm 10.7$ ) in the Rotterdam  
218 Study ( $p = 0.86$ ). The percentage of women was 52.5% in ERF, 60.4% in ASPS-Fam and 55.3% in the  
219 Rotterdam study, these differences were non-significant ( $p = 0.13$ ) (**Table 1**).

220

### 221 **Heritability estimates**

222 In total 454,184 (33.3% of all voxels) were FDR-significant in the family-based estimates. Mean  
223 heritability of significant voxels was  $0.44 \pm 0.12$  SD (**all voxels  $0.29 \pm 0.17$  SD**), with heritability  
224 estimates ranging from 0.23 to 1. In total 68,616 (4.9% of all voxels) were FDR-significant in the  
225 population-based estimates. Mean heritability of the significant voxels was  $0.34 \pm 0.04$  SD (**all voxels**  
226  **$0.11 \pm 0.10$** ), with heritability estimates ranging from 0.25 to 0.56. We found heritability of 44,349

227 voxels (3.2% of all voxels) to be FDR significant in the family- as well as the population-based  
228 heritability estimates. These significantly heritable voxels were clustered, mostly within subcortical  
229 brain structures (**Figure 1**). **Table 2** shows the percentage of voxels that were significantly heritable  
230 of the total of voxels in a structure in both estimates, as well as the average regional heritability,  
231 considering all voxel-wise heritability estimates. Highest percentage of significantly heritable in both  
232 estimates voxels were located in the caudate nucleus (right 72.4% and left 68.6%) followed by the  
233 putamen (right 57.5% and left 32.6%). Other subcortical structures with a large percentage of  
234 significantly heritable voxels were; left pallidum (32.2%), left nucleus accumbens (29.7%), right  
235 pallidum (28.5%), left amygdala (21.4%), left hippocampus (17.9%), left thalamus (14.4%), right  
236 amygdala (12.8%) and the right insula (11.4%). Apart from the subcortical structures, parts of the  
237 right lateral occipitotemporal gyrus (gyrus fusiformis) (10.4%), left straight gyrus (gyrus rectus)  
238 (10.4%), left subcallosal area (8.0%) and the left lingual gyrus (7.9%) harbored a proportion  
239 significantly heritable voxels (**Table 2 and Figure 1**).

240 When comparing regional heritability, estimates calculated in families was always higher than the  
241 population-based estimates ( $p < 0.001$ ) (**Figure 2 A**) and the difference in heritability between family-  
242 based estimates and population-based estimates was relatively stable (mean difference of regional  
243 heritability =  $0.21 \pm 0.08$ ) (**Table 2**). Therefore, the regional heritability pattern of the family-based  
244 estimates significantly predicted the regional pattern of heritability in the population-based study  
245 (Pearson's correlation coefficient = 0.73,  $p = 2.6 \times 10^{-13}$ ) (**Figure 2 B**).

246

#### 247 **Enhancement of association signal**

248 We explored if applying our heritability map could enhance the statistical association signal of  
249 previously discovered genome-wide significant loci. As expected the T-allele of rs77956314 (*HRK*)  
250 associated with a smaller total volume of the hippocampus ( $p = 5.1 \times 10^{-7}$ ) and the C-allele of  
251 rs945270 (*KTN1*) significantly associated with larger total volume of the putamen ( $p = 4.3 \times 10^{-3}$ ).

252 When excluding the less heritable voxels the average heritability in the remaining voxels increased  
253 **(Figure 3 A and 3 B). With rising average heritability we observed a gradual decrease in p-values**  
254 **(Figure 3C), and consequently a more significant association of HRK with the more heritable part**  
255 **of the hippocampus.** The maximum enrichment of association was reached when the 10% most  
256 significantly heritable voxels when combining heritability information from family-based and  
257 population-based studies was used. This increase corresponds to a 95.9 times more significant  
258 association, as the  $p$ -value decreased from  $p=5.1 \times 10^{-7}$  to  $p = 5.4 \times 10^{-9}$ . **Using only the family-based**  
259 **estimates the association was 12.9 times more significant. A less substantial decrease in p-value**  
260 **was observed for the association of KTN1 with the more heritable part of the putamen (Figure 3**  
261 **D).** The  $p$ -value decreased when restricting to voxels that belong to the 25% most heritable voxels  
262 from the only the family-based study. This corresponds to a 5.5 times more significant association ( $p$ -  
263 value decrease from  $p = 4.3 \times 10^{-3}$  to  $p = 7.9 \times 10^{-4}$ ).

264

## 265 Discussion

266 In this study we presented grey matter voxel heritability maps at resolution of  $1 \times 1 \times 1$  mm from  
267 population- and family-based studies. First we found that clusters of voxels that are significantly  
268 heritable in family-based heritability estimates as well as in an unrelated population-based study are  
269 predominantly located in subcortical regions. Second, when comparing the overall regional patterns  
270 of voxel-wise heritability the family-based estimates were always higher compared to population-  
271 based estimates and predicted the population-based heritability estimates. Lastly, we showed that  
272 the heritability estimates from our studies could be used to enhance the association signal of two  
273 genetic variants with subcortical volumes.

274 **Voxels with significant heritability formed clusters within mainly the subcortical structures. This is**  
275 **in line with the findings of previous studies that the volumes of subcortical structure are among**  
276 **the most heritable in the brain [Blokland, et al., 2012].** There are multiple explanations for this

277 consistent finding. First, subcortical structures probably are under tight genetic control as they exert  
278 vital functions within the brain. **The percentage of significantly heritable voxels was relatively low**  
279 **in the frontal and parietal lobes. Although intra-individual measurability was high throughout the**  
280 **brain (Supplementary Figure 1), intra-individual differences in cortical folding patterns could**  
281 **explain the lower heritability in frontal and parietal regions. These might give a reliable**  
282 **measurability of the voxels, while it makes comparisons of voxel values between individuals less**  
283 **meaningful, thus yielding a lower heritability compared with the subcortical structures.** Finally,  
284 environmental effects could have a larger effect on cortical grey matter compared to subcortical  
285 structures. **As the effects of non-genetic factors (e.g. lifestyle factors) accumulate over an**  
286 **individual's lifetime, the heritability of total brain volume and brain structures volume was found**  
287 **to reduce in adulthood up until old age [Batouli, et al., 2014] in line with the accumulation of**  
288 **environmental influences over age. Their reported maximum age was 70 years. We studied**  
289 **relatively old participants (~65 years), therefore study participants might have reduced estimated**  
290 **heritability because of their older age**

291 Apart from the subcortical structures, we found three cortical regions in the left hemisphere, the  
292 dominant hemisphere in over 95% of individuals, involved in speech production and word processing  
293 to have more than 5% significant voxels; the subcallosal area (also called Broca area), central part of  
294 the superior temporal gyrus (contains Wernicke's area) and the lingual gyrus. Moreover, their right  
295 counterparts contained less significant voxels compared to the left side. Language skills [Gayan and  
296 Olson, 1999] and brain networks [Budisavljevic, et al., 2015] are thought to be under tight genetic  
297 control and the left hemisphere language areas have been found more heritable than the right  
298 hemisphere before [Thompson, et al., 2001]. Regions with significant heritability could in theory be  
299 connected by white matter connections, which in turn then also are under high genetic control,  
300 suggesting a common genetic architecture. In a recent report evidence for this theory was found  
301 [Shen, et al., 2016]. Cortical thickness in some regions with high heritability, were connected by

302 heritable white matter connections. These connections and the cortical regions were anatomically  
303 distant but showed significant genetically correlation [Shen, et al., 2016].

304 We found a relatively stable difference in the regional patterns of the total additive genetic  
305 heritability. The heritability calculated from familial relations was always higher than the total  
306 additive variance explained by all autosomal variants calculated in unrelated subjects. This known  
307 difference between family and population-based heritability estimates has been extensively  
308 described [Zuk, et al., 2012; Zuk, et al., 2014]. The difference can in part be explained by  
309 overestimation of heritability in families due to sharing of environmental factors within the family.  
310 These factors are interpreted as genetic effects and cause the overestimation of heritability in twin  
311 and nuclear family studies [Koran, et al., 2014]. Subjects in multi-generational families share less  
312 environmental factors. Therefore multi-generational families, as ASPS-Fam and especially the ERF  
313 study, are more likely to yield an unbiased estimate of heritability. However, we assumed that all  
314 environmental factors affecting brain voxel volume are uncorrelated among family members (unique  
315 environmental effects) therefore some unassessed common environmental effects might be causing  
316 the higher heritability in our family-based estimates. At the same time an underestimation of the  
317 heritability calculated from genetic data in unrelated populations could occur because of an  
318 incomplete coverage of the causal variants and exclusion of rare variants. We used imputed data to  
319 increase coverage of the causal variants. Imputed data provide a much denser coverage of the  
320 genome than only genotyped variants, but we did exclude rare variants ( $MAF < 0.01$ ) which may in  
321 part be responsible for some missing heritability.

322 The overall regional patterns of heritability from families strongly predicted the population-based  
323 heritability. This suggests that the regional pattern of variance explained by additive genetic effects  
324 is similar across populations, despite different ways to measure heritability, study design and  
325 scanner types. On the website (<http://www.imagine.nl/heritability>) both the population-based  
326 estimates and the family-based estimates can be viewed separately and can be downloaded.



327 Combining current maps with results from other studies will further increase accuracy of the  
328 heritability estimates.

### 329 **Heritability in genetic studies**

330 Within the putamen and hippocampus we observed highly heritable clusters of grey matter voxels  
331 alternating with parts of the subcortical structures that were less heritable. Differences in heritability  
332 within structures might be due to technical limitations (e.g. voxels that are difficult to measure) or  
333 due to genetic or functional correlations. We hypothesized that studying the genetics of only highly  
334 heritable voxels could enhance signals in imaging genetics, either through reducing signal to noise  
335 ratio or through studying a more genetically homogeneous trait. We picked two genetic variants  
336 with a proven and strongly replicated biological effect, identified through genome-wide association  
337 studies, on the subcortical structure volume (hippocampus, putamen) to explore if enhancement  
338 was possible [Hibar, et al., 2015]. We show enhancement of the statistical signal of almost hundred-  
339 fold for the association of *HRK* (rs77956314) with hippocampal volume and a five-fold increase for  
340 the association of *KTN1* (rs945270) with putamen volume. **Based on Figure 3 we can deduct that for**  
341 **future genetic studies in both examples a maximum power for association analyses was observed**  
342 **using voxels with a heritability over ~0.3 from the population-based heritability estimates and a**  
343 **heritability over ~0.7 from family-based heritability estimates. Despite these encouraging results**  
344 **there are limitations of our analysis. First, we only tested two genetic variants in two subcortical**  
345 **structures.** While we expect that the increased signal of genetic variants with more heritable voxels  
346 will not be limited to the two variants tested in current study, future studies applying this method  
347 should be performed to determine whether this truly is the case. Second, we calculated heritability  
348 estimates and genetic association of *HRK* and *KTN1* variants with voxels in the same subjects of the  
349 Rotterdam Study. As voxels with a large (technical) measurement error have lower heritability and  
350 therefore were excluded first in our analysis, the decreased measurement error of the more  
351 heritable voxels could result in the more significant association of genetic variants. In other words,

352 the enhancement of signal is a reflection of a higher signal to noise ratio. Also a higher test re-test  
353 reliability of the highly heritable voxels, reduce signal to noise ratio. **Third, we used the same data**  
354 **for the calculation of population-based heritability estimates and genetic testing, resulting in a**  
355 **possible inflation of the increase in signal due to non-independence [Kriegeskorte, et al., 2009].**  
356 **However, when only the family-based heritability estimates were used to select the voxels for**  
357 **genetic associations (Figure 3 C,D) the analyses were independent. In these analyses, we still**  
358 **observed an increase in the signal – and the enhancement was actually even stronger for the**  
359 **putamen – arguing against inflation due to non-independence. However, for the hippocampus the**  
360 **best enhancement was achieved using the combined sample when restricting to less than 55% the**  
361 **most significant voxels. While this could be due to non-independence, this is contradicted by the**  
362 **fact that the population-only results (i.e., fully dependent) are in fact worse at this and lower**  
363 **percentages. An explanation other than non-independence could be that the combined sample**  
364 **provides more accurate heritability estimates and therefore results in a better enhancement. Last,**  
365 highly heritable voxels which are in close proximity of each other could share their genetic  
366 background. However finding a cluster of heritable voxels does not directly prove genetic  
367 correlation.

368

### 369 **Strengths and limitations**

370 Major strengths of this study are the large sample size of the population based study and unified  
371 imaging processing. Subjects from ERF and the Rotterdam Study subjects were scanned using the  
372 same 1.5T scanner, identical MRI protocols and images were processed with exactly the same  
373 software. The ASPS-Fam was scanned on a 3T scanner, but segmented using similar protocols and  
374 VBM processing was performed in the same way as ERF and the Rotterdam Study. Important to note  
375 is that softwares used for tissue segmentation are different, but both implement the same kNN  
376 algorithm [Vrooman, et al., 2007]. The ERF and the Rotterdam Study both are both from the

377 Netherlands, a genetically homogeneous country [Boomsma, et al., 2014]. The ASPS-Fam study is  
378 from Austria, Austrians likely have slightly different genetic architecture than the Dutch. **Maximum**  
379 **likelihood iterative optimization was used to estimation heritability. The iterations are prone to**  
380 **convergence failures when sample sizes are small. The percentage of voxels that did not converge**  
381 **was 9% in ASPS-Fam ( $N_{\text{participants}} = 369$ ) and 36% in ERF ( $N_{\text{participants}} = 122$ ). The methods used for**  
382 **population-based estimation of heritability always output an estimate.** It has been shown that not  
383 converging occurs frequently in small datasets in SOLAR producing conservative estimates [Blangero,  
384 et al., 2013; Koran, et al., 2014]. We further note that using only VBM to assess heritability of brain  
385 morphology is a limitation of the current study. Cortical thickness, surface area and other MRI  
386 measures, **including tensor-based (i.e. deformation) morphometry (TBM) [Brun, et al., 2009; Yoon,**  
387 **et al., 2011]** and shape analysis are all potentially interesting for future heritability and genetic  
388 studies. The differences between measures have been attributed both to biology [Voets, et al., 2008;  
389 Winkler, et al., 2010] and methodology [Blankstein, et al., 2009; Hutton, et al., 2009]. Most probably,  
390 these measures reflect a different genetic architecture [Winkler, et al., 2010] and should therefore  
391 be studied separately.

## 392 **Future perspectives**

393 **Genetic association with several voxels within an anatomical structure is biologically relevant as it**  
394 **shows an important genetic contribution to a sub region of the structure. Apart from the biological**  
395 **relevance, this sub region of voxels could have clinical significance. For example, it was shown**  
396 **previously that subfields of the anatomically defined hippocampus contributed differently to**  
397 **schizophrenia [Kuhn, et al., 2012] and  $\beta$ -Amyloid load [Schroeder, et al., 2016].** If only highly  
398 heritability brain voxels are studied in future voxel-wise genome-wide association studies we do not  
399 expect statistical signals to be uniformly enhanced. However, for the tested genetic variant that was  
400 identified for putamen volume, we did find statistical enhancement. High heritability estimates  
401 capture a variety of sources that can affect power to detect associations, including lower signal to

402 noise ratios and higher genetic homogeneity (i.e. genetic correlation). Using these benefits to  
403 increase statistical signal is desirable, irrespective of the underlying cause. Ideally we envision  
404 selecting groups of voxels for genetic studies based on high heritability and measured high genetic  
405 correlation. Genetic correlation can be calculated for any of the commonly used MRI-measures, but  
406 it would still require genetic testing of sufficiently powered (large) studies. A promising future  
407 direction would be to enable the calculation of genetic correlations, genetic association (millions of  
408 voxels times millions of genetic variants) and meta-analyses of these associations. Programs which  
409 make the calculation of genetic correlation and genetic association computationally possible in  
410 sufficiently powered studies (i.e. meta-analyses) are essential to the field. Currently these programs  
411 tailored to large scale genetic studies are developed and genetic studies started [**Roshchupkin, et**  
412 **al., 2016b**]. The results of these studies will be able to prove to which extend clusters of heritable  
413 voxels have a common genetic architecture.

#### 414 **Conclusions**

415 Heritability estimates can be reliably estimated using different methods and on different cohorts and  
416 combining heritability estimates from multiple studies leads to the construction of a reliable  
417 heritability map of grey matter. These maps can be used to prioritize highly heritable regions in  
418 future genetic imaging studies.

#### 419 **Acknowledgements**

420 **Erasmus Rucphen family study:** The ERF study as a part of EUROSPAN (European Special Populations  
421 Research Network) was supported by European Commission FP6 STRP grant number 018947 (LSHG-  
422 CT-2006-01947) and also received funding from the European Community's Seventh Framework  
423 Program (FP7/2007-2013)/grant agreement HEALTH-F4-2007-201413 by the European Commission  
424 under the program "Quality of Life and Management of the Living Resources" of 5th Framework  
425 Program (no. QL2-CT-2002-01254). Najaf Amin is supported by the Netherlands Brain Foundation  
426 (project number F2013 (1)-28). We are grateful to all study participants and their relatives, general

427 practitioners and neurologists for their contributions and to P. Veraart for her help in genealogy, J.  
428 Vergeer for the supervision of the laboratory work and P. Snijders for his help in data collection.

429 **The Austrian Stroke Prevention Family Study:** The research reported in this article was funded by  
430 the Austrian Science Fond (FWF) grant number P20545-P05 and P13180. The Medical University of  
431 Graz supports the databank of the ASPs. The authors thank the staff and the participants of the ASPs  
432 for their valuable contributions. The authors thank Birgit Reinhart for her long-term administrative  
433 commitment and Ing Johann Semmler for the technical assistance at creating the DNA bank.

434 **Rotterdam Study:** The generation and management of GWAS genotype data for the Rotterdam  
435 Study (RS-I, RS-II, RS-III) was executed by the Human Genotyping Facility of the Genetic Laboratory of  
436 the Department of Internal Medicine, Erasmus MC, Rotterdam, The Netherlands. The GWAS  
437 datasets are supported by the Netherlands Organization of Scientific Research NWO Investments  
438 (nr. 175.010.2005.011, 911-03-012), the Genetic Laboratory of the Department of Internal Medicine,  
439 Erasmus MC, the Research Institute for Diseases in the Elderly (014-93-015; RIDE2), the Netherlands  
440 Genomics Initiative (NGI)/Netherlands Organization for Scientific Research (NWO) Netherlands  
441 Consortium for Healthy Aging (NCHA), project nr. 050-060-810. We thank Pascal Arp, Mila Jhamai,  
442 Marijn Verkerk, Lizbeth Herrera and Marjolein Peters, MSc, and Carolina Medina-Gomez, MSc, for  
443 their help in creating the GWAS database, and Karol Estrada, PhD, Yurii Aulchenko, PhD, and Carolina  
444 Medina-Gomez, MSc, for the creation and analysis of imputed data. This study makes use of an  
445 extended dataset of RS-II and RS-III samples based on Illumina Omni 2.5 and 5.0 GWAS genotype  
446 data, imputed to 1KG using the two-phase imputation method. This dataset was funded by the  
447 Genetic Laboratory of the Department of Internal Medicine, the department of Forensic Molecular  
448 Biology, and the department of Dermatology, Erasmus MC, Rotterdam, The Netherlands We thank  
449 Linda Broer, PhD, for the creation of imputed data, with the support of Marijn Verkerk and Carolina  
450 Medina-Gomez, MSc, for the analysis setup. The Rotterdam Study is funded by Erasmus Medical  
451 Center and Erasmus University, Rotterdam, Netherlands Organization for the Health Research and

452 Development (ZonMw), the Research Institute for Diseases in the Elderly (RIDE), the Ministry of  
453 Education, Culture and Science, the Ministry for Health, Welfare and Sports, the European  
454 Commission (DG XII), and the Municipality of Rotterdam. The authors are grateful to the study  
455 participants, the staff from the Rotterdam Study and the participating general practitioners and  
456 pharmacists.

## 457 **References**

- 458 Adams, H.H., Verlinden, V.J., Callisaya, M.L., van Duijn, C.M., Hofman, A., Thomson, R., Uitterlinden,  
459 A.G., Vernooij, M.W., van der Geest, J.N., Srikanth, V., Ikram, M.A. (2016) Heritability and  
460 Genome-Wide Association Analyses of Human Gait Suggest Contribution of Common  
461 Variants. *J Gerontol A Biol Sci Med Sci*, 71:740-6.
- 462 Almasy, L., Blangero, J. (1998) Multipoint quantitative-trait linkage analysis in general pedigrees. *Am*  
463 *J Hum Genet*, 62:1198-211.
- 464 Batouli, S.A., Trollor, J.N., Wen, W., Sachdev, P.S. (2014) The heritability of volumes of brain  
465 structures and its relationship to age: a review of twin and family studies. *Ageing Res Rev*,  
466 13:1-9.
- 467 Benjamini, Y., Hochberg, Y. (1995) Controlling the False Discovery Rate - a Practical and Powerful  
468 Approach to Multiple Testing. *J Roy Stat Soc B Met*, 57:289-300.
- 469 Bis, J.C., DeCarli, C., Smith, A.V., van der Lijn, F., Crivello, F., Fornage, M., DeBette, S., Shulman, J.M.,  
470 Schmidt, H., Srikanth, V., Schuur, M., Yu, L., Choi, S.H., Sigurdsson, S., Verhaaren, B.F.,  
471 DeStefano, A.L., Lambert, J.C., Jack, C.R., Jr., Struchalin, M., Stankovich, J., Ibrahim-Verbaas,  
472 C.A., Fleischman, D., Zijdenbos, A., den Heijer, T., Mazoyer, B., Coker, L.H., Enzinger, C.,  
473 Danoy, P., Amin, N., Arfanakis, K., van Buchem, M.A., de Bruijn, R.F., Beiser, A., Dufouil, C.,  
474 Huang, J., Cavalieri, M., Thomson, R., Niessen, W.J., Chibnik, L.B., Gislason, G.K., Hofman, A.,  
475 Pikula, A., Amouyel, P., Freeman, K.B., Phan, T.G., Oostra, B.A., Stein, J.L., Medland, S.E.,  
476 Vasquez, A.A., Hibar, D.P., Wright, M.J., Franke, B., Martin, N.G., Thompson, P.M., Enhancing  
477 Neuro Imaging Genetics through Meta-Analysis, C., Nalls, M.A., Uitterlinden, A.G., Au, R.,  
478 Elbaz, A., Beare, R.J., van Swieten, J.C., Lopez, O.L., Harris, T.B., Chouraki, V., Breteler, M.M.,  
479 De Jager, P.L., Becker, J.T., Vernooij, M.W., Knopman, D., Fazekas, F., Wolf, P.A., van der  
480 Lugt, A., Gudnason, V., Longstreth, W.T., Jr., Brown, M.A., Bennett, D.A., van Duijn, C.M.,  
481 Mosley, T.H., Schmidt, R., Tzourio, C., Launer, L.J., Ikram, M.A., Seshadri, S., Cohorts for, H.,  
482 Aging Research in Genomic Epidemiology, C. (2012) Common variants at 12q14 and 12q24  
483 are associated with hippocampal volume. *Nat Genet*, 44:545-51.
- 484 Blangero, J., Diego, V.P., Dyer, T.D., Almeida, M., Peralta, J., Kent, J.W., Jr., Williams, J.T., Almasy, L.,  
485 Goring, H.H. (2013) A kernel of truth: statistical advances in polygenic variance component  
486 models for complex human pedigrees. *Adv Genet*, 81:1-31.
- 487 Blangero, J., Williams, J.T., Almasy, L. (2001) Variance component methods for detecting complex  
488 trait loci. *Adv Genet*, 42:151-81.
- 489 Blankstein, U., Chen, J.Y.W., Mincic, A.M., McGrath, P.A., Davis, K.D. (2009) The complex minds of  
490 teenagers: Neuroanatomy of personality differs between sexes. *Neuropsychologia*, 47:599-  
491 603.
- 492 Blokland, G.A., de Zubicaray, G.I., McMahon, K.L., Wright, M.J. (2012) Genetic and environmental  
493 influences on neuroimaging phenotypes: a meta-analytical perspective on twin imaging  
494 studies. *Twin Res Hum Genet*, 15:351-71.

495 Boomsma, D.I., Wijmenga, C., Slagboom, E.P., Swertz, M.A., Karssen, L.C., Abdellaoui, A., Ye, K.,  
496 Guryev, V., Vermaat, M., van Dijk, F., Francioli, L.C., Hottenga, J.J., Laros, J.F., Li, Q., Li, Y.,  
497 Cao, H., Chen, R., Du, Y., Li, N., Cao, S., van Setten, J., Menelaou, A., Pulit, S.L., Hehir-Kwa,  
498 J.Y., Beekman, M., Elbers, C.C., Byelas, H., de Craen, A.J., Deelen, P., Dijkstra, M., den  
499 Dunnen, J.T., de Knijff, P., Houwing-Duistermaat, J., Koval, V., Estrada, K., Hofman, A.,  
500 Kanterakis, A., Enckevort, D., Mai, H., Kattenberg, M., van Leeuwen, E.M., Neerincx, P.B.,  
501 Oostra, B., Rivadeneira, F., Suchiman, E.H., Uitterlinden, A.G., Willemsen, G., Wolffenbuttel,  
502 B.H., Wang, J., de Bakker, P.I., van Ommen, G.J., van Duijn, C.M. (2014) The Genome of the  
503 Netherlands: design, and project goals. *Eur J Hum Genet*, 22:221-7.

504 Brouwer, R.M., Mandl, R.C., Peper, J.S., van Baal, G.C., Kahn, R.S., Boomsma, D.I., Hulshoff Pol, H.E.  
505 (2010) Heritability of DTI and MTR in nine-year-old children. *Neuroimage*, 53:1085-92.

506 Brun, C.C., Lepore, N., Pennec, X., Lee, A.D., Barysheva, M., Madsen, S.K., Avedissian, C., Chou, Y.Y.,  
507 de Zubicaray, G.I., McMahon, K.L., Wright, M.J., Toga, A.W., Thompson, P.M. (2009)  
508 Mapping the regional influence of genetics on brain structure variability--a tensor-based  
509 morphometry study. *Neuroimage*, 48:37-49.

510 Budisavljevic, S., Dell'Acqua, F., Rijdsdijk, F.V., Kane, F., Picchioni, M., McGuire, P., Toulopoulou, T.,  
511 Georgiades, A., Kalidindi, S., Kravariti, E., Murray, R.M., Murphy, D.G., Craig, M.C., Catani, M.  
512 (2015) Age-Related Differences and Heritability of the Perisylvian Language Networks. *J*  
513 *Neurosci*, 35:12625-34.

514 Fonov, V., Evans, A.C., Botteron, K., Almli, C.R., McKinstry, R.C., Collins, D.L., Brain Development  
515 Cooperative, G. (2011) Unbiased average age-appropriate atlases for pediatric studies.  
516 *Neuroimage*, 54:313-27.

517 Ganjgahi, H., Winkler, A.M., Glahn, D.C., Blangero, J., Kochunov, P., Nichols, T.E. (2015) Fast and  
518 powerful heritability inference for family-based neuroimaging studies. *Neuroimage*,  
519 115:256-68.

520 Gayan, J., Olson, R.K. (1999) Reading disability: evidence for a genetic etiology. *Eur Child Adolesc*  
521 *Psychiatry*, 8 Suppl 3:52-5.

522 Good, C.D., Johnsrude, I.S., Ashburner, J., Henson, R.N., Friston, K.J., Frackowiak, R.S. (2001) A voxel-  
523 based morphometric study of ageing in 465 normal adult human brains. *Neuroimage*, 14:21-  
524 36.

525 Hammers, A., Allom, R., Koepp, M.J., Free, S.L., Myers, R., Lemieux, L., Mitchell, T.N., Brooks, D.J.,  
526 Duncan, J.S. (2003) Three-dimensional maximum probability atlas of the human brain, with  
527 particular reference to the temporal lobe. *Hum Brain Mapp*, 19:224-47.

528 Hibar, D.P., Stein, J.L., Renteria, M.E., Arias-Vasquez, A., Desrivieres, S., Jahanshad, N., Toro, R.,  
529 Wittfeld, K., Abramovic, L., Andersson, M., Aribisala, B.S., Armstrong, N.J., Bernard, M.,  
530 Bohlken, M.M., Boks, M.P., Bralten, J., Brown, A.A., Chakravarty, M.M., Chen, Q., Ching, C.R.,  
531 Cuellar-Partida, G., den Braber, A., Giddaluru, S., Goldman, A.L., Grimm, O., Guadalupe, T.,  
532 Hass, J., Woldehawariat, G., Holmes, A.J., Hoogman, M., Janowitz, D., Jia, T., Kim, S., Klein,  
533 M., Kraemer, B., Lee, P.H., Olde Loohuis, L.M., Luciano, M., Macare, C., Mather, K.A.,  
534 Mattheisen, M., Milaneschi, Y., Nho, K., Pappmeyer, M., Ramasamy, A., Risacher, S.L., Roiz-  
535 Santianez, R., Rose, E.J., Salami, A., Samann, P.G., Schmaal, L., Schork, A.J., Shin, J., Strike,  
536 L.T., Teumer, A., van Donkelaar, M.M., van Eijk, K.R., Walters, R.K., Westlye, L.T., Whelan,  
537 C.D., Winkler, A.M., Zwiers, M.P., Alhusaini, S., Athanasiu, L., Ehrlich, S., Hakobjan, M.M.,  
538 Hartberg, C.B., Haukvik, U.K., Heister, A.J., Hoehn, D., Kasperaviciute, D., Liewald, D.C.,  
539 Lopez, L.M., Makkinje, R.R., Matarin, M., Naber, M.A., McKay, D.R., Needham, M., Nugent,  
540 A.C., Putz, B., Royle, N.A., Shen, L., Sprooten, E., Trabzuni, D., van der Marel, S.S., van Hulzen,  
541 K.J., Walton, E., Wolf, C., Almasy, L., Ames, D., Arepalli, S., Assareh, A.A., Bastin, M.E.,  
542 Brodaty, H., Bulayeva, K.B., Carless, M.A., Cichon, S., Corvin, A., Curran, J.E., Czisch, M., de  
543 Zubicaray, G.I., Dillman, A., Duggirala, R., Dyer, T.D., Erk, S., Fedko, I.O., Ferrucci, L., Foroud,  
544 T.M., Fox, P.T., Fukunaga, M., Gibbs, J.R., Goring, H.H., Green, R.C., Guelfi, S., Hansell, N.K.,  
545 Hartman, C.A., Hegenscheid, K., Heinz, A., Hernandez, D.G., Heslenfeld, D.J., Hoekstra, P.J.,

546 Holsboer, F., Homuth, G., Hottenga, J.J., Ikeda, M., Jack, C.R., Jr., Jenkinson, M., Johnson, R.,  
 547 Kanai, R., Keil, M., Kent, J.W., Jr., Kochunov, P., Kwok, J.B., Lawrie, S.M., Liu, X., Longo, D.L.,  
 548 McMahon, K.L., Meisenzahl, E., Melle, I., Mohnke, S., Montgomery, G.W., Mostert, J.C.,  
 549 Muhleisen, T.W., Nalls, M.A., Nichols, T.E., Nilsson, L.G., Nothen, M.M., Ohi, K., Olvera, R.L.,  
 550 Perez-Iglesias, R., Pike, G.B., Potkin, S.G., Reinvang, I., Reppermund, S., Rietschel, M.,  
 551 Romanczuk-Seiferth, N., Rosen, G.D., Rujescu, D., Schnell, K., Schofield, P.R., Smith, C., Steen,  
 552 V.M., Sussmann, J.E., Thalamuthu, A., Toga, A.W., Traynor, B.J., Troncoso, J., Turner, J.A.,  
 553 Valdes Hernandez, M.C., van 't Ent, D., van der Brug, M., van der Wee, N.J., van Tol, M.J.,  
 554 Veltman, D.J., Wassink, T.H., Westman, E., Zielke, R.H., Zonderman, A.B., Ashbrook, D.G.,  
 555 Hager, R., Lu, L., McMahon, F.J., Morris, D.W., Williams, R.W., Brunner, H.G., Buckner, R.L.,  
 556 Buitelaar, J.K., Cahn, W., Calhoun, V.D., Cavalleri, G.L., Crespo-Facorro, B., Dale, A.M., Davies,  
 557 G.E., Delanty, N., Depondt, C., Djurovic, S., Drevets, W.C., Espeseth, T., Gollub, R.L., Ho, B.C.,  
 558 Hoffmann, W., Hosten, N., Kahn, R.S., Le Hellard, S., Meyer-Lindenberg, A., Muller-Myhsok,  
 559 B., Nauck, M., Nyberg, L., Pandolfo, M., Penninx, B.W., Roffman, J.L., Sisodiya, S.M., Smoller,  
 560 J.W., van Bokhoven, H., van Haren, N.E., Volzke, H., Walter, H., Weiner, M.W., Wen, W.,  
 561 White, T., Agartz, I., Andreassen, O.A., Blangero, J., Boomsma, D.I., Brouwer, R.M., Cannon,  
 562 D.M., Cookson, M.R., de Geus, E.J., Deary, I.J., Donohoe, G., Fernandez, G., Fisher, S.E.,  
 563 Francks, C., Glahn, D.C., Grabe, H.J., Gruber, O., Hardy, J., Hashimoto, R., Hulshoff Pol, H.E.,  
 564 Jonsson, E.G., Kloszewska, I., Lovestone, S., Mattay, V.S., Mecocci, P., McDonald, C.,  
 565 McIntosh, A.M., Ophoff, R.A., Paus, T., Pausova, Z., Ryten, M., Sachdev, P.S., Saykin, A.J.,  
 566 Simmons, A., Singleton, A., Soininen, H., Wardlaw, J.M., Weale, M.E., Weinberger, D.R.,  
 567 Adams, H.H., Launer, L.J., Seiler, S., Schmidt, R., Chauhan, G., Satizabal, C.L., Becker, J.T.,  
 568 Yanek, L., van der Lee, S.J., Ebling, M., Fischl, B., Longstreth, W.T., Jr., Greve, D., Schmidt, H.,  
 569 Nyquist, P., Vinke, L.N., van Duijn, C.M., Xue, L., Mazoyer, B., Bis, J.C., Gudnason, V.,  
 570 Seshadri, S., Ikram, M.A., Alzheimer's Disease Neuroimaging, I., Consortium, C., Epigen,  
 571 Imagen, Sys, Martin, N.G., Wright, M.J., Schumann, G., Franke, B., Thompson, P.M.,  
 572 Medland, S.E. (2015) Common genetic variants influence human subcortical brain structures.  
 573 *Nature*, 520:224-9.  
 574 Hofman, A., Brusselle, G.G., Darwish Murad, S., van Duijn, C.M., Franco, O.H., Goedegebure, A.,  
 575 Ikram, M.A., Klaver, C.C., Nijsten, T.E., Peeters, R.P., Stricker, B.H., Tiemeier, H.W.,  
 576 Uitterlinden, A.G., Vernooij, M.W. (2015) The Rotterdam Study: 2016 objectives and design  
 577 update. *Eur J Epidemiol*, 30:661-708.  
 578 Hulshoff Pol, H.E., Schnack, H.G., Posthuma, D., Mandl, R.C., Baare, W.F., van Oel, C., van Haren,  
 579 N.E., Collins, D.L., Evans, A.C., Amunts, K., Burgel, U., Zilles, K., de Geus, E., Boomsma, D.I.,  
 580 Kahn, R.S. (2006) Genetic contributions to human brain morphology and intelligence. *J*  
 581 *Neurosci*, 26:10235-42.  
 582 Hutton, C., Draganski, B., Ashburner, J., Weiskopf, N. (2009) A comparison between voxel-based  
 583 cortical thickness and voxel-based morphometry in normal aging. *Neuroimage*, 48:371-80.  
 584 Ibrahim-Verbaas, C.A., Zorkoltseva, I.V., Amin, N., Schuur, M., Coppus, A.M., Isaacs, A., Aulchenko,  
 585 Y.S., Breteler, M.M., Ikram, M.A., Axenovich, T.I., Verbeek, M.M., van Swieten, J.C., Oostra,  
 586 B.A., van Duijn, C.M. (2012) Linkage analysis for plasma amyloid beta levels in persons with  
 587 hypertension implicates Abeta-40 levels to presenilin 2. *Hum Genet*, 131:1869-76.  
 588 Ikram, M.A., van der Lugt, A., Niessen, W.J., Koudstaal, P.J., Krestin, G.P., Hofman, A., Bos, D.,  
 589 Vernooij, M.W. (2015) The Rotterdam Scan Study: design update 2016 and main findings.  
 590 *Eur J Epidemiol*, 30:1299-315.  
 591 Jahanshad, N., Kochunov, P.V., Sprooten, E., Mandl, R.C., Nichols, T.E., Almasy, L., Blangero, J.,  
 592 Brouwer, R.M., Curran, J.E., de Zubicaray, G.I., Duggirala, R., Fox, P.T., Hong, L.E., Landman,  
 593 B.A., Martin, N.G., McMahon, K.L., Medland, S.E., Mitchell, B.D., Olvera, R.L., Peterson, C.P.,  
 594 Starr, J.M., Sussmann, J.E., Toga, A.W., Wardlaw, J.M., Wright, M.J., Hulshoff Pol, H.E.,  
 595 Bastin, M.E., McIntosh, A.M., Deary, I.J., Thompson, P.M., Glahn, D.C. (2013) Multi-site



596 genetic analysis of diffusion images and voxelwise heritability analysis: a pilot project of the  
597 ENIGMA-DTI working group. *Neuroimage*, 81:455-69.

598 Jahanshad, N., Lee, A.D., Barysheva, M., McMahon, K.L., de Zubicaray, G.I., Martin, N.G., Wright,  
599 M.J., Toga, A.W., Thompson, P.M. (2010) Genetic influences on brain asymmetry: a DTI study  
600 of 374 twins and siblings. *Neuroimage*, 52:455-69.

601 Kochunov, P., Fu, M., Nugent, K., Wright, S.N., Du, X., Muellerklein, F., Morrissey, M., Eskandar, G.,  
602 Shukla, D.K., Jahanshad, N., Thompson, P.M., Patel, B., Postolache, T.T., Strauss, K.A.,  
603 Shuldiner, A.R., Mitchell, B.D., Hong, L.E. (2016) Heritability of complex white matter  
604 diffusion traits assessed in a population isolate. *Hum Brain Mapp*, 37:525-35.

605 Kochunov, P., Glahn, D.C., Lancaster, J.L., Winkler, A.M., Smith, S., Thompson, P.M., Almasry, L.,  
606 Duggirala, R., Fox, P.T., Blangero, J. (2010) Genetics of microstructure of cerebral white  
607 matter using diffusion tensor imaging. *Neuroimage*, 53:1109-16.

608 Kochunov, P., Jahanshad, N., Marcus, D., Winkler, A., Sprooten, E., Nichols, T.E., Wright, S.N., Hong,  
609 L.E., Patel, B., Behrens, T., Jbabdi, S., Andersson, J., Lenglet, C., Yacoub, E., Moeller, S.,  
610 Auerbach, E., Ugurbil, K., Sotiropoulos, S.N., Brouwer, R.M., Landman, B., Lemaitre, H., den  
611 Braber, A., Zwiers, M.P., Ritchie, S., van Hulzen, K., Almasry, L., Curran, J., deZubicaray, G.I.,  
612 Duggirala, R., Fox, P., Martin, N.G., McMahon, K.L., Mitchell, B., Olvera, R.L., Peterson, C.,  
613 Starr, J., Sussmann, J., Wardlaw, J., Wright, M., Boomsma, D.I., Kahn, R., de Geus, E.J.,  
614 Williamson, D.E., Hariri, A., van 't Ent, D., Bastin, M.E., McIntosh, A., Deary, I.J., Hulshoff Pol,  
615 H.E., Blangero, J., Thompson, P.M., Glahn, D.C., Van Essen, D.C. (2015) Heritability of  
616 fractional anisotropy in human white matter: a comparison of Human Connectome Project  
617 and ENIGMA-DTI data. *Neuroimage*, 111:300-11.

618 Koran, M.E., Thornton-Wells, T.A., Jahanshad, N., Glahn, D.C., Thompson, P.M., Blangero, J., Nichols,  
619 T.E., Kochunov, P., Landman, B.A. (2014) Impact of family structure and common  
620 environment on heritability estimation for neuroimaging genetics studies using Sequential  
621 Oligogenic Linkage Analysis Routines. *J Med Imaging (Bellingham)*, 1:014005.

622 Kriegeskorte, N., Simmons, W.K., Bellgowan, P.S., Baker, C.I. (2009) Circular analysis in systems  
623 neuroscience: the dangers of double dipping. *Nat Neurosci*, 12:535-40.

624 Kuhn, S., Musso, F., Mobascher, A., Warbrick, T., Winterer, G., Gallinat, J. (2012) Hippocampal  
625 subfields predict positive symptoms in schizophrenia: first evidence from brain  
626 morphometry. *Transl Psychiatry*, 2:e127.

627 Peper, J.S., Schnack, H.G., Brouwer, R.M., Van Baal, G.C., Pjetri, E., Szekely, E., van Leeuwen, M., van  
628 den Berg, S.M., Collins, D.L., Evans, A.C., Boomsma, D.I., Kahn, R.S., Hulshoff Pol, H.E. (2009)  
629 Heritability of regional and global brain structure at the onset of puberty: a magnetic  
630 resonance imaging study in 9-year-old twin pairs. *Hum Brain Mapp*, 30:2184-96.

631 Polderman, T.J., Benyamin, B., de Leeuw, C.A., Sullivan, P.F., van Bochoven, A., Visscher, P.M.,  
632 Posthuma, D. (2015) Meta-analysis of the heritability of human traits based on fifty years of  
633 twin studies. *Nat Genet*, 47:702-9.

634 Roshchupkin, G.V., Adams, H.H., van der Lee, S.J., Vernooij, M.W., van Duijn, C.M., Uitterlinden, A.G.,  
635 van der Lugt, A., Hofman, A., Niessen, W.J., Ikram, M.A. (2016a) Fine-mapping the effects of  
636 Alzheimer's disease risk loci on brain morphology. *Neurobiol Aging*, 48:204-211.

637 Roshchupkin, G.V., Adams, H.H., Vernooij, M.W., Hofman, A., Van Duijn, C.M., Ikram, M.A.,  
638 Niessen, W.J. (2016b) HASE: Framework for efficient high-dimensional association analyses.  
639 *Sci. Rep.*, 6.

640 Sayed-Tabatabaei, F.A., van Rijn, M.J., Schut, A.F., Aulchenko, Y.S., Croes, E.A., Zillikens, M.C., Pols,  
641 H.A., Witteman, J.C., Oostra, B.A., van Duijn, C.M. (2005) Heritability of the function and  
642 structure of the arterial wall: findings of the Erasmus Rucphen Family (ERF) study. *Stroke*,  
643 36:2351-6.

644 Schmidt, R., Fazekas, F., Kapeller, P., Schmidt, H., Hartung, H.P. (1999) MRI white matter  
645 hyperintensities: three-year follow-up of the Austrian Stroke Prevention Study. *Neurology*,  
646 53:132-9.

647 Schmidt, R., Lechner, H., Fazekas, F., Niederkorn, K., Reinhart, B., Grieshofer, P., Horner, S.,  
648 Offenbacher, H., Koch, M., Eber, B., Schumacher, M., Kapeller, P.A., Freidl, W.C., Dusek, T.  
649 (1994) Assessment of cerebrovascular risk profiles in healthy persons: definition of research  
650 goals and the Austrian Stroke Prevention Study (ASPS). *Neuroepidemiology*, 13:308-13.

651 Schroeder, C., Park, M.T., Germann, J., Chakravarty, M.M., Michels, L., Kollias, S., Kroll, S.L., Buck, A.,  
652 Treyer, V., Savaskan, E., Unschuld, P.G., Nitsch, R.M., Kalin, A.M., Hock, C., Gietl, A.F., Leh,  
653 S.E. (2016) Hippocampal shape alterations are associated with regional Abeta load in  
654 cognitively normal elderly individuals. *Eur J Neurosci*.

655 Seiler, S., Pirpamer, L., Hofer, E., Duering, M., Jouvent, E., Fazekas, F., Mangin, J.F., Chabriat, H.,  
656 Dichgans, M., Ropele, S., Schmidt, R. (2014) Magnetization transfer ratio relates to cognitive  
657 impairment in normal elderly. *Front Aging Neurosci*, 6:263.

658 Shen, K.K., Dore, V., Rose, S., Fripp, J., McMahon, K.L., de Zubicaray, G.I., Martin, N.G., Thompson,  
659 P.M., Wright, M.J., Salvado, O. (2016) Heritability and genetic correlation between the  
660 cerebral cortex and associated white matter connections. *Hum Brain Mapp*, 37:2331-47.

661 Shrout, P.E., Fleiss, J.L. (1979) Intraclass correlations: uses in assessing rater reliability. *Psychol Bull*,  
662 86:420-8.

663 Smith, S.M., Jenkinson, M., Woolrich, M.W., Beckmann, C.F., Behrens, T.E., Johansen-Berg, H.,  
664 Bannister, P.R., De Luca, M., Drobnjak, I., Flitney, D.E., Niazy, R.K., Saunders, J., Vickers, J.,  
665 Zhang, Y., De Stefano, N., Brady, J.M., Matthews, P.M. (2004) Advances in functional and  
666 structural MR image analysis and implementation as FSL. *Neuroimage*, 23 Suppl 1:S208-19.

667 Stein, J.L., Medland, S.E., Vasquez, A.A., Hibar, D.P., Senstad, R.E., Winkler, A.M., Toro, R., Appel, K.,  
668 Bartecek, R., Bergmann, O., Bernard, M., Brown, A.A., Cannon, D.M., Chakravarty, M.M.,  
669 Christoforou, A., Domin, M., Grimm, O., Hollinshead, M., Holmes, A.J., Homuth, G.,  
670 Hottenga, J.J., Langan, C., Lopez, L.M., Hansell, N.K., Hwang, K.S., Kim, S., Laje, G., Lee, P.H.,  
671 Liu, X., Loth, E., Lourdasamy, A., Mattingsdal, M., Mohnke, S., Maniega, S.M., Nho, K.,  
672 Nugent, A.C., O'Brien, C., Pappmeyer, M., Putz, B., Ramasamy, A., Rasmussen, J., Rijpkema,  
673 M., Risacher, S.L., Roddey, J.C., Rose, E.J., Ryten, M., Shen, L., Sprooten, E., Strengman, E.,  
674 Teumer, A., Trabzuni, D., Turner, J., van Eijk, K., van Erp, T.G., van Tol, M.J., Wittfeld, K.,  
675 Wolf, C., Woudstra, S., Aleman, A., Alhusaini, S., Almasy, L., Binder, E.B., Brohawn, D.G.,  
676 Cantor, R.M., Carless, M.A., Corvin, A., Czisch, M., Curran, J.E., Davies, G., de Almeida, M.A.,  
677 Delanty, N., Depondt, C., Duggirala, R., Dyer, T.D., Erk, S., Fagerness, J., Fox, P.T., Freimer,  
678 N.B., Gill, M., Goring, H.H., Hagler, D.J., Hoehn, D., Holsboer, F., Hoogman, M., Hosten, N.,  
679 Jahanshad, N., Johnson, M.P., Kasperaviciute, D., Kent, J.W., Jr., Kochunov, P., Lancaster, J.L.,  
680 Lawrie, S.M., Liewald, D.C., Mandl, R., Matarin, M., Mattheisen, M., Meisenzahl, E., Melle, I.,  
681 Moses, E.K., Muhleisen, T.W., Nauck, M., Nothen, M.M., Olvera, R.L., Pandolfo, M., Pike,  
682 G.B., Puls, R., Reinvang, I., Renteria, M.E., Rietschel, M., Roffman, J.L., Royle, N.A., Rujescu,  
683 D., Savitz, J., Schnack, H.G., Schnell, K., Seiferth, N., Smith, C., Steen, V.M., Valdes Hernandez,  
684 M.C., Van den Heuvel, M., van der Wee, N.J., Van Haren, N.E., Veltman, J.A., Volzke, H.,  
685 Walker, R., Westlye, L.T., Whelan, C.D., Agartz, I., Boomsma, D.I., Cavalleri, G.L., Dale, A.M.,  
686 Djurovic, S., Drevets, W.C., Hagoort, P., Hall, J., Heinz, A., Jack, C.R., Jr., Foroud, T.M., Le  
687 Hellard, S., Macciardi, F., Montgomery, G.W., Poline, J.B., Porteous, D.J., Sisodiya, S.M., Starr,  
688 J.M., Sussmann, J., Toga, A.W., Veltman, D.J., Walter, H., Weiner, M.W., Alzheimer's Disease  
689 Neuroimaging, I., Consortium, E., Consortium, I., Saguenay Youth Study, G., Bis, J.C., Ikram,  
690 M.A., Smith, A.V., Gudnason, V., Tzourio, C., Vernooij, M.W., Launer, L.J., DeCarli, C.,  
691 Seshadri, S., Cohorts for, H., Aging Research in Genomic Epidemiology, C., Andreassen, O.A.,  
692 Apostolova, L.G., Bastin, M.E., Blangero, J., Brunner, H.G., Buckner, R.L., Cichon, S., Coppola,  
693 G., de Zubicaray, G.I., Deary, I.J., Donohoe, G., de Geus, E.J., Espeseth, T., Fernandez, G.,  
694 Glahn, D.C., Grabe, H.J., Hardy, J., Hulshoff Pol, H.E., Jenkinson, M., Kahn, R.S., McDonald, C.,  
695 McIntosh, A.M., McMahon, F.J., McMahon, K.L., Meyer-Lindenberg, A., Morris, D.W., Muller-  
696 Myhsok, B., Nichols, T.E., Ophoff, R.A., Paus, T., Pausova, Z., Penninx, B.W., Potkin, S.G.,  
697 Samann, P.G., Saykin, A.J., Schumann, G., Smoller, J.W., Wardlaw, J.M., Weale, M.E., Martin,

698 N.G., Franke, B., Wright, M.J., Thompson, P.M., Enhancing Neuro Imaging Genetics through  
699 Meta-Analysis, C. (2012) Identification of common variants associated with human  
700 hippocampal and intracranial volumes. *Nat Genet*, 44:552-61.

701 Thompson, P.M., Cannon, T.D., Narr, K.L., van Erp, T., Poutanen, V.P., Huttunen, M., Lonnqvist, J.,  
702 Standertskjold-Nordenstam, C.G., Kaprio, J., Khaledy, M., Dail, R., Zoumalan, C.I., Toga, A.W.  
703 (2001) Genetic influences on brain structure. *Nat Neurosci*, 4:1253-8.

704 Visscher, P.M., Hill, W.G., Wray, N.R. (2008) Heritability in the genomics era--concepts and  
705 misconceptions. *Nat Rev Genet*, 9:255-66.

706 Visscher, P.M., Medland, S.E., Ferreira, M.A., Morley, K.I., Zhu, G., Cornes, B.K., Montgomery, G.W.,  
707 Martin, N.G. (2006) Assumption-free estimation of heritability from genome-wide identity-  
708 by-descent sharing between full siblings. *PLoS Genet*, 2:e41.

709 Visscher, P.M., Yang, J., Goddard, M.E. (2010) A commentary on 'common SNPs explain a large  
710 proportion of the heritability for human height' by Yang et al. (2010). *Twin Res Hum Genet*,  
711 13:517-24.

712 Voets, N.L., Hough, M.G., Douaud, G., Matthews, P.M., James, A., Winmill, L., Webster, P., Smith, S.  
713 (2008) Evidence for abnormalities of cortical development in adolescent-onset  
714 schizophrenia. *Neuroimage*, 43:665-75.

715 Vrooman, H.A., Cocosco, C.A., van der Lijn, F., Stokking, R., Ikram, M.A., Vernooij, M.W., Breteler,  
716 M.M., Niessen, W.J. (2007) Multi-spectral brain tissue segmentation using automatically  
717 trained k-Nearest-Neighbor classification. *Neuroimage*, 37:71-81.

718 Willer, C.J., Li, Y., Abecasis, G.R. (2010) METAL: fast and efficient meta-analysis of genomewide  
719 association scans. *Bioinformatics*, 26:2190-1.

720 Willer, C.J., Sanna, S., Jackson, A.U., Scuteri, A., Bonnycastle, L.L., Clarke, R., Heath, S.C., Timpson,  
721 N.J., Najjar, S.S., Stringham, H.M., Strait, J., Duren, W.L., Maschio, A., Busonero, F., Mulas, A.,  
722 Albai, G., Swift, A.J., Morken, M.A., Narisu, N., Bennett, D., Parish, S., Shen, H., Galan, P.,  
723 Meneton, P., Hercberg, S., Zelenika, D., Chen, W.M., Li, Y., Scott, L.J., Scheet, P.A., Sundvall,  
724 J., Watanabe, R.M., Nagaraja, R., Ebrahim, S., Lawlor, D.A., Ben-Shlomo, Y., Davey-Smith, G.,  
725 Shuldiner, A.R., Collins, R., Bergman, R.N., Uda, M., Tuomilehto, J., Cao, A., Collins, F.S.,  
726 Lakatta, E., Lathrop, G.M., Boehnke, M., Schlessinger, D., Mohlke, K.L., Abecasis, G.R. (2008)  
727 Newly identified loci that influence lipid concentrations and risk of coronary artery disease.  
728 *Nat Genet*, 40:161-9.

729 Winkler, A.M., Kochunov, P., Blangero, J., Almasy, L., Zilles, K., Fox, P.T., Duggirala, R., Glahn, D.C.  
730 (2010) Cortical thickness or grey matter volume? The importance of selecting the phenotype  
731 for imaging genetics studies. *Neuroimage*, 53:1135-46.

732 Yang, J., Benyamin, B., McEvoy, B.P., Gordon, S., Henders, A.K., Nyholt, D.R., Madden, P.A., Heath,  
733 A.C., Martin, N.G., Montgomery, G.W., Goddard, M.E., Visscher, P.M. (2010) Common SNPs  
734 explain a large proportion of the heritability for human height. *Nat Genet*, 42:565-9.

735 Yang, J., Lee, S.H., Goddard, M.E., Visscher, P.M. (2011) GCTA: a tool for genome-wide complex trait  
736 analysis. *Am J Hum Genet*, 88:76-82.

737 Yoon, U., Perusse, D., Lee, J.M., Evans, A.C. (2011) Genetic and environmental influences on  
738 structural variability of the brain in pediatric twin: deformation based morphometry.  
739 *Neurosci Lett*, 493:8-13.

740 Zuk, O., Hechter, E., Sunyaev, S.R., Lander, E.S. (2012) The mystery of missing heritability: Genetic  
741 interactions create phantom heritability. *Proc Natl Acad Sci U S A*, 109:1193-8.

742 Zuk, O., Schaffner, S.F., Samocha, K., Do, R., Hechter, E., Kathiresan, S., Daly, M.J., Neale, B.M.,  
743 Sunyaev, S.R., Lander, E.S. (2014) Searching for missing heritability: designing rare variant  
744 association studies. *Proc Natl Acad Sci U S A*, 111:E455-64.

745

746

747 **Figure 1:** Example of FDR-Significant voxels in both population-based (A) and family-based (B)  
748 estimates. Significant voxels cluster in subcortical structures, such as the caudate nucleus. All results  
749 can be interactive accessed ([www.imagene.nl/heritability](http://www.imagene.nl/heritability)) and downloaded from the website.

750 **Figure 2: A** Barplot showing regional brain heritability. Structures that are in both the left as well as  
751 the right hemisphere were averaged for this figure. It can clearly be seen that the heritability from  
752 family-based studies is higher than heritability from the unrelated population ( $P < 0.001$ ). **B** Scatter  
753 plot of the average regional heritability of all brain structures. The correlation of the family-based  
754 and population-based estimates was high (Pearson's correlation coefficient = 0.73,  $p = 2.6 \times 10^{-13}$ ).  
755 Data points per structure correspond to family and population heritability in table 2.

756 **Figure 3:** Enhancement of the association signal of variants with the most heritable voxels of the  
757 hippocampus and putamen. **A,B:** Average heritability (y-axis) of the voxels in hippocampus (A) and  
758 putamen (B) given a percentage of the most heritable voxels in that region (x-axis) in steps of 5%.  
759 **C,D:** The  $-\log(p\text{-value})$  increase comparing the p-value of association with subsets of the most  
760 heritable voxels and all voxels in the region. The  $-\log(p\text{-value})$  increase for association of  
761 hippocampal with rs77956314 (*HRK* gene) and putamen voxels with rs945270 (*KTN1* gene) is shown.  
762 Associations were corrected for age, sex, and the first three principal components.

763 **Supplementary Figure 1: Example of the intraclass correlation (ICC) in 83 individuals scanned twice**  
764 **within several weeks. In general voxels have a high ICC. All results can be interactive accessed**  
765 **([www.imagene.nl/heritability](http://www.imagene.nl/heritability)) and downloaded from the website.**

766