EigenGWAS: finding loci under selection through genome-wide association studies of eigenvectors in structured populations

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Abstract

We apply the statistical framework for genome-wide association studies (GWAS) to eigenvector decomposition (EigenGWAS), which is commonly used in population genetics to characterise the structure of genetic data. We show that loci under selection can be detected in a structured population by using eigenvectors as phenotypes in a single-marker GWAS. We find *LCT* to be under selection between HapMap CEU-TSI cohorts, a finding that was replicated across European countries in the POPRES samples. *HERC2* was also found to be differentiated between both the CEU-TSI cohort and among POPRES samples, reflecting the likely anthropological differences in skin and hair colour between northern and southern European populations. We show that when determining the effect of a SNP on an eigenvector, three methods of single-marker regression of eigenvectors, best linear unbiased prediction of eigenvectors, and singular value decomposition of SNP data are equivalent to each other. We also demonstrate that estimated SNP effects on eigenvectors from a reference panel can be used to predict eigenvectors (the projected eigenvectors) in a target sample with high accuracy, particularly for the primary eigenvectors. Under this GWAS framework, ancestry informative markers and loci under selection can be identified, and population structure can be captured and easily interpreted. We have developed freely available software to facilitate the application of the methods.

Introduction

In population genetics, eigenvectors have been routinely used to quantify genetic differentiation across populations and to infer demographic history (Cavalli-Sforza et al. 1996; Novembre et al. 2008; Reich et al. 2009). More recently, eigenvectors are commonly used as covariates in genome-wide association studies (GWAS) to adjust for population stratification (Price et al. 2006). Eigenvectors are usually estimated for each individual (individual-level eigenvectors, involving the inversion of a $N \times N$ matrix, where N is sample size). Theoretical studies have suggested that individual-level primary eigenvectors are measures of population differentiation reflecting F_{st} among subpopulations (Patterson et al. 2006; McVean 2009; Bryc et al. 2013) and can be interpreted as the divergence of individuals from their most recent common ancestor. Eigenvectors can also be estimated for each SNP (SNP-level eigenvectors, which involve inversion of a $M \times M$ matrix, M is the number of SNPs) and these SNP-level eigenvectors can be interpreted as F_{st} metrics of each SNP (Weir 1996). SNP-level eigenvectors from a reference population are useful for revealing the population structure of independent samples (Zhu et al. 2008) as they can be used to project, or predict, the eigenvector values of individuals. However, due to high-dimensional nature of GWAS data (commonly expressed as $M \gg N$), direct estimation of SNP-level eigenvectors is nearly impossible when using millions of single nucleotide polymorphisms (SNPs).

Recently, Chen et al. proposed that singular value decomposition (SVD) could calculate SNP-level eigenvectors based on individual-level eigenvectors (Chen et al. 2013). While this enables SNP-level eigenvalues to be obtained in a computationally efficient manner for any set of genotype data, it is not possible to determine the SNPs that contribute most to the leading eigenvector, or to test whether specific SNPs are differentiated along the genetic gradient described by the eigenvector. Recently, these limitations were overcome, using an approximation method (Galinsky et al. 2015), enabling *p*-values to be estimated that reflect the strength of differentiation at a given SNP.

Here, we propose an alternative simple, fast approach for the estimation of SNP-level eigenvectors. By using individual-level eigenvectors as phenotypes in a linear regression, we demonstrate that the regression coefficients generated by single-SNP regression are equivalent to SVD SNP effects as proposed by Chen et al (Chen et al. 2013). As the single-SNP regression resembles the popular single-marker GWAS method, as implemented in PLINK (Purcell et al. 2007), we call this method EigenGWAS. We show that the EigenGWAS framework represents an alternative way for identifying regions under selection along gradients of ancestry.

Methods and Materials

HapMap3 samples. HapMap3 samples were collected globally to represent genetic diversity of human population (Altshuler et al. 2010). HapMap3 contains representative samples from many continents: CEU and TSI represent population from north and south Europe, CHB and JPT from East Asia, and CHD Chinese collected in Denver, Colorado. Loci with palindrome alleles (A/T alleles, or G/C alleles) were excluded, and 919,133 HapMap3 SNPs were used for the analysis.

1000 Genomes project. 1000 Genomes project samples were used as a prediction set for projecting eigenvectors (The 1000 Genomes Project Consortium 2012). We selected the Puerto Rico cohort (PUR, 105 samples) and the Pakistan cohort (Punjabi from Lahore, Pakistan, 95 samples) for analysis.

POPRES samples. POPRES (Nelson et al. 2008) is a reference population for over 6,000 samples from Asian, African, and European nations. In this study, we selected 2,466 European descendants. The POPRES genotype sample was imputed to a 1000 Genomes reference panel (The 1000 Genomes Project Consortium 2012). Imputation for the POPRES was performed in two stages. First, the target data was haplotyped using HAPI-UR (Williams et al. 2012). Second, Impute2 was used to impute the haplotypes to the 1000 genomes reference panel (Howie et al. 2011). We then selected SNPs which were present across all datasets at an imputation information score of >0.8. A full imputation procedure is described at https://github.com/CNSGenomics/impute-pipe. After quality control and removing loci with palindromic alleles (A/T alleles, or G/C alleles) 643,995 SNPs for POPRES remained. In addition, we also conducted the analysis using non-imputed 234,127 common markers between POPRES and HapMap3. As the results were between these two datasets were very similar, this report focused on the results from 643,995 SNPs, which were more informative.

Simulation study. 2,000 unrelated samples with 500,000 biallelic markers, which were in linkage equilibrium to each other, were simulated. The minor allele frequencies ranged from 0.01~0.5, and Hardy-Weinberg equilibrium was assumed for each locus. All individuals were simulated from a homogeneous population, with no population stratification. In order to calculate F_{st} at each locus, we divided the sample into sub-populations based upon eigenvectors that were estimated from a genetic relationship matrix calculated using all 500,000 markers (see below). Unless otherwise specified, the used simulation data refers to this data.

Calculating individual-level eigenvectors

We assume that there is a reference sample consisting of N unrelated individuals and M markers. $X_i = (x_{i1}, x_{i2}, \dots, x_{iM})^T$, is a vector of the ith individual's genotypes along M loci, with x the number of the reference alleles. An $N \times N$ genetic relatedness (correlation) matrix $\boldsymbol{A}$ (matrix in bold font) for each pair of individuals is defined as $A_{ij} = \frac{1}{M} \Sigma_{l=1}^{M} \frac{(x_{il}-2f_l)(x_{jl}-2f_l)}{2f_l(1-f_l)}$, in which f_l is the frequency of the reference allele. The principal component analysis (PCA) is then implemented on the A matrix (Price et al. 2006), generating $\mathbb{E}$, which is an $N \times K$ ($K \leq N$) matrix, in which E_k is the eigenvector corresponding to the kth largest eigenvector.

Unified framework for BLUP, SVD, and EigenGWAS

Theoretically, PCA can also be implemented on a $M \times M$ matrix, but this is often infeasible because the $M \times M$ matrix is very large. However, for individual i, eigenvector k can also be written as:

$E_{k.i} = \beta_k \boldsymbol{X}_i^T$ **(Equation 1)**

in which β_k is a $M \times 1$ SNP-level vector of the SNP effects on E_k, and x_i is the genotype of the ith individual across M loci. In the text below, we denote individual-level eigenvector as eigenvector ($N \times 1$ vector), and SNP-level eigenvector ($M \times 1$) as SNP effects.

We review three possible methods to estimate β given eigenvectors. The first method is best linear prediction (BLUP), which is commonly used in animal breeding and recently has been introduced to human genetics for prediction (Henderson 1975; Goddard et al. 2009). The second method is to convert an individual-level eigenvector to SNP-level eigenvector using SVD, as proposed by Chen et al (Chen et al. 2013). The third method is the approach outlined here, EigenGWAS, which is a single-marker regression, as commonly used in GWAS analysis.

Method 1 and 2: BLUP and SVD

For a quantitative trait, $y = \mu + \beta \boldsymbol{X} + e$, in which y is the phenotype, μ is the grand mean, β is the vector for additive effects, X is the genotype matrix, and e is the residual. Without loss of generality, the BLUP equation can be expressed as:

$\hat{\beta} = \widetilde{\boldsymbol{X}}^T \boldsymbol{V}^{-1} y$ **(Equation 2)**

in which $\hat{\beta}$ is the estimates of the SNP effects, $\widetilde{\boldsymbol{X}}$ is the standardized genotype matrix, $\boldsymbol{V}$ is the variance covariance with $\boldsymbol{V} = {\sigma_A}^2 \boldsymbol{A} + \left(\sigma_y^2 - {\sigma_A}^2\right)\boldsymbol{I}$, and y is the trait of interest (Henderson 1975). Replacing y with individual-level eigenvector (E_k), Eq 2 can be written as

$\hat{\beta}_k = \widetilde{\boldsymbol{X}}^T \boldsymbol{A}^{-1} E_k$ **(Equation 3)**

in which β_k is the BLUP estimate of the SNP effects, E_k is the kth eigenvector estimated from the reference sample., The $\boldsymbol{V}$ matrix can be replaced with $\boldsymbol{A}$ because the eigenvector has no residual error (i.e. h^2=1). This method has also been proposed as an equivalent computing algorithm for genomic predictions (Maier et al. 2015).

In addition, the connection between PCA and SVD can be established through the transformation between the $N \times N$ matrix to the $M \times M$ matrix (McVean 2009). Let $\boldsymbol{A} = \boldsymbol{PDP}^{-1}$, in which $\boldsymbol{D}$ is a $N \times N$ diagonal matrix with λ_k, $\boldsymbol{P}$ is $N \times N$ matrix with the eigenvectors. $\boldsymbol{B} = \boldsymbol{X}^T(\boldsymbol{PDP}^{-1})^{-1}\boldsymbol{P} = \boldsymbol{X}^T\boldsymbol{PD}^{-1}$, in which $\boldsymbol{B}$ is $M \times N$ matrix. This is equivalent to the equation used in Chen et al (Chen et al. 2013) where $\boldsymbol{B}^T = \boldsymbol{D}^{-1}(\boldsymbol{X}^T\boldsymbol{P})^T$. Thus, eigenvector transformation can be viewed as a special case of BLUP in which the heritability is 1 (Eq 3). However, under SVD another analysis step is then required to evaluate the significance of the estimated SNP effect. In an EigenGWAS framework an empirical *p-value* is produced when estimating the regression coefficient.

<u>Method 3: estimating SNP effects on eigenvectors with EigenGWAS</u>

Given the realized genetic relationship matrix A, for unrelated homogeneous (i.i.d.) samples, $E(A_{ij}) = 0$ $(i \neq j)$, and consequently $E(\boldsymbol{A}) = \boldsymbol{I}$**, an identity matrix**. Due to sampling variance of the genetic relationship matrix $\boldsymbol{A}$, the off diagonal is a number slightly different from zero even for unrelated samples (Chen 2014). If we replace the matrix with its mathematical expectation – the identity matrix, Equation 3 can be further reduced to $\beta_k = \widetilde{\boldsymbol{X}}^T E_k$, which is equivalent to single-marker regression $E_k = a + bx + e$, as implemented in PLINK (Purcell et al. 2007). Furthermore, standardization for $\boldsymbol{X}$ is not required because it will not affect *p*-value. Thus, SNP effects can be estimated using the single-marker regression, which is computationally much easier in practice and is implemented in many software packages. Each SNP effect, $\hat{\beta}_{k.m}$, is estimated independently, and the *p*-value of each marker can be estimated, which requires additional steps in BLUP and SVD.

We summarise the properties and their transformation of SVD, BLUP, and EigenGWAS as below:

1) E_k is determined by the $\boldsymbol{A}$ matrix, or in another words, it is determined by the genotypes completely. If we consider each E_k is the trait of interest – a quantitative trait, its heritability is 1.
2) $h^2 = 1$. SVD and BLUP are both computational tool in converting a vector from $N \times N$ matrix to a $M \times M$ matrix. SVD is a special case to BLUP when $h^2 = 1$ for BLUP.

3) $h^2 = 1$ and $E(\boldsymbol{A}) = \boldsymbol{I}$. When these two conditions are set, BLUP is further reduced to single-marker association studies, which is EigenGWAS as suggested in this study.

Recently, in an independent work Galinsky et al (Galinsky et al. 2015) introduced an approximation to find the proper scaling for SNP effects ("SNP weight" in Galinsky's terminology) estimated from SVD, in order to produce accurate *p*-values. In our EigenGWAS framework, *p*-values for individual-level SNP eigenvector are automatically generated. In practice, it is conceptually easier to conduct EigenGWAS on eigenvectors than to conduct BLUP/SVD. Also, if computational speed is of concern, EigenGWAS can be easily parallelized for each chromosome, each region, or even each locus.

F_{st} and EigenGWAS for a divergent population

Wright's F_{st} (Wright 1951) is one of the most used statistic to characterize the structure of a population. As defined by Weir, for a pair of subpopulations, $F_{st}^W = \frac{2\sum_{i=1}^{2} w_i[(p_i-\bar{p})^2]}{\bar{p}\bar{q}}$ (Weir 1996). Nei's estimator is $F_{st}^N = \frac{(p_1-p_2)^2}{2\bar{p}\bar{q}}$ for a biallelic locus (Nei 1973); for two subdivisions of same proportion to the total sample, $F_{st}^N = F_{st}^W$ (for extreme case, $p_1 = 0$, $p_1 = 1$, $w_1 = w_2 = 0.5$,$\bar{p} = w_1p_1 + w_2p_2 = 0.5$, and $F_{st}^W = F_{st}^N = 2$).

If fitting into a linear regression for a dataset with C percentage of samples from subpopulation 1 and $(1-C)$ from subpopulation 2, we can write a linear regression model $E_k = a + \beta x + e$. We can estimate $\beta = \frac{cov(E_k,x)}{var(x)} = \frac{E(E_kx)-E(E_k)E(x)}{var(x)} = \frac{E(E_kx)}{var(x)} = \frac{(1-C)i(2p_1-2\bar{p})+Ci(2\bar{p}-2p_2)}{2\bar{p}\bar{q}} = \frac{2iC(1-C)(2p_1-2p_2)}{2\bar{p}\bar{q}}$, assuming Hardy-Weinberg equilibrium and i is the selection intensity given a threshold that partitions samples into C and $(1-C)$ proportions (Falconer and Mackay 1996); the sampling variance for β is $\sigma_\beta^2 = \frac{\sigma_e^2}{n\sigma_x^2}$; and the variation explain by the locus is $var(\beta x) = 4[2C(1-C)i]^2\frac{(p_1-p_2)^2}{2\bar{p}\bar{q}} = [2C(1-C)i]^2F_{st}^N$. A chi-square test for β is $\chi_1^2 = \frac{\left[\frac{2C(1-C)i(2p_1-2p_2)}{2\bar{p}\bar{q}}\right]^2}{\frac{\sigma_e^2}{n\sigma_x^2}} = \frac{n[2C(1-C)i]^2}{\sigma_e^2}\frac{(2p_1-2p_2)^2}{2\bar{p}\bar{q}} = \frac{4n[2C(1-C)i]^2}{\sigma_e^2}F_{st}^N$.

As $\frac{4n[2C(1-C)i]^2}{\sigma_e^2}$ is a constant for all loci (ignoring the difference may be introduced due to missing data),

$\chi_1^2 \propto F_{st}^N$ **(Equation 4)**

Under the null hypothesis that allele frequency differences are driven by genetic drift only, the EigenGWAS test statistics will be proportional to F_{st}. Of note, E_k is a centralized normal-distributed variable, and under the null model partitioning the samples into two groups upon $E_k > 0$ or $E \leq 0$ should roughly split the samples into two equal sizes. So, under the null hypothesis, in which when $C \approx 0.5$, $F_{st}^W \approx F_{st}^N$, $\chi_{1.b}^2 = \frac{4n[2C(1-C)i]^2}{\sigma_e^2} F_{st}^W$.

Conventional methods for estimation of F_{st} rely upon grouping samples in some way, which generates a prior for F_{st}. In contrast, EigenGWAS-based F_{st} does not need explicit grouping of the samples, and population stratification can be examined in any sample using EigenGWAS even if the groupings are not known. When group structure is known then there will be high concordance between EigenGWAS test statistic and conventional F_{st}, and we test this using the CEU&TSI cohort.

Validation and prediction for population structure

Once β_k is estimated, it is straightforward to get genealogical profile for an independent target sample. In general, it is equivalent to genomic prediction, and the theory for prediction can be applied (Daetwyler et al. 2008; Dudbridge 2013). The predicted genealogical score can be generated as

$\tilde{E}_k = \hat{\beta}_{k.m}\boldsymbol{X}$ **(Equation 5)**

in which E_k is the predicted k^{th} eigenvector, $\hat{\beta}_{k.m}$ is the estimated SNP effects, and $\boldsymbol{X}$ is the genotype for the target sample. We focus on the correlation between the predicted eigenvectors and the direct eigenvectors, and thus it does not matter whether $\boldsymbol{X}$ or $\widetilde{\boldsymbol{X}}$ is used.

In contrast to conventional prediction studies, which focus on a metric phenotype of interest, prediction of population structure is focussed on a "latent" variable. This latent variable is the genetic structure of population, which is shaped by allele frequency and linkage disequilibrium of markers. Thus, expectations of prediction accuracy differ from what has been established for conventional prediction (Daetwyler et al. 2008; Dudbridge 2013) $R^2 = h^2\left(\frac{h^2}{h^2+\frac{M}{N}}\right) < h^2 \ll 1$. We therefore assess prediction of accuracy for E_1 across markers, when using different prediction thresholding (Purcell et al. 2009).

Here we proposed an equation for prediction accuracy, especially for E_1

$$R^2 = \frac{\left(h^2+\frac{M}{N_e}\right)^2}{h^2\left(1+2\frac{M}{N_e}\right)+\frac{M}{N_e}\left(1+\frac{M}{N_e}\right)} \approx \frac{1}{1+N_e/M} \qquad \textbf{(Equation 6)}$$

when there is no heritability, the predictor can be simplified to $R^2 = \frac{1}{1+\frac{N_e}{M}}$, meaning that as the number of markers increases prediction accuracy should rapidly reach 1. Here the h^2 is interpreted as the genetic difference in the source population, or real ancestry informative markers. For a homogeneous population, the genetic difference is large due to genetic drift, and $h^2 \approx 0$.

For this study, the genetic relationship matrix (***A*** matrix), principal component analysis, and BLUP estimation were conducted using GCTA software (Yang et al. 2011a). Single-marker GWAS was conducted using PLINK (Purcell et al. 2007), or GEAR (https://github.com/gc5k/GEAR/wiki/EigenGWAS; https://github.com/gc5k/GEAR/wiki/ProPC).

Results

Properties of the estimating SNP effects for eigenvectors

We applied EigenGWAS to the HapMap cohort, a known structured population. Eigenvectors were estimated via principal component analysis based on the ***A*** matrix using all 919,133 SNPs. We conducted EigenGWAS for HapMap, using E_k as the phenotype and investigated the performance of EigenGWAS from E_1 to E_{10}. From E_1 to E_{10}, we found 546,716 significant signals (231,677 quasi-independent signals after clumping) on E_1 and gradually reduced to 236 (163 after clumping) signals on E_{10} (**Fig. 1**). The large number of genome-wide significant loci are likely because HapMap3 was comprised of samples from different ethnicities, and these loci can be interpreted as ancestry informative markers (AIM). For each E_k, its associated eigenvalue was highly correlated with the λ_{GC} resulted from its EigenGWAS. The top five eigenvalues associated to HapMap samples were 100.14, 47.66, 7.168, 5.92, and 4.40, and the corresponding λ_{GC} of eigenvector GWAS were 103.72, 44.69, 6.47, 5.17, and 3.96, respectively (**Table 1**). The large eigenvalues observed were consistent with previous theory that the magnitude of eigenvalues indicating structured population (Patterson et al. 2006). The connection between λ_{GC} and eigenvalues, provides a straightforward interpretation: a large λ_{GC} indicates underlying population structure (Devlin and Roeder 1999). Therefore, correction for λ_{GC} will filter out signals due to population stratification, allowing loci under selection to be identified.

We demonstrate theoretically that for EigenGWAS, the estimated SNP effects using single-marker GWAS are equivalent to the estimates from BLUP, and the correlation between the estimates from these two methods was very high (greater than 0.98 on average) (**Fig. 2**), even in HapMap samples that consist of a mix of ethnicities where the $\boldsymbol{A}$ matrix is non-zero for off-diagonal elements (**Supplementary Fig. 1**). This confirms that our EigenGWAS approach provides an accurate representation of the SNP effects on eigenvalues.

We also conducted EigenGWAS on the POPRES samples, from which we selected 2,466 European samples. On E_1, there were 10,885 (3,004 quasi-independent signals after clumping) genome-wide significant signals, and reduced to 1,639 (90 after clumping) on E_{10} (**Table 1**). As in the HapMap sample, we observed a concordance between eigenvalues and λ_{GC} in POPRES. The top five eigenvalues were 5.104, 2.207, 2.157, 2.077, and 1.971, with their associated EigenGWAS λ_{GC} were 5.005, 1.929, 1.910, 1.464, and 1.866, respectively (**Table 1**), indicating population structure. The GRM matrix estimated from the POPRES data resembled a diagonal matrix, which had off-diagonal elements close to zero, suggesting that POPRES is a more homogenous samples as compared to HapMap (**Supplementary Fig. 1**). Correlations between the estimates from EigenGWAS and BLUP were high, with an average of greater than 0.999 from E_1 to E_{10} (**Supplementary Fig. 2**).

The chi-square statistics of the estimated SNP effects on eigenvectors from EigenGWAS were correlated with F_{st} for each SNP, consistent with previous established relationship between eigenvectors and F_{st} (Patterson et al. 2006; McVean 2009). Using naïve threshold of $E_k > 0$, 2,466 POPRES samples were divided into nearly two even groups, which would be served as two subgroups in calculating F_{st}. $E_1 > 0$ split the POPRES samples into North and South Europe; samples from UK, Ireland, Germany, Austria, and Australia were in one group, and samples from Italy, Spain, and Portugal were in the other group; samples from Switzerland and France were nearly evenly split into two groups. F_{st} for each SNP was consequently calculated based on these two groups. For every eigenvector until E_{10}, we observed strong correlations between F_{st} and the chi-square test statistics for EigenGWAS signals (**Fig. 3**), and the averaged correlation was 0.925 (S.D., 0.067). For example, the correlation was 0.89 (p-value<1e-16) between chi-square test statistics and F_{st} for E_1 in POPRES (**Supplementary Table 1**). This correlation is consistent with our theory, where F_{st} has a strong linear relationship with its EigenGWAS chi-square test statistic.

We also validated our results in a simulation study. Given 2,000 simulated samples, each of which had 500,000 unlinked SNPs, the EigenGWAS showed few GWAS signals (2 genome-wide significant signals on E_1, (**Supplementary Fig. 4**). After splitting the samples into 2 groups depending on $E_i > 0$, the correlation between chi-square test statistics and F_{st} is about 0.67 from E_1 to E_{10} (**Supplementary Fig. 5**). As expected, λ_{GC} ranged from around 1.124 to 1.130, with a mean of 1.124 for EigenGWAS on the top 10 eigenvectors, indicating little population stratification for the simulated data.

Using EigenGWAS to identify loci under selection in structured populations

We propose EigenGWAS as a method of finding loci differentiated among populations, or across a gradiant of ancestry. Intuitively, every EigenGWAS hit is an AIM, which differ in allele frequency along an eigenvector due to genetic drift or selection. A locus under selection should be more differed across populations than genetic drift can bring out. Thus, correction for λ_{GC}, controls for background population structure, providing a test of whether an AIM shows greater allelic differentiation than expected under the process of genetic drift.

We pooled together CEU (112 individuals) and TSI (88 individuals), which represent Northwestern and Southern European populations in HapMap. EigenGWAS was conducted on E_1, which partitioned CEU and TSI into two groups accurately using $E_1 > 0$ as threshold (**Supplementary Fig. 6**). We corrected for λ_{GC}, which was 1.723, for CEU&TSI. Adjustment for λ_{GC} significantly reduced population stratification (Supplementary Fig 7), and was consequently possible to filter out the baseline difference between these two cohorts. After correction, we found evidence of selection at the lactose persistence locus, *LCT* (*p*-value=1.21e-20). Due to hitchhiking effect, the region near *LCT* also showed divergent allele frequencies. For example, the *DARS* gene, 0.15M away from *LCT*, was also significantly associated with E_1 (*p*-values=1.51e-23). *HERC2* was slightly below genome-wide significance level (*p*-value=8.22e-08), indicating that anthropological difference reflected geographic locations of two cohorts but not under selection as strong as *LCT*.

We then conducted EigenGWAS in the POPRES sample by treating E_1 as a quantitative trait, and calculated the approximate F_{st} for each SNP given two groups split by the threshold of $E_1 > 0$ (**Supplementary Fig. 8**). Given 643,995 SNPs, the genome-wide threshold was *p*-value < 7.76e-08 for the significance level of $\alpha = 0.05$. $\lambda_{GC} = 5.00$, which indicated substantial population stratification as expected for POPRES. Correcting for λ_{GC} systematically reduced the EigenGWAS

χ^2 test statistics (**Supplementary Fig 9**), and we replicated the significance of *LCT* (*p*-value=1.23e-22) and *DARS* (*p*-value=8.99e-22) (**Table 2**), suggesting selection at these regions. *HERC2* was also replicated with *p*-value 8.15e-09, and with F_{st} of 0.041.

Prediction accuracy for projected eigenvector

We investigated three aspects of EigenGWAS prediction: 1) the number of loci needed to achieve high accuracy for the projected eigenvectors; 2) the required sample size of the training set; 3) the importance of matching the population structure between the training and the test sets.

Using the POPRES samples, we split 5% (125 individuals), 10% (250 individuals), 20% (500 individuals), 30% (750 individuals), 40% (1000 individuals), and 50% (1250 individuals) of the sample as the training set, and used the remainder of the samples as the test set. Eigenvectors were estimated using all markers in each training set. As predicted by our theory (Eq 6), the prediction accuracy of the projected eigenvector was consistent with $R^2 = \frac{1}{1+\frac{N_e}{M}}$ in which $N_e = 1{,}000$ for E_1. If only 100 and 1,000 random SNPs were sampled as predictors, the expected maximal $R^2 = 0.091$ and 0.5, respectively and accuracy reached almost 1 if more than 100,000 SNPs were sampled. In agreement with our theory (**Fig. 6**), if the number of predictors were too small the prediction accuracy was poor, with prediction accuracy increasing with the addition of more markers for E_1. When the sample size of the discovery was 1,000 or above, maximal prediction accuracy was achieved, as predicted in our theory. Therefore, a discovery with a sample size greater than 1,000 should be sufficient to predict the first eigenvector of an independent set, provided that population structure is the same across the discovery and prediction samples (**Fig. 6**). In contrast, the prediction accuracy for prediction eigenvectors decreased (**Fig. 6**) quickly for eigenvectors other than E_1. For example, the prediction accuracy for E_2 was below $R^2 < 0.2$ and $R^2 < 0.15$ for E_3. For $E_4 \sim E_{10}$, the prediction accuracy dropped down to nearly zero. This is consistent with the top 2~3 eigenvectors explaining the majority of variation (McVean 2009), if the training and the test sets had their population structure matched.

If EigenGWAS SNPs of low *p*-value were likely to be AIMs, we would hypothesise that AIM markers would be more efficient in giving high accuracy for the predicted eigenvectors (**Fig. 6**). For E_1, the prediction accuracy reached 1 more quickly by using markers selected by *p*-value thresholds. The prediction accuracy for projected E_2 was dependent upon the threshold. For projected E_2 given a 50:50 split of POPRES sample, applying the threshold of *p*-value < 1e-6 (927 SNPs), $R^2 = 0.136$, as

high as using all markers. For other projected eigenvectors, the pattern of accuracy did not change much after applying *p*-value thresholds because in general, the prediction accuracy was low. This indicated that eigenvectors other than the first two eigenvectors capture little replicable population structure in POPRES.

In practice, the training and the test set may not match perfectly on population structure, and this will likely lead to a reduction in prediction accuracy. To demonstrate this, we split the POPRES samples into two sets: pooling Swiss (991 samples) and French (96 samples) samples into one group (SF), and the rest of the samples into the other group (NSF). We used SF as the training and the NSF as the testing. As SF was almost an average of North European and South European gene flow, making a less stratified population, its EigenGWAS effects would be consequently small and less "heritable". When using all SNPs effects estimated from SF set, the observed prediction accuracy for NSF set was $R^2 = 0.33$ and 0.005 for E_1 and E_2, respectively. These results indicate that a matched training and test set is important for prediction accuracy of the projected eigenvectors.

Ancestry information may still be elucidated well even if the training set and the test set do not match well in their population structure. Using HapMap3 as the training set, we also tried to infer the ancestry of the Puerto Rican cohort (PUR, 105 individuals) and Pakistani cohorts (PJL, 95 individuals) from 1000 Genomes project (The 1000 Genomes Project Consortium 2012). In chromosome 1, 74,500 common SNs were found between HapMap3 and 1000 Genomes project. As illustrated, using only 74,500 common markers between HapMap3 and 1000 Genome projects SNPs on chromosome 1, it projected Eigenvectors accurately revealed the demographic history of Puerto Rican cohort, an admixture of African and European gene flows, and Pakistan cohort, an admixture of Asian and European gene flows (**Fig. 7**).

As a negative control, we replicated the prediction study for simulated data used in the previous section. The simulated data was split to two equal sample size. As there was no population structure in the simulated data, the prediction accuracy was poor, $R^2 < 0.01$ from E_1 to E_{10}. This demonstrates that prediction can be used to validate whether population structure exists within a genotype sample.

We concluded that to achieve high prediction accuracy of projected eigenvectors for independent samples, there are several conditions to be met: 1) the training set should harbour sufficient population stratification; 2) the sample size of the training should be sufficiently large; 3) the test

sets should be as concordant as possible in its population structure; 4) when there is no real population structure, the prediction accuracy is very low close to zero; 5) depending on the population, high prediction was largely achievable for the projected E_1.

Discussion

Eigenvectors have been routinely employed in population genetics, and various approaches have been proposed to offer interpretation and efficient algorithms (Patterson et al. 2006; McVean 2009; Rokhlin et al. 2009; Chen et al. 2013; Galinsky et al. 2015). In this study, we created a GWAS framework for studying and validating population structure, and offer an interpretation of eigenvectors within this framework. The EigenGWAS framework (least square) identifies ancestry informative markers and loci under selection across gradients of ancestry.

We integrated SVD, BLUP, and single-marker regression into a unified framework for the estimation of SNP-level eigenvectors. SVD is a special case of BLUP when heritability is of 1 for the trait and the target phenotype is an eigenvector. Furthermore, the BLUP is equivalent to the commonly used GWAS method for estimating SNP effects. As demonstrated, the correlation between BLUP and GWAS is almost 1 for the estimated SNP effects. EigenGWAS offers an alternative way in estimating F_{st} that can replace conventional F_{st} when population labels are unknown, populations are admixed, or differentiation occurs across a gradient. As demonstrated for CEU&TSI samples, EigenGWAS bring out nearly identical estimation of F_{st} compared with conventional estimation.

Different from conventional GWAS, which requires conventional phenotypes, the proposed EigenGWAS provides a novel method for finding loci under selection based on eigenvectors, which are generated from the genotype data itself. An EigenGWAS hit may reflect the consequence of process and thus additional evidence is needed to differentiate selection from drift. *LCT* is a known locus under selection, which differs in its allele frequency as indicated by F_{st} statistic between Northern and Southern Europeans. We replicated the significance of *LCT* in CEU&TSI samples and POPRES European samples. *DARS* has been found in association with hypomyelination with brainstem and spinal cord involvement and leg spasticity (Taft et al. 2013). In addition, we also found *HERC2* locus independently, which may indicate the existence of anthropological difference in certain characters, such as hair, skin, or eyes color across European nations.

Although by definition selection and genetic drift are different biological processes, both lead to allele frequency differentiation across populations and often difficult to tear them apart. In this study, with and without adjustment for λ_{GC} from EigenGWAS offers a straightforward way to filter out population stratification. For example, with adjustment for λ_{GC}, *LCT* and *DARS* were still significant in both EigenGWAS, while *HERC2* was not significant in neither. If adjustment for λ_{GC} removed the average genetic drift since the most recent common ancestor for the whole sample, it might indicate that *HERC2* reflected the anthropological difference between subsamples but not under selection as strong as that for *LCT*. Nevertheless, *LCT* was differentiated due to selection that was on top of genetic drift, and for *DARS,* it might be significant due to hitchhiking effect. So, *LCT, DARS,* and *HERC2* were significant in EigenGWAS for different mechanisms.

In EigenGWAS application, it provides a clear scenario that λ_{GC} is necessary if genetic drift/population stratification should be filtered out. It has been debated whether correction for λ_{GC} is necessary for GWAS (Devlin and Risch 1995; Yang et al. 2011b). If the inflation is due to population stratification, as initially λ_{GC} introduced, it seems necessary to control for it. In contrast, if it is due to polygenic genetic architecture, then correction for λ_{GC} will be a overkilling for GWAS signals. Interestingly, Patterson et al (Patterson et al. 2006) found that the top eigenvalues reflect population stratification, and in our study we found λ_{GC} from EigenGWAS was numerically so similar to its corresponding eigenvalues. It in another aspect indicates λ_{GC} captures population stratification. So, in concept and implementation, the correction for λ_{GC} is technically reasonable. Of note, Galinsky et al also proposed a similar procedure to filter out population stratification in a study similar to ours (Galinsky et al. 2015), but we believe our framework is much easier to understand and implement in practice.

Once we have EigenGWAS SNP effects estimated, it is straightforward to project those effects onto an independent sample. The prediction of population structure was to that of recent studies (Chen et al. 2013). We found that the prediction accuracy for the top eigenvector could be as high as almost 1. Given a training set of about 1,000 samples, the prediction accuracy could be very high if there were a reasonable number of common markers in the order of 100,000. This number, which needs to be available in both reference set and the target set, is achievable. Further investigation may be needed to check whether this number of markers is related to effective number or markers after correction for linkage disequilibrium for GWAS data. When the population structure of the test sample resembles the training sample, high accuracy will be achieved for the leading projected eigenvectors.

Therefore, this approach is likely to be extremely beneficial for extremely large samples, such as UK Biobank samples and 23andMe, both of which have more than half million samples where direct eigenvector analysis may be infeasible. Our results suggest that sampling about 1,000 individuals from the whole sample as the training set and subsequently project EigenGWAS SNP effects to the reminding samples will be sufficient to reach a reasonable high resolution of the population structure.

Many improvements to the inference of ancestry using projected eigenvectors have been suggested (Chen et al. 2013). As the concordance of population structure between the training and test sets is often unknown (population structure, upon from genetic or social-cultural perspectives, its definition can be difficult or controversial), improvement of the inference of ancestry may or may not be achieved dependent upon the scale of the precision required for a sample. However, for classification of samples at ethnicity level, projected eigenvectors are likely to have high accuracy, as demonstrated in the Puerto Rican cohort and the Pakistani cohort. Therefore, when identifying ethnic outliers, using projected eigenvectors from HapMap is likely to be sufficient in practice.

Eigenvector analysis of GWAS data is an important well utilized data technique, and here we show that its interpretation depends on many factors, such as proportion of different subpopulations, and F_{st} between subpopulations. Our EigenGWAS approach provides intuitive interpretation of population structure, enabling ancestry informative markers to be identified, and potentially loci under selection to be identified. To facilitate the use of projected eigenvectors, we provide estimated SNP effects from HapMap samples and POPRES and software that can largely reduce the logistics involved in conventional way in generating eigenvectors, such as reference allele match, and strand flips.

Web resource and data availability

GEAR is available at http://cnsgenomics.com/

GCTA is available at http://cnsgenomics.com/

PLINK is available at http://pngu.mgh.harvard.edu/~purcell/plink/index.shtml

1000 Genomes Project: http://www.1000genomes.org/

Author contributions: GBC, SHL, and BB conceived study. GBC, SHL, BB, and MRR designed the experiment. GBC and SHL developed the theory and methods. BB conducted the quality control for HapMap data, and MRR conducted quality control for POPRES data. GBC performed the

analyses of the study. GBC and ZXZ developed GEAR software. GBC, MRR, SHL, and BB wrote the paper.

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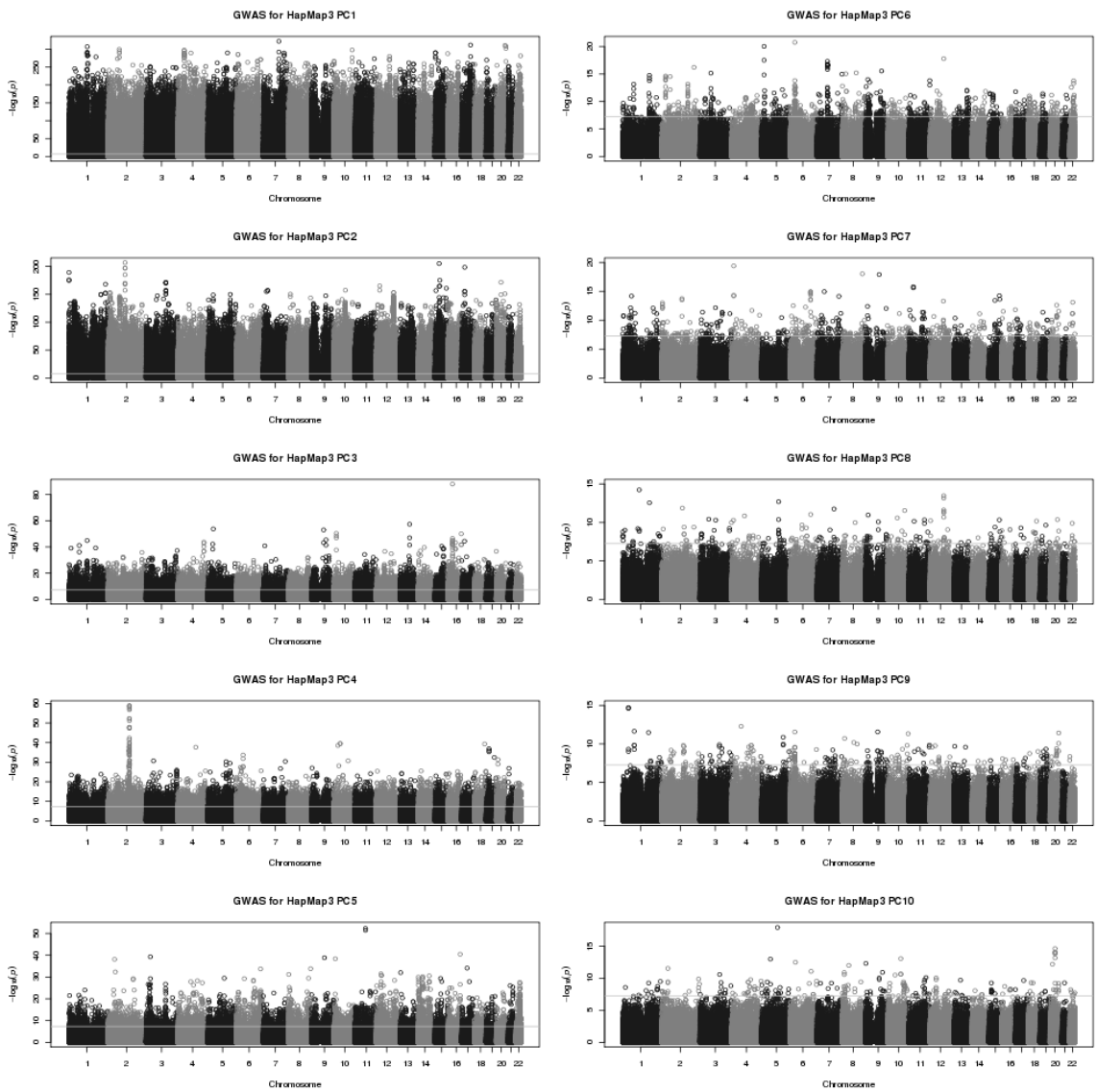


Figure 1 Manhattan plots for EigenGWAS for top 10 eigenvectors for HapMap. Using E_i as the phenotype, the single-marker association was conducted for nearly 919,133 markers. The left panel illustrates from $E_1 \sim E_5$; the right panel from $E_6 \sim E_{10}$. The horizontal lines indicate genome-wide significant after Bonferroni correction.

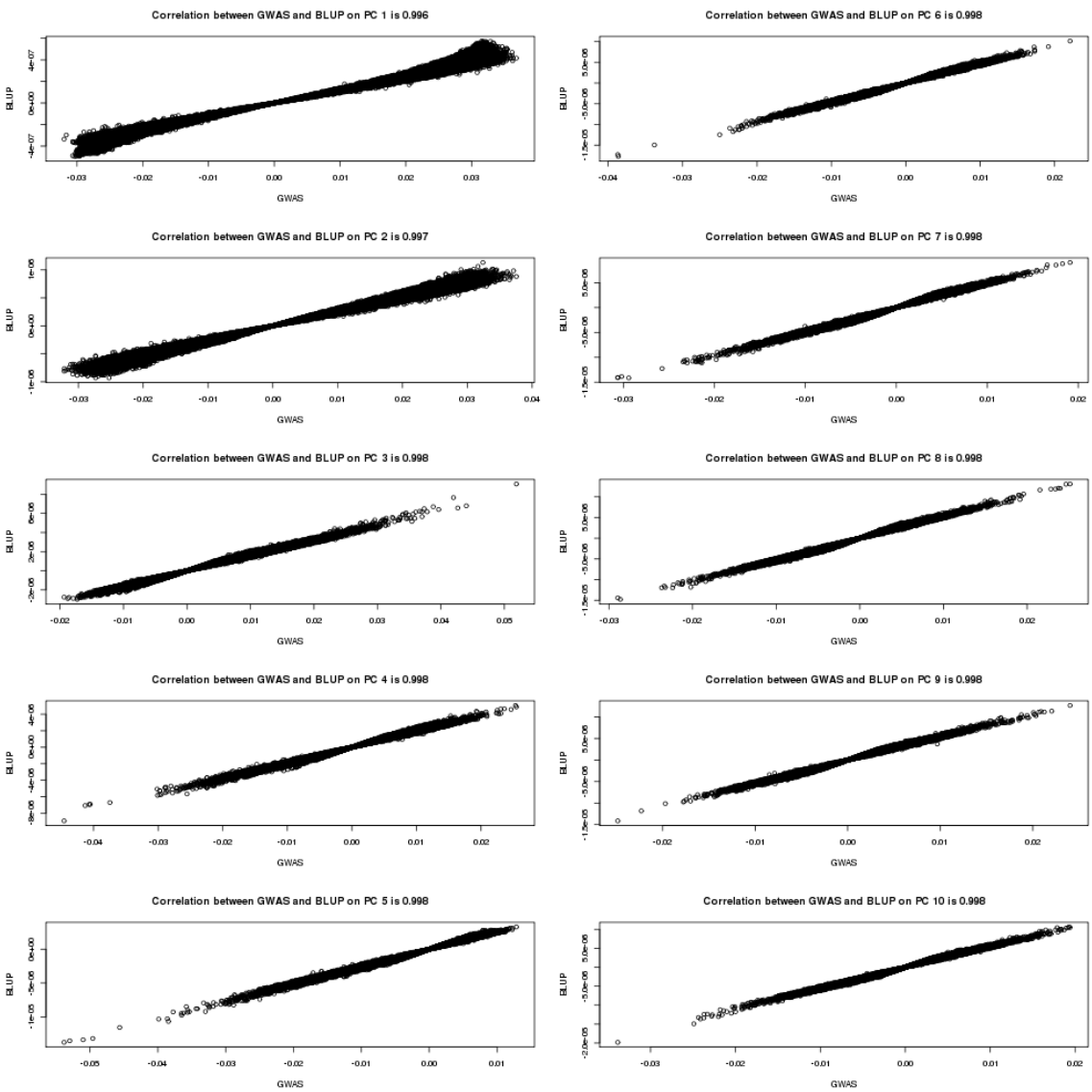


Figure 2 Correlation for the SNP effects estimated using EigenGWAS and BLUP for HapMap3. The x-axis represents EigenGWAS estimation for SNP effects, and the y-axis represents BLUP estimation for SNP effects. The left panel illustrates from $E_1 \sim E_5$; the right panel from $E_6 \sim E_{10}$. As illustrated, the correlation is nearly 1.

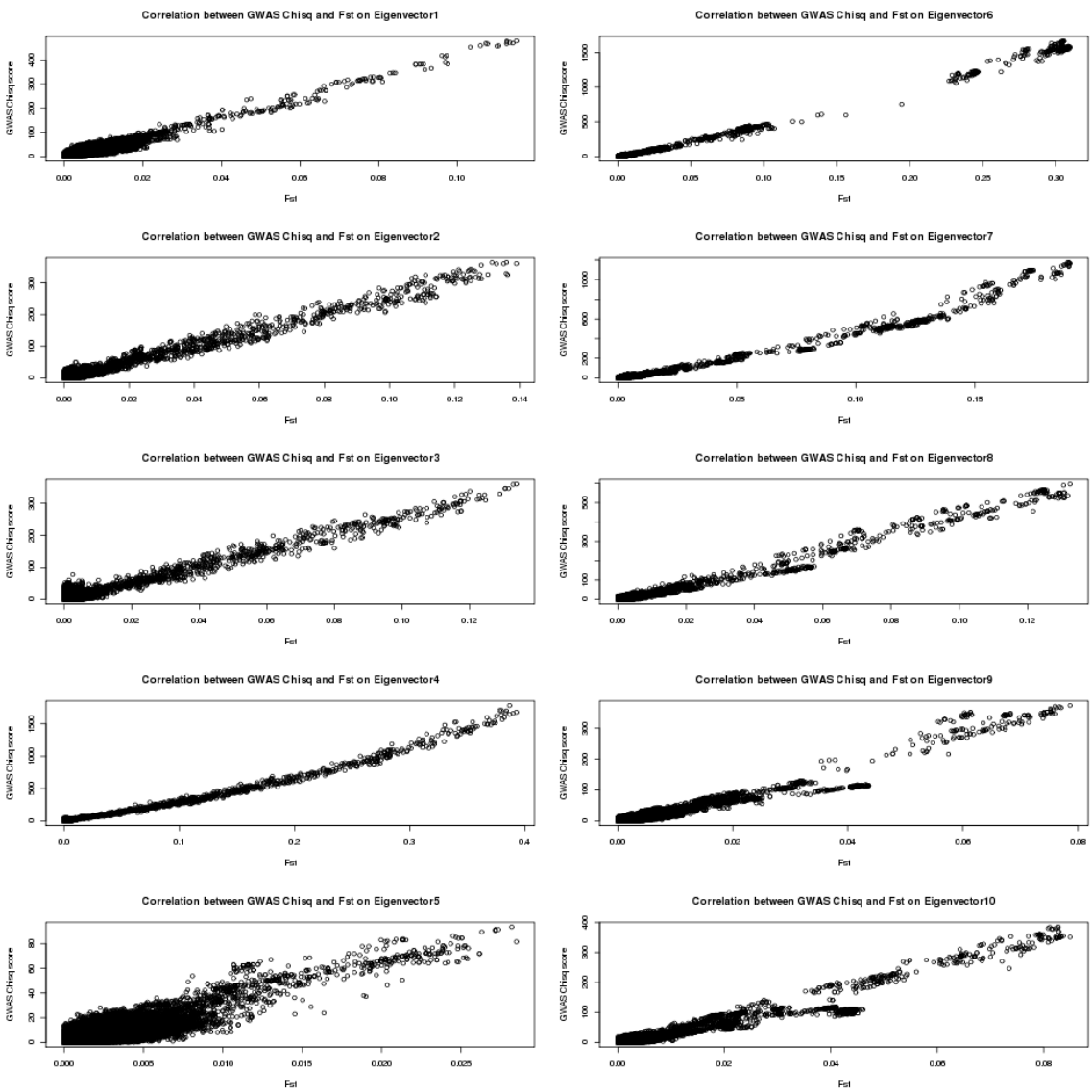


Figure 3 The correlation between F_{st} and χ_1^2 for EigenGWAS SNP effects for POPRES. For each eigenvector, upon $E_i > 0$ or $E_i \leq 0$, the samples were POPRES samples were split into two groups, upon which F_{st} was calculated for each locus.

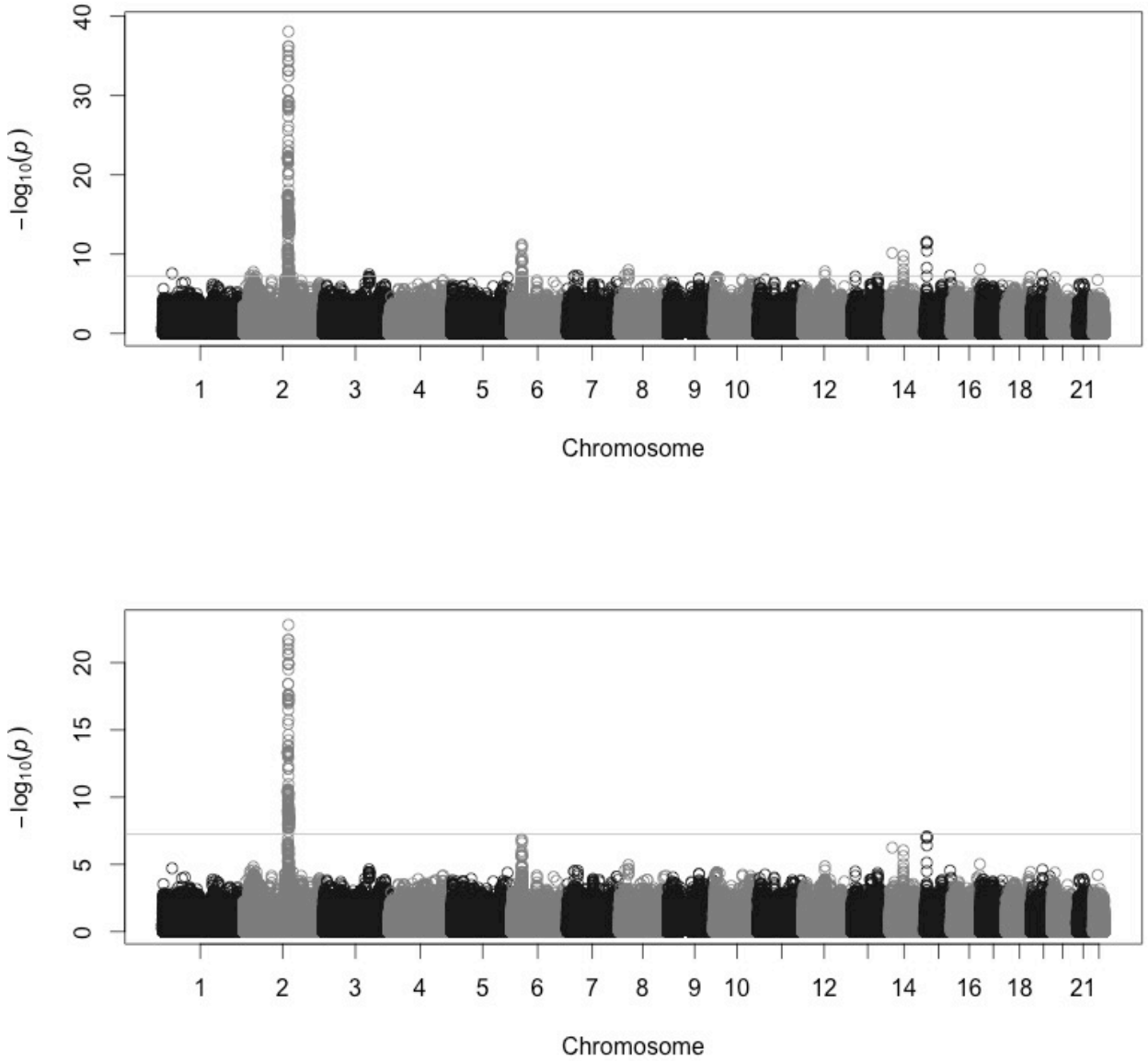


Figure 4 EigenGWAS for CEU (112 samples) & TSI (88 samples) from HapMap. a) Manhattan plot for EigenGWAS on E_1 without correction for λ_{GC}. When there was no correction, on chromosome 2 found *LCT,* chromosome 6 *MICA* (HMC region), chromosome 14 *HIF1A*, and chromosome 15 *HERC2.* The line in the middle was for genome-wide significant level at $\alpha = 0.05$ given multiple correction. b) Manhattan plot for EigenGWAS on E_1 with λ_{GC} correction, and *LCT* was still significant, and *HERC2* slightly below whole genome-wide significance level. The genome-wide significance threshold was *p*-values = 5.44e-08 for $\alpha = 0.05$.

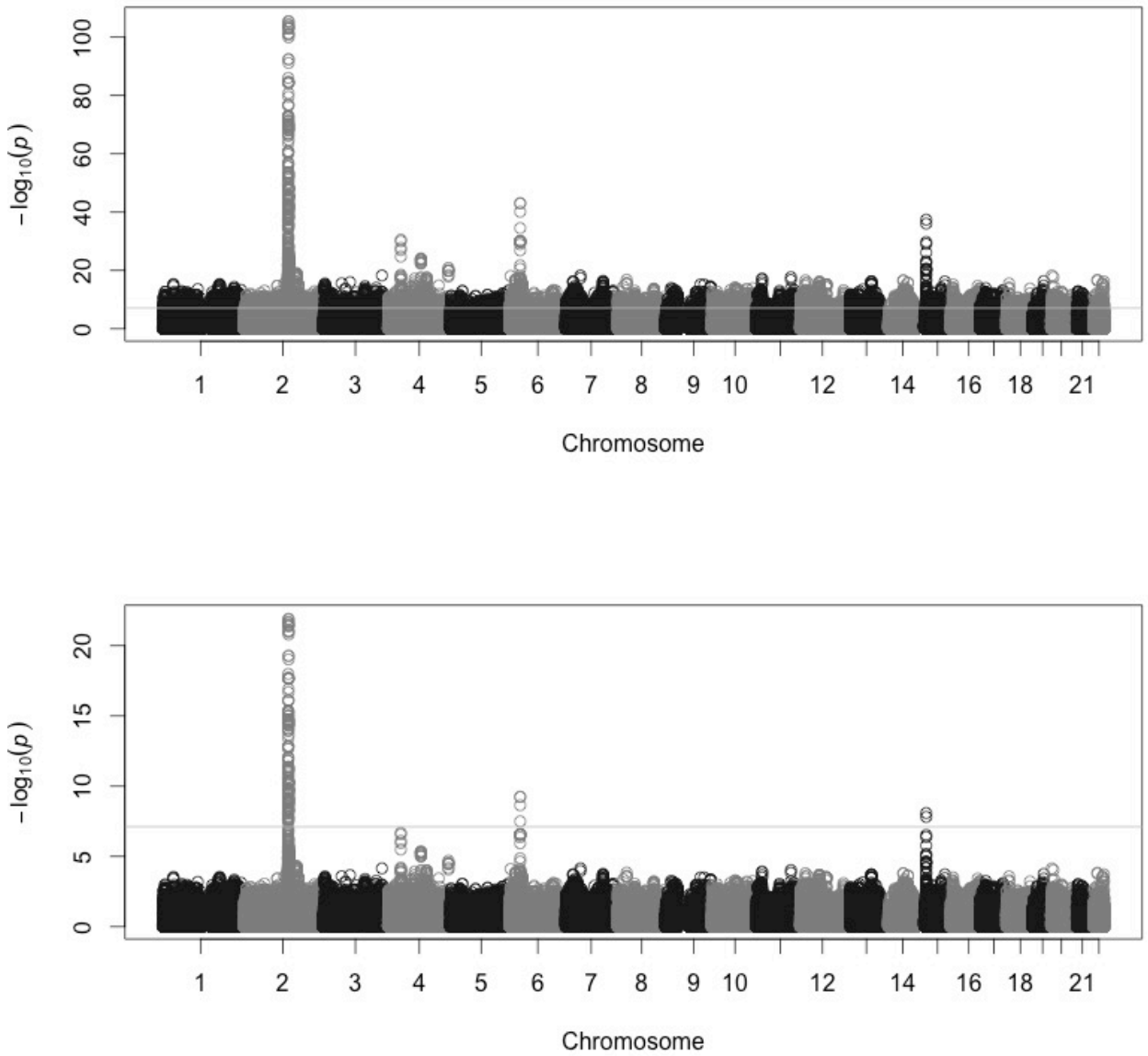


Figure 5 EigenGWAS for POPRES samples on eigenvector 1. a) Manhattan plot for EigenGWAS without correction for λ_{GC}. b) After correction for λ_{GC}, on Chromosome 2 found *LCT,* chromosome 6 *SLC44A4*, and chromosome 15 *HERC2.* The genome-wide significance level was *p*-values = 7.76e-08 given $\alpha = 0.05$.

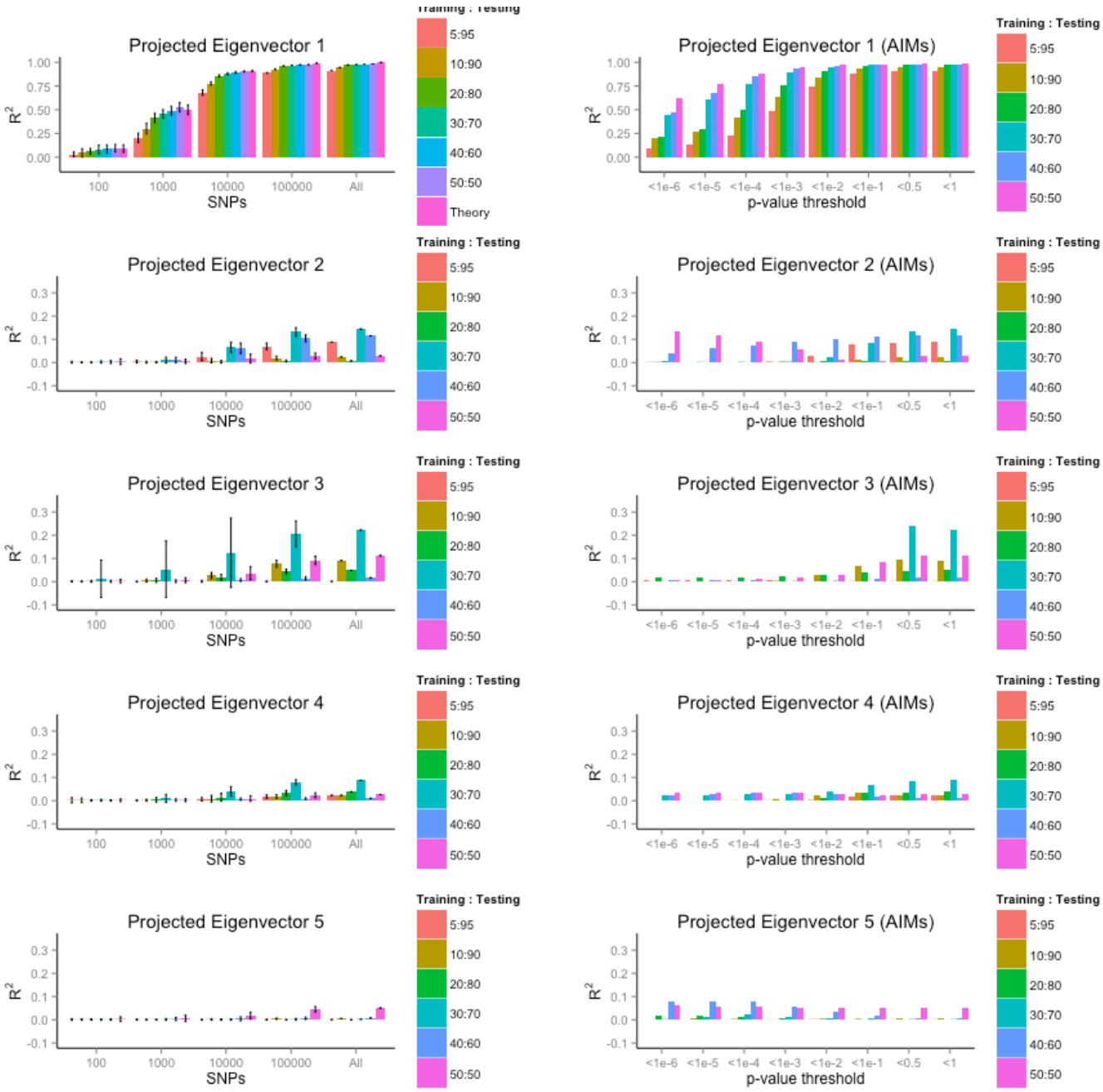


Figure 6 Prediction accuracy of the projected eigenvectors for POPRES samples. Given 2,466 POPRES samples, the data were split to 5%:95%, 10%:90%, 20%:80%, 30%:70%, 40%:60%, and 50%:50, as training and test set. The left columns represent prediction accuracy (R^2) using randomly selected numbers (100, 1,000, 10,000, 100,100, all) of markers, the 95% confidence interval were calculated from 30 replication for resampling given number of markers. In contrast, the right columns represent the predicted accuracy for 8 p-value thresholds (1e-6, 1e-5, 1e-4, 1e-3, 1e-2, 1e-1, 0.5, and 1) for EigenGWAS SNPs.

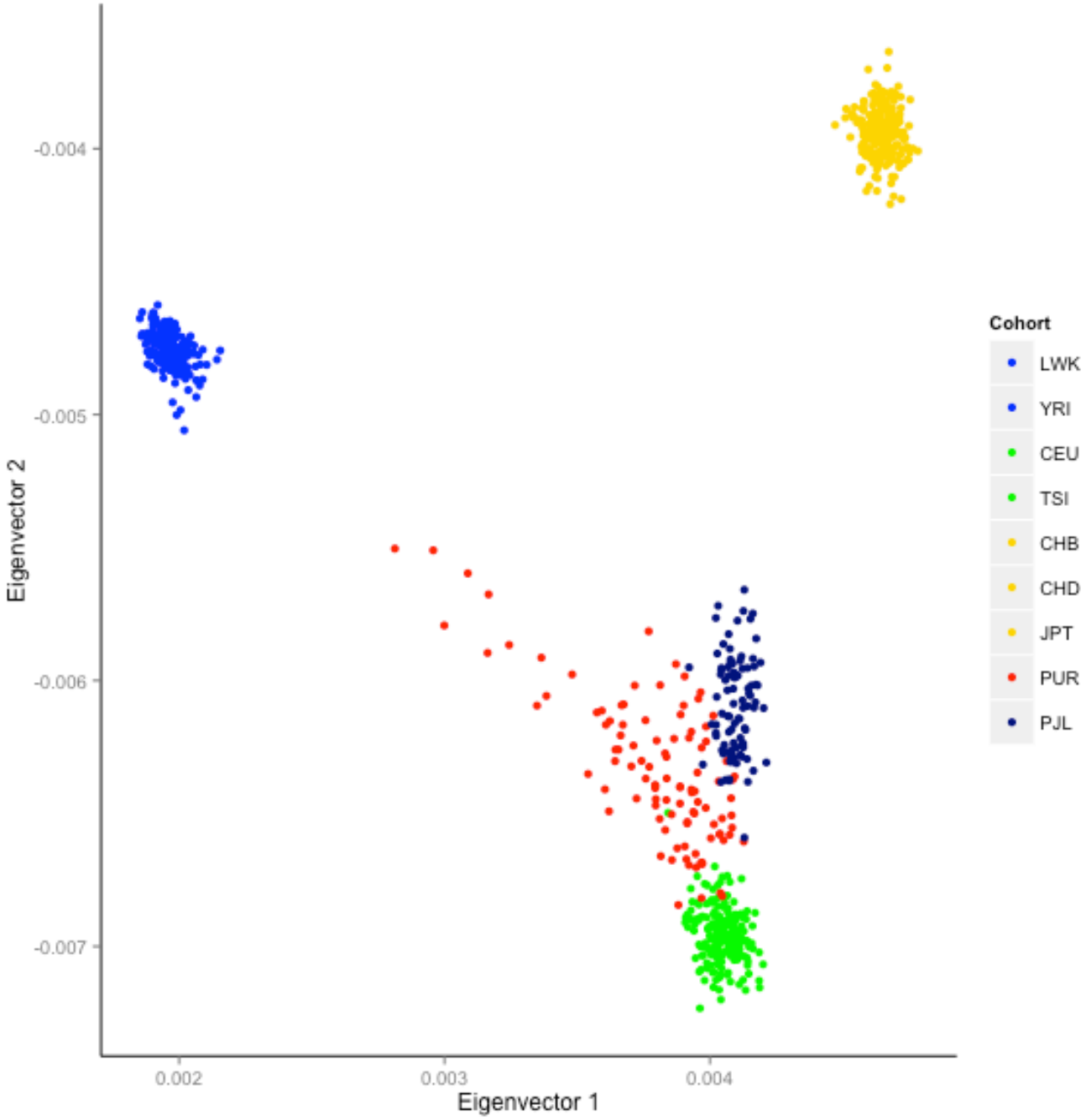


Figure 7 Projected eigenvectors for Puerdo Rican cohort (PUR) and Pakistan cohort (PJL) in 1000 Genome project. The training set was HapMap3 samples build on 919,133 SNPs. The eigenvectors 1 and 2 for were generated based on the 74,500 common SNPs on chromosome 1. PUR showed an admixture of African and European gene flows, and PJL Asian and European gene flows.

Table 1 GWAS signals for on eigenvectors for HapMap and POPRES

	HapMap				POPRES			
Eigenvector (E_i)	Eigen value	GWAS λ_{GC}	#GWAS hits	#After clumping	Eigen value	GWAS λ_{GC}	#GWAS hits	#After clumping
1	100.135	103.715	546,716	231,677	5.104	5.005	10,885	3,004
2	47.658	44.686	382,867	161,022	2.207	1.929	1,254	289
3	7.168	6.471	33,317	15,344	2.157	1.910	1,201	340
4	5.923	5.173	21,935	12,401	2.077	1.464	1,353	331
5	4.402	3.964	9,554	4,727	1.971	1.866	781	76
6	2.449	1.982	1,113	567	1.871	1.295	1,162	111
7	2.285	1.986	593	389	1.843	1.337	1,239	130
8	2.107	1.742	236	171	1.818	1.486	1,259	152
9	2.056	1.729	268	174	1.807	1.503	1,701	113
10	2.0217	1.661	236	163	1.798	1.492	1,639	90

Notes: HapMap has 988 samples, and 919,133 SNPs; its GWAS hits were those had p-values < 5.44e-08 given $\alpha = 0.05$. POPRES has 2,466 European samples, and 643,995 SNPs; its GWAS hits were those had p-values < 7.76e-08 given $\alpha = 0.05$.

After clumping, the reported numbers were quasi-independent GWAS hits. Within 250K bp and linkage disequilibrium of $r^2 > 0.5$ only the most significant GWAS hit was counted as a GWAS hit (see PLINK --clump default option).

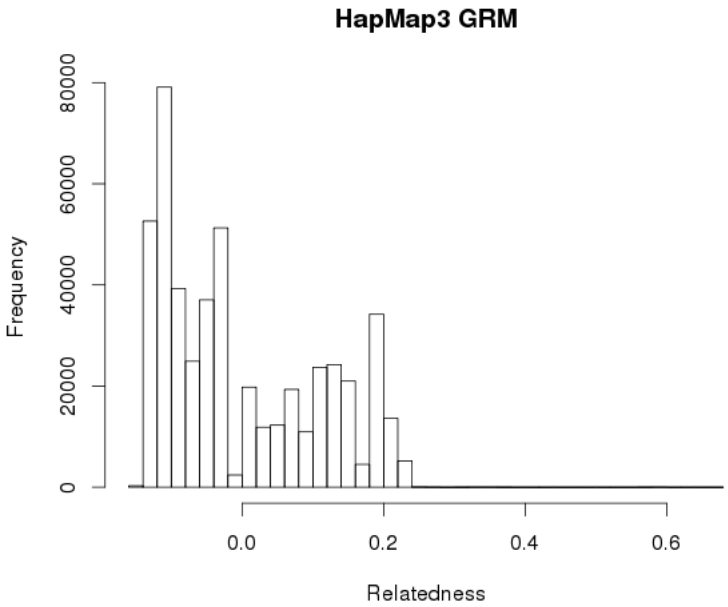
λ_{GC} was calculated as the ratio between the median of observed χ^2 from EigenGWAS to the median of χ^2 value, which is 0.455.

Table 2 Gene discovery using eigenvector GWAS on E_1

Gene	Lead SNP	Position	Allele	p-value (λ_{GC})	MAF (TSI:CEU)	F_{st}	Annotation
CEU & TSI samples							
LCT	rs6719488	2:135817629	G/T	6.68e-34 (1.21e-20)	0.733:0.206	0.558	Lactose persistent locus
DARS	rs13404551	2:135964425	C/T	8.18e-39 (1.51e-23)	0.756:0.206	0.604	Genetic hitchhiking due to LCT.
MICA	rs2256175	6:31412672	T/C	8.94e-10 (2.60e-6)	0.665:0.360	0.183	MHC class I polypeptide-related sequence A
HIF1A	rs2256205	14:61670944	A/G	1.51e-10 (8.86e-7)	0.464:0.179	0.192	HIF-1A thus plays an essential role in embryonic vascularization, tumor angiogenesis and pathophysiology of ischemic disease.
HERC2	rs8039195	15:26189679	C/T	2.75e-12 (8.22e-08)	0.403:0.122	0.212	Genetic variations in this gene are associated with skin/hair/eye pigmentation variability
POPRES European samples							
					Southern Europeans : Northern Europeans		
LCT	rs3754686	2:135817629	T/C	3.30e-106 (1.23e-22)	0.514:0.279	0.110	
DARS	rs13404551	2:135964425	C/T	6.32e-102 (8.99e-22)	0.518:0.293	0.106	
SLC4A4	rs605203	6:31819235	C/A	8.94e-44 (5.77e-10)	0.214:0.343	0.040	Defects in this gene can cause sialidosis, a lysosomal storage disease
HERC2	rs1667394	15:26189679	C/T	3.90e-38 (8.15e-09)	0.276:0.173	0.041	

Notes: The p-value cutoff for CEU&TSI was 5.44e-08 (919,133 SNPs), for POPRES was 7.76e-08 (643,995 SNPs) at genome-wide significance level of $\alpha = 0.05$. $\lambda_{GC} = 1.725$ for CEU&TSI, and $\lambda_{GC} = 5.00$.

F_{st} is calculated by partitioning the sample into two groups upon $E_1 > 0$. For TSI&CEU set, partitioning on E_1perfectly separated TSI (88 samples) and CEU (112 samples). For POPRES, partitioning on E_1 separated southern European population (1,092 samples) and northern European population (1,374 samples).



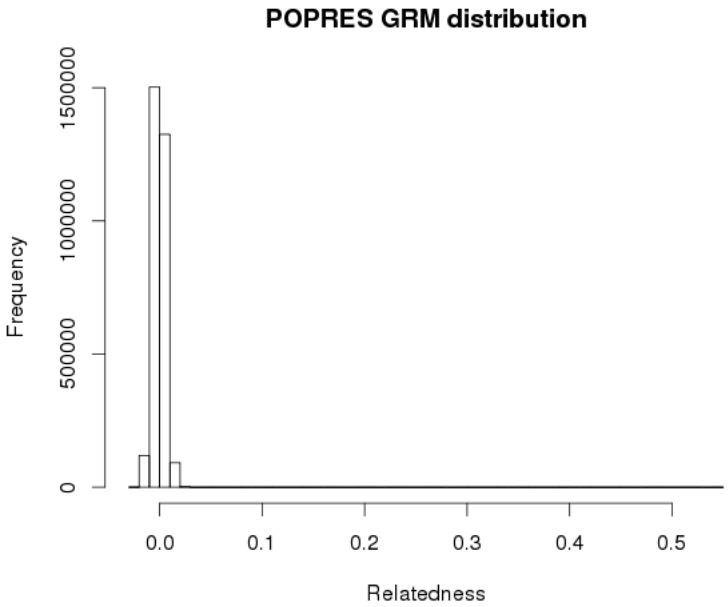


Figure S1 The distribution of the entries in genetic relatedness matrix for HapMap3 and POPRES. a) HapMap is a mix of various ethnicities, the many off-diagonal elements also showed very large number. b) For POPRES Europeans, which is a relative homogenous population, its off-diagonal elements were very close zero.

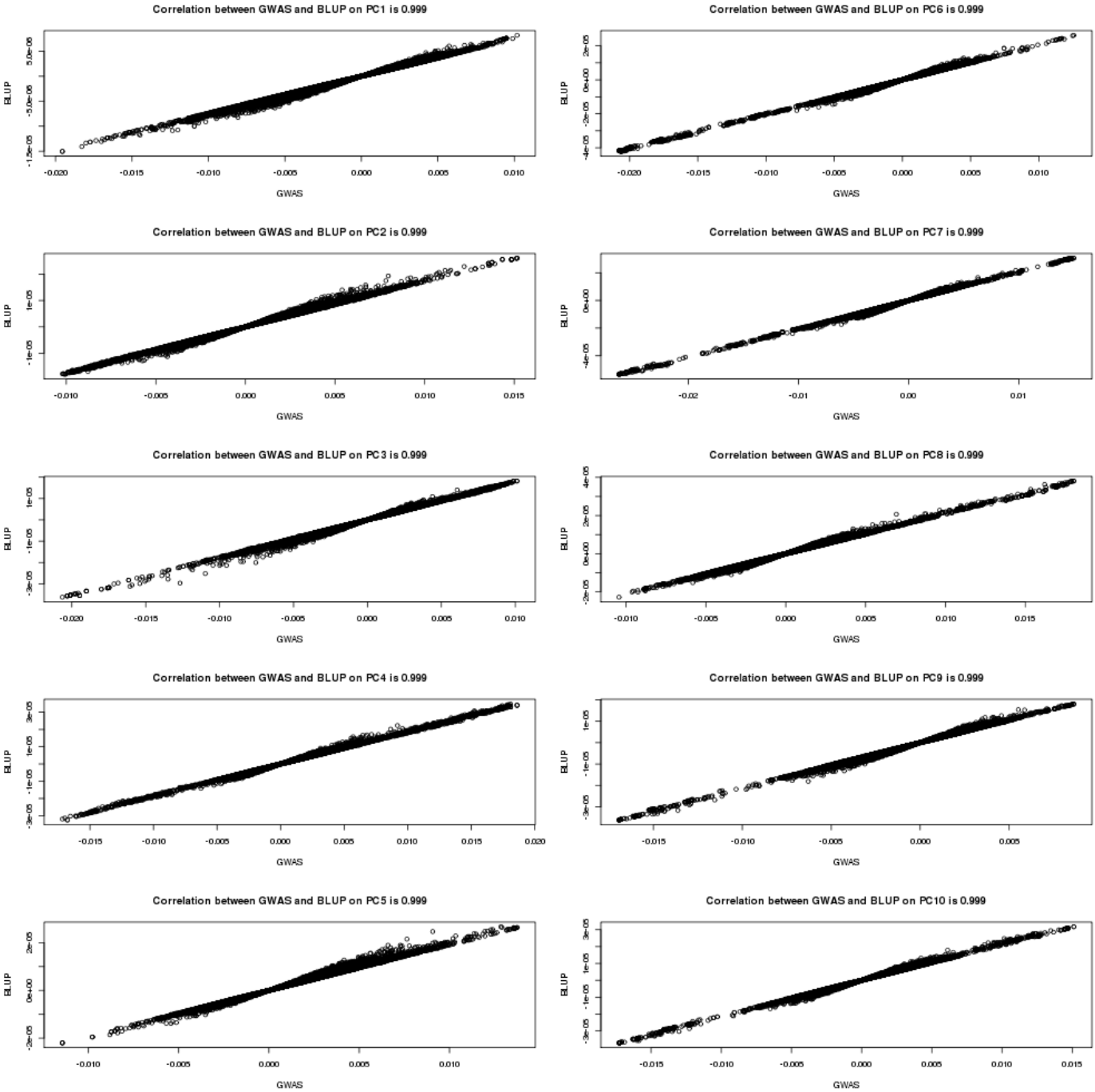


Figure S2 Correlation for the SNP effects estimated using EigenGWAS and BLUP for POPRES samples. The x-axis represents EigenGWAS estimation for SNP effects, and the y-axis represents BLUP estimation for SNP effects. The left panel illustrates from $E_1 \sim E_5$; the right panel from $E_6 \sim E_{10}$. As illustrated, the correlation is nearly 1.

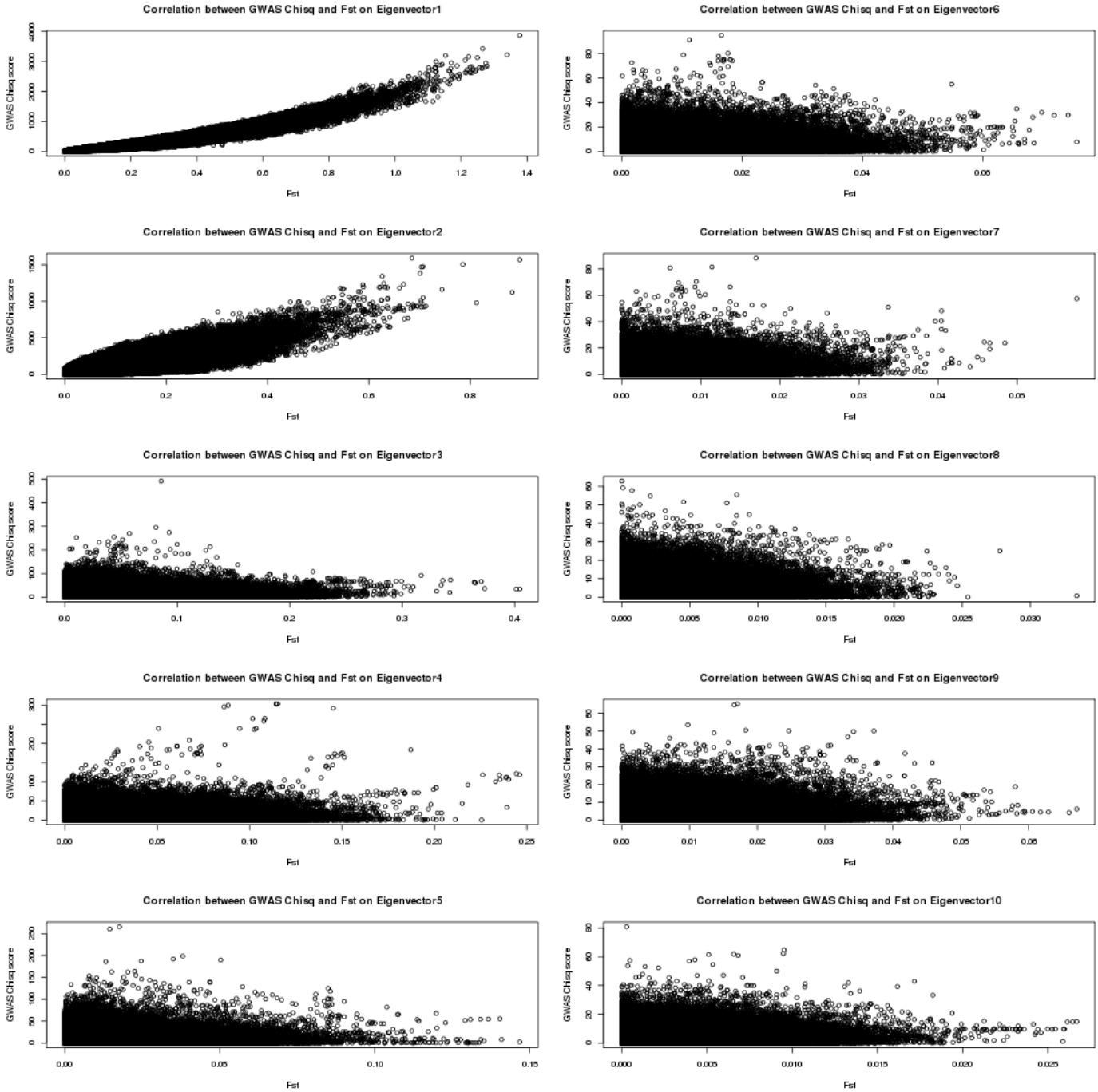


Figure S3 The correlation between EigenGWAS chi-square tests and F_{st} for HapMap3 samples. The correlation between EigenGWAS chi-square tests and F_{st} from E_1 to E_{10} (left panel, from top to bottom $E_1 \sim E_5$; right panel, from top to bottom $E_6 \sim E_{10}$) were 0.965, 0.819, 0.094, 0.146, 0.155, 0.186, 0.244, 0.159, 0.142, and 0.156, respectively.

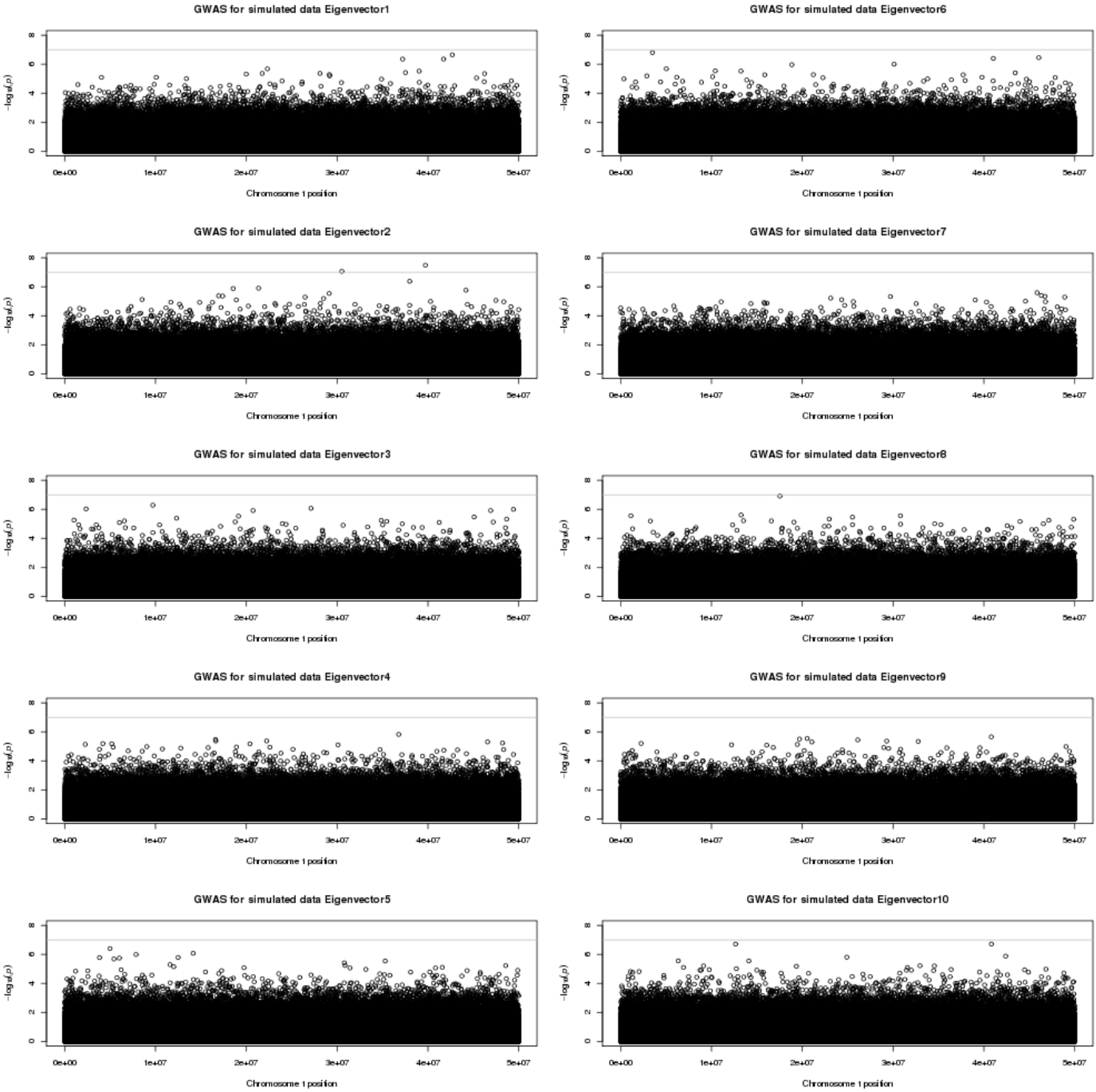


Figure S4 EigenGWAS for Simulated data. The simulated data has 2000 samples, and 500,000 biallelic markers. Markers are in linkage equilibiurm, and the minor allele frequency ranges from 0.01 to 0.5 under a uniform distribution. Eigenvalues associated to the first ten eigenvectors are 1.12935, 1.12895, 1.12842, 1.12763, 1.12725, 1.12622, 1.12605, 1.12595, 1.12546, and 1.1253, respectively.

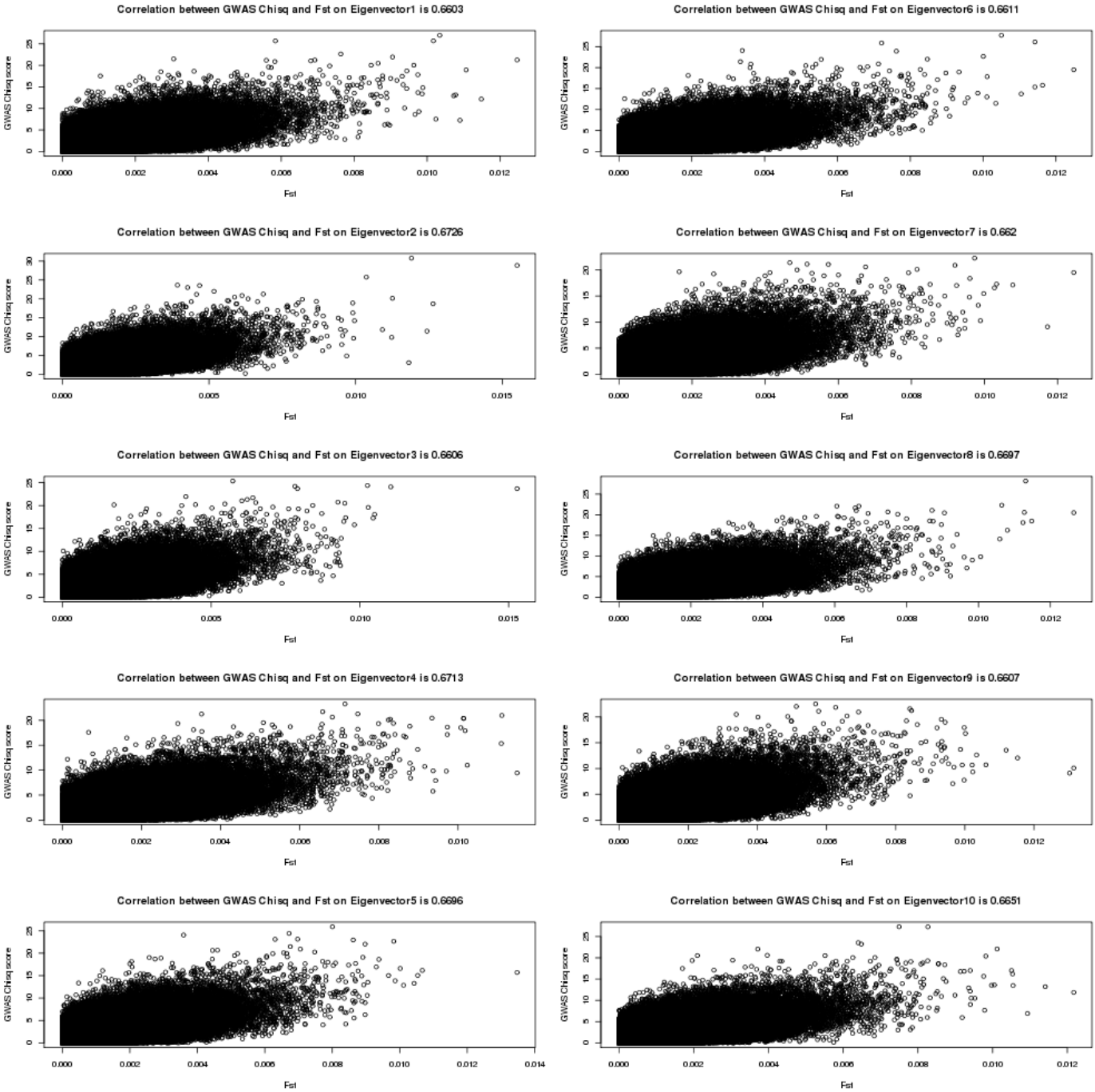


Figure S5 The correlation between chisquare test statistics for EigenGWAS SNP effects and their F_{st}. Depending on $E_i > 0$ or $E_i \leq 0$, the samples were split into two groups, upon which F_{st} was calcuated. The average correlation between chi-square tests and F_{st} was around 0.66.

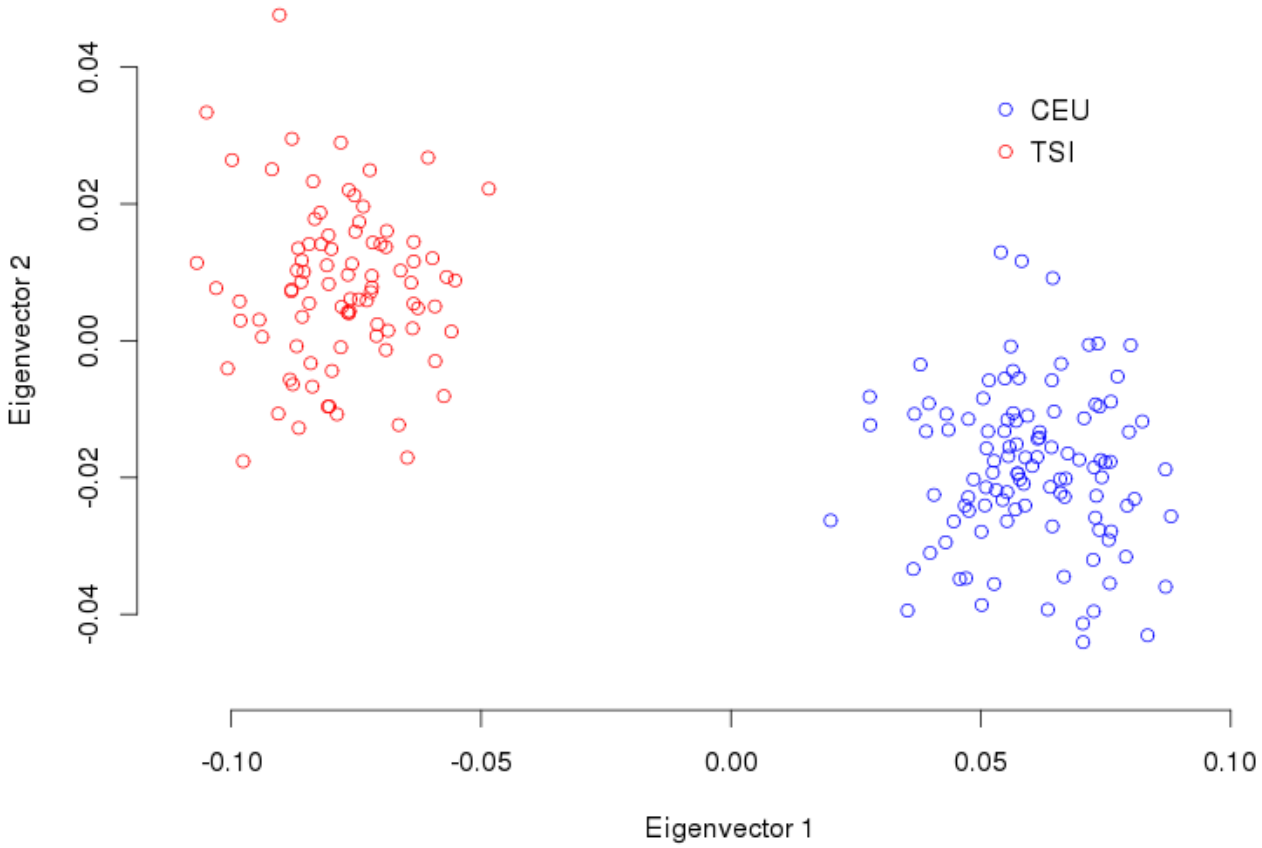


Figure S6 Eigenvecotor1 against eigenvector 2 for 88 TSI samples and 112 CEU samples. Eigenvetors were generated directly based on 919,313 SNPs over 88 TSI and 112 CEU samples from HapMap.

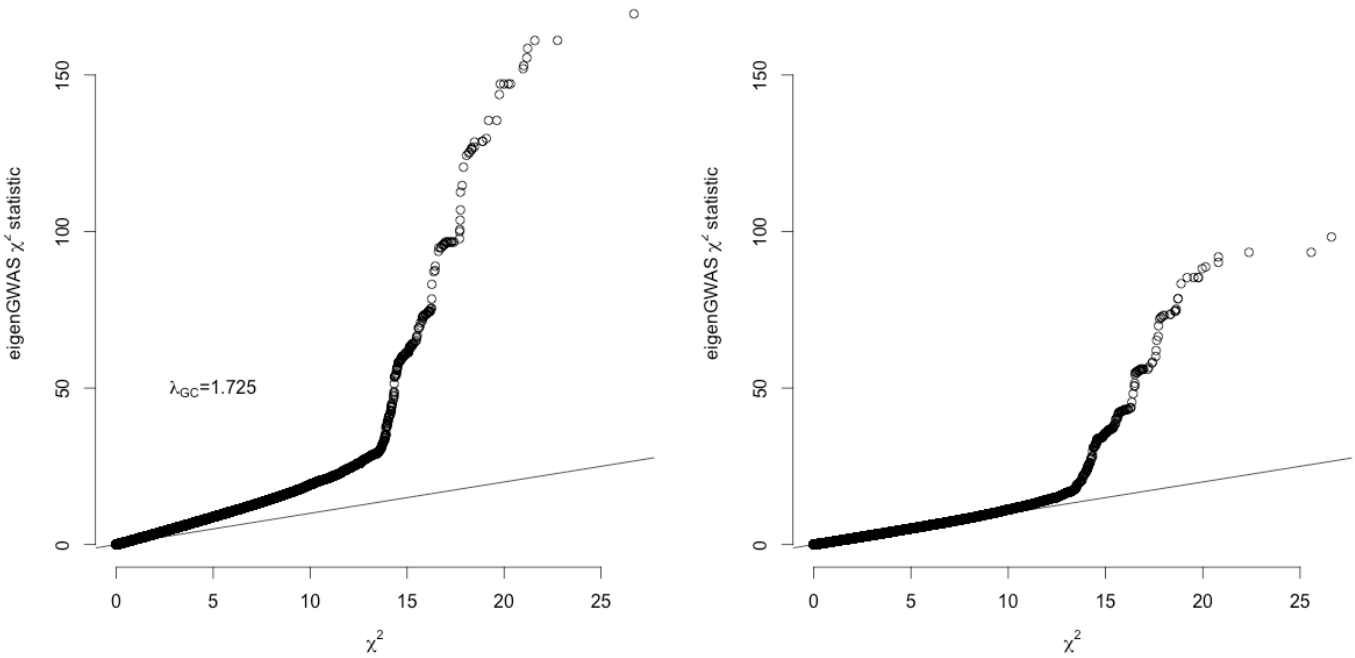


Figure S7 QQ plot for EigenGWAS χ^2 statistics against the χ^2 observed from the null for CEU&TSI cohort. The left one was the origninal EigenGWAS for CEU&TSI cohort, which had $\lambda_{GC} = 1.725$, and the right one was the one corrected for λ_{GC}.

Figure S8 Eigenvector 1 against Eigenveoctor 2 for POPRES European samples.

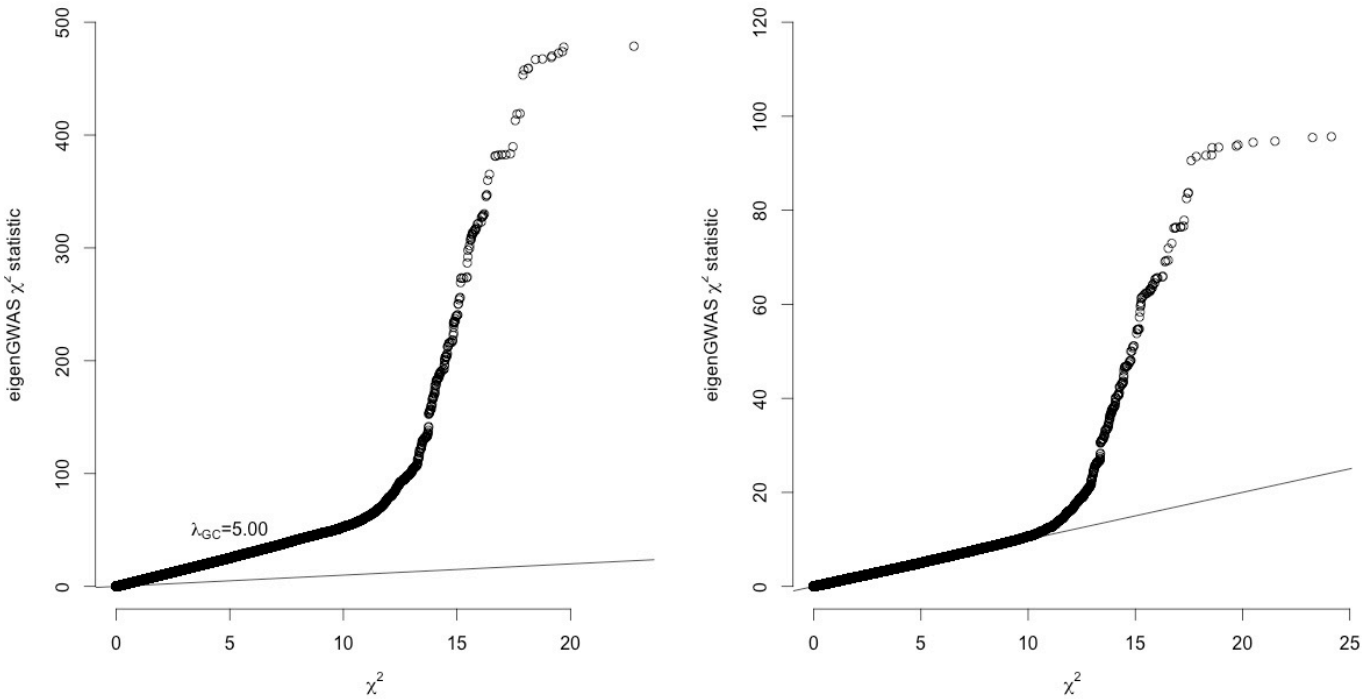


Figure S9 QQ plot for EigenGWAS χ^2 statistics against the χ^2 observed from the null for POPRES. The left one was the origninal EigenGWAS for POPRES cohort, which had $\lambda_{GC} = 5.00$, and the right one was the one corrected for λ_{GC}.

Table S1 The correlation between F_{st} and chi-sq test for SNP effects on each EigenGWAS

Phenotype	POPRES	*p*-value		HapMap	*p*-value
E_1	0.887	<1e-16		0.965	<1e-16
E_2	0.933	<1e-16		0.819	<1e-16
E_3	0.904	<1e-16		0.094	<1e-16
E_4	0.987	<1e-16		0.146	<1e-16
E_5	0.765	<1e-16		0.155	<1e-16
E_6	0.994	<1e-16		0.186	<1e-16
E_7	0.977	<1e-16		0.244	<1e-16
E_8	0.963	<1e-16		0.159	<1e-16
E_9	0.917	<1e-16		0.142	<1e-16
E_{10}	0.927	<1e-16		0.156	<1e-16

Table S2 Gene discovery using EigenGWAS for POPRES using 234,127 SNPs

Gene	Phenotype	Lead SNP	Alleles	*p*-value	Allele frequency (samples)	F_{st}	Position (CHR:BP)
LCT	E_1	rs2304371	C/T	4.19e-46	0.817 (1373):0.676 (1062)	0.110	2:135817629
MCM6	E_1	rs309180	G/A	5.223e-93	0.706 (1386):0.483 (1080)	0.102	2:135856685
HERC2	E_1	rs8039195	A/G	8.902e-36	0.694 (1385):0.765 (1080)	0.055	15:28268218

Table S3 GWAS results for POPRES based on 234,127 SNPs

	POPRES		
E_i	Eigen value	λ_{GC}	#GWAS hits
1	5.104	5.282	5373
2	2.207	2.118	544
3	2.157	1.703	713
4	2.077	1.467	481
5	1.971	1.726	447
6	1.871	1.303	464
7	1.843	1.469	513
8	1.818	1.660	295
9	1.807	1.637	309
10	1.798	1.584	240