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1 **A meta-analysis of genome-wide association studies of epigenetic age**
2 **acceleration**

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29

30 **Abstract**

31

32 'Epigenetic age acceleration' is a valuable biomarker of ageing, predictive of morbidity and
33 mortality, but for which the underlying biological mechanisms are not well established. Two
34 commonly used measures, derived from DNA methylation, are Horvath-based (Horvath-EAA) and
35 Hannum-based (Hannum-EAA) epigenetic age acceleration. We conducted genome-wide
36 association studies of Horvath-EAA and Hannum-EAA in 13,493 unrelated individuals of European
37 ancestry, to elucidate genetic determinants of differential epigenetic ageing. We identified ten
38 independent SNPs associated with Horvath-EAA, five of which are novel. We also report 21
39 Horvath-EAA-associated genes including several involved in metabolism (*NHLRC*, *TPMT*) and
40 immune system pathways (*TRIM59*, *EDARADD*). GWAS of Hannum-EAA identified one
41 associated variant (rs1005277), and implicated 12 genes including several involved in innate
42 immune system pathways (*UBE2D3*, *MANBA*, *TRIM46*), with metabolic functions (*UBE2D3*,
43 *MANBA*), or linked to lifespan regulation (*CISD2*). Both measures had nominal inverse genetic
44 correlations with father's age at death, a rough proxy for lifespan. Nominally significant genetic
45 correlations between Hannum-EAA and lifestyle factors including smoking behaviours and
46 education support the hypothesis that Hannum-based epigenetic ageing is sensitive to variations in
47 environment, whereas Horvath-EAA is a more stable cellular ageing process. We identified novel
48 SNPs and genes associated with epigenetic age acceleration, and highlighted differences in the
49 genetic architecture of Horvath-based and Hannum-based epigenetic ageing measures.
50 Understanding the biological mechanisms underlying individual differences in the rate of epigenetic
51 ageing could help explain different trajectories of age-related decline.

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53

54

55

56 **Author Summary**

57

58 DNA methylation, a type of epigenetic process, is known to vary with age. Methylation levels at
59 specific sites across the genome can be combined to form estimates of age known as ‘epigenetic
60 age’. The difference between epigenetic age and chronological age is referred to as ‘epigenetic age
61 acceleration’, with positive values indicating that a person is biologically older than their years.
62 Understanding why some people seem to age faster than others could shed light on the biological
63 processes behind age-related decline; however, the mechanisms underlying differential rates of
64 epigenetic ageing are largely unknown. Here, we investigate genetic determinants of two commonly
65 used epigenetic age acceleration measures, based on the Horvath and Hannum epigenetic clocks.
66 We report novel genetic variants and genes associated with epigenetic age acceleration, and
67 highlight differences in the genetic factors influencing these two measures. We identify ten genetic
68 variants and 21 genes associated with Horvath-based epigenetic age acceleration, and one variant
69 and 12 genes associated with the Hannum-based measure. There were no genome-wide significant
70 variants or genes in common between the Horvath-based and Hannum-based measures, supporting
71 the hypothesis that they represent different aspects of ageing. Our results suggest a partial genetic
72 basis underlying some previously reported phenotypic associations.

73

74

75 **Introduction**

76

77 Ageing is associated with a decline in physical and cognitive health, and is the main risk factor for
78 many debilitating and life-threatening conditions including cardiovascular disease, cancer, and
79 neurodegeneration (1). Ageing is a multi-dimensional construct, incorporating physical,
80 psychosocial, and biological changes. Everyone experiences the same rate of chronological ageing,
81 but the rate of ‘biological ageing’, age-related decline in physiological functions and tissues, differs

82 between individuals. Various phenotypic and molecular biomarkers have been used to study
83 biological ageing, including a number of 'biological clocks', the best known of which is telomere
84 length. Telomeres shorten with increasing age, and telomere length has been found to predict
85 morbidity and mortality (2). More recently, research into epigenetics – chemical modifications to
86 DNA without altering the genetic sequence – has yielded another method for measuring biological
87 age.

88

89 DNA methylation is an epigenetic modification, typically characterised by the addition of a methyl
90 group to a cytosine-guanine dinucleotide (CpG) (3), that can influence gene expression and is
91 associated with variation in complex phenotypes. This process is essential for normal development
92 and is associated with a number of key processes including ageing. DNA methylation levels are
93 dynamic, varying with age across the life course (4,5) and are influenced by both genetic and
94 environmental factors (6).

95

96 Weighted averages of methylation at multiple CpG sites can be integrated into estimates of
97 chronological age referred to as 'epigenetic age'. Two influential studies have used this method to
98 create 'epigenetic clocks', which accurately predict chronological age in humans. Hannum et al.
99 used DNA methylation profiles from whole blood from two cohorts to identify 71 CpG sites that
100 could be used to generate an estimate of age (7), while Horvath used data from 51 different tissue
101 types from multiple studies to identify 353 CpG sites whose methylation levels can be combined to
102 form an age predictor (8). There are only six CpGs in common across the two epigenetic clocks,
103 and they are thought to capture slightly different aspects of the biology of ageing (further details are
104 given in **S1 Text**).

105

106 Both the Hannum and Horvath epigenetic clocks are strongly correlated ($r>0.95$) with chronological
107 age (7,8). However, despite these high correlations, there can be substantial differences between

108 epigenetic and chronological age in an individual, and it is unclear what drives these differences. A
109 greater epigenetic age relative to chronological age is commonly described as ‘epigenetic age
110 acceleration’ (EAA), and implies that a person is biologically older than their years. EAA has been
111 shown to be informative for both current and future health trajectories (9). Recently, a growing
112 number of studies have used EAA to investigate age-related disorders, and the epigenetic clock is
113 increasingly being recognised as a valuable marker of biological ageing (10,11).

114
115 The simplest definition of EAA is the residual that results from regressing epigenetic age on
116 chronological age. However, it is well known that the abundance of different cell types in the blood
117 changes with age (12,13), and hence two broad categories of EAA measures have been
118 distinguished: those that are independent of age-related changes in blood cell composition, and
119 those that incorporate and are enhanced by blood cell count information (10). This study focuses on
120 two commonly used variations, based on the Horvath and Hannum epigenetic clocks, which assess
121 different metrics to estimate biological ageing. Horvath-based epigenetic age acceleration (Horvath-
122 EAA) is based on the CpG markers from Horvath’s age predictor and is calculated such that it is
123 independent of both chronological age and age-related changes in the cellular composition of blood.
124 Hannum-based epigenetic age acceleration (Hannum-EAA), calculated based on the CpGs
125 described by Hannum et al., up-weights the contributions of age-associated immune blood cells. As
126 both the Horvath and Hannum epigenetic clocks correlate well with age, in a population with a wide
127 age range they are guaranteed to correlate with each other. However, Horvath-based and Hannum-
128 based epigenetic age acceleration estimates are not guaranteed to be correlated. Full details of the
129 calculation of Horvath-EAA and Hannum-EAA are given in **S1 Text**.

130
131 Horvath-EAA, described in previous publications as ‘intrinsic’ epigenetic age acceleration (IEAA),
132 can be interpreted as a measure of cell-intrinsic ageing that exhibits preservation across multiple
133 tissues, appears unrelated to lifestyle factors, and probably indicates a fundamental cell ageing

134 process that is largely conserved across cell types (8,10). In contrast, Hannum-EAA, referred to in
135 previous studies as ‘extrinsic’ epigenetic age acceleration (EEAA), can be considered a biomarker
136 of immune system ageing, explicitly incorporating aspects of immune system decline such as age-
137 related changes in blood cell counts, correlating with lifestyle and health-span related
138 characteristics, and thus yielding a stronger predictor of all-cause mortality (10,14).

139
140 Previous studies have identified relationships between epigenetic ageing and numerous traits,
141 including several age-related health outcomes, for example Alzheimer’s disease pathology (15),
142 cognitive impairment (15), and age at menopause (16). Higher EAA has been associated with
143 poorer measures of physical and cognitive fitness (9) and higher risk of all-cause mortality (11).
144 Many associations are specific to either Horvath-EAA or Hannum-EAA, a discordance that may
145 reflect the differences in the two estimates and supports the theory that they represent different
146 aspects of ageing (14,17,18).

147
148 While EAA has been associated with various markers of physical and mental fitness, the
149 mechanisms underlying epigenetic ageing remain largely unknown. There has been little research
150 conducted thus far on genetic contributions to epigenetic age acceleration. However, Lu et al.
151 (2018) recently published results of the first genome-wide association analysis of blood EAA in a
152 sample of 9,907 individuals, identifying five genetic loci associated with Horvath-EAA and three
153 Hannum-EAA-associated loci (19).

154
155 This current study, with a sample size of 13,493 individuals, constitutes the largest study of the
156 genetic determinants of DNA methylation-based ageing to date. Single nucleotide polymorphism
157 (SNP)-based and gene-based approaches were used to identify genes and loci associated with
158 Hannum-based and Horvath-based estimates of EAA. Functional mapping and annotation of genetic
159 associations were performed, alongside gene-based and gene-set analyses, in an attempt to elucidate

160 the genes and pathways implicated in differential rates of epigenetic ageing between individuals and
161 shed light on the underlying biological mechanisms. We report novel SNPs and genes associated
162 with epigenetic age acceleration, and highlight differences in the genetic architectures of the
163 Horvath-based and Hannum-based EAA measures.

164

165

166 **Results**

167

168 **Estimation of epigenetic age and epigenetic age acceleration in the GS sample**

169 A summary of the estimated epigenetic age variables is given in **Table A in S1 Data**. Both the
170 Horvath- and Hannum-based estimates of biological age were highly correlated with chronological
171 age ($r=0.94$, $SE=0.005$ and $r=0.93$, $SE=0.005$ respectively). The two DNA methylation age
172 estimates were also highly correlated with each other ($r=0.93$, $SE=0.005$); however, the two
173 estimates of epigenetic age acceleration, Horvath-EAA and Hannum-EAA, were only weakly
174 correlated ($r=0.30$, $SE=0.013$).

175

176 **GWAS of Horvath-EAA and Hannum-EAA in GS and replication of previously identified loci**

177 The GWAS results for the Generation Scotland (GS) cohort yielded two significant ($P<5\times 10^{-8}$)
178 variants for Horvath-EAA, but no SNPs achieved genome-wide significance for association with
179 Hannum-EAA (minimum P -value 7.85×10^{-8}) (**Table B in S1 Data**, full output available online at
180 www.link_live_when_ms_accepted.com). Manhattan plots and quantile-quantile plots for the
181 GWAS of Horvath-EAA and Hannum-EAA are shown in **Figs A and B in S2 Text**. There was a
182 moderate genetic correlation between the two traits in the GS sample ($r_G=0.597$, $SE=0.279$), and
183 both measures had high genetic correlations with the previously reported findings of Lu et al.
184 ($r_G=0.724$, $SE=0.312$ and $r_G=1.021$, $SE=0.356$ for Horvath-EAA and Hannum-EAA respectively).
185 All but one of the significant SNPs from the Lu et al. analysis of Horvath-EAA replicated (same

186 direction of effect and with $P < 0.05$) in GS (**Table C in S1 Data**, P -value range 3.25×10^{-2} to
187 3.53×10^{-8}). Two of the three significant SNPs from Lu et al.'s Hannum-EAA GWAS were
188 replicated in GS (P -values 1.76×10^{-3} and 1.75×10^{-4}).

189

190 **GWAS meta-analysis**

191 We conducted genome-wide association meta-analyses of Horvath-EAA and Hannum-EAA using
192 13,493 European-ancestry individuals aged between ten and 98 years from 12 cohorts, adjusting for
193 sex. Manhattan plots for Horvath-EAA and Hannum-EAA are shown in **Fig 1**, with QQ plots of the
194 observed P -values versus those expected shown in **Fig 2**. We did not find apparent evidence for
195 genomic inflation in either the GS study (Horvath-EAA: genomic inflation factor $\lambda_{GC} = 1.017$,
196 Linkage Disequilibrium (LD) score regression intercept (SE) = 1.002 (0.007); Hannum-EAA:
197 $\lambda_{GC} = 1.023$, intercept (SE) = 0.998 (0.006), **Table D in S1 Data, Fig B in S2 Text**) or the meta-
198 analysis (Horvath-EAA: $\lambda_{GC} = 1.035$, intercept (SE) = 1.006 (0.008), Hannum-EAA: $\lambda_{GC} = 1.044$,
199 intercept (SE) = 1.002 (0.007), **Fig 2**); Lu et al. previously reported no evidence for genomic
200 inflation for any of the individual studies making up their meta-analysis (19).

201

202 We identified 439 variants with a genome-wide significant association ($P < 5 \times 10^{-8}$) with Horvath-
203 EAA, of which ten were independent. The significantly associated variants mapped to nine genomic
204 loci on six chromosomes (**Table 1**, full details in **Table E of S1 Data**). Of the ten independent
205 significant variants identified here, five were novel, that is, not within ± 500 Kb of a significant
206 variant ($P < 5 \times 10^{-8}$) reported by Lu et al. (19). The novel findings were a SNP on chromosome
207 1q24.2 in the *Clorf112* gene, three SNPs on chromosome three, at 3q21.3 (nearest gene: *GATA2-
208 ASI*), 3q22.3 in the *PIK3CB* gene, and 3q25.1 in the *LINC01214* gene, and a SNP on chromosome
209 12q23.3 (nearest genes: *RP11-412D9.4* and *TMEM263*). The risk alleles at these loci conferred
210 between 0.33 (SE = 0.054) and 1.34 (SE = 0.127) years higher Horvath-EAA (**Table 1**). These ten
211 independent lead SNPs showed complete sign concordance for association with Horvath-EAA

212 across GS and the Lu study (**Table F in S1 Data**). Comparing the genomic loci identified in the
213 current study with the five reported by Lu et al., only one locus that was previously reported was
214 not identified at genome-wide significance here (rs11706810 at 3q25.33, meta-analysis *P*-value
215 8.68×10^{-8}). **Figs C-L in S2 Text** show the regional association plots for the independent signals. Of
216 the ten independent SNPs achieving genome-wide significance, none associated with any other
217 phenotype in currently published GWAS available via the NHGRI-EBI catalog.

218 **Table 1. Independent variants with a meta-analysis genome-wide significant association with Horvath-based or Hannum-based epigenetic age**
 219 **acceleration.**

220

Phenotype	Index SNP	Chromosome	Position	A1/A2	Freq	Beta	SE	<i>P</i> -value	Gene ^a	function	Previously reported
Horvath-EAA	rs1011267	1q24.2	169677720	A/G	0.503	-0.327	0.054	1.579E-09	<i>C1orf112</i>	intron variant	novel
	rs79070372	3q21.3	128510481	A/G	0.111	0.505	0.087	6.074E-09	<i>GATA2-AS1</i>	non coding transcript variant	novel
	rs388649	3q22.3	138777967	A/T	0.495	-0.338	0.055	6.054E-10	<i>PIK3CB</i>	intron variant	novel
	rs6440667	3q25.1	150287063	C/G	0.161	0.440	0.075	4.28E-09	<i>LINC01214</i>	intron variant	novel
	rs2736099	5p15.33	1287225	A/G	0.367	0.373	0.061	8.58E-10	<i>TERT</i>	intron variant	yes
	rs7744541	6p22.3	18104469	A/T	0.418	0.439	0.055	1.93E-15		intergenic variant	yes
	rs76244256	6p22.3	18140332	T/C	0.046	-1.341	0.127	6.231E-26	<i>TPMT</i>	intron variant	yes
	rs4712953	6p22.2	25671618	A/T	0.725	0.346	0.059	3.604E-09	<i>SCGN</i>	intron variant	yes
	rs10778517	12q23.3	106947886	T/G	0.565	0.335	0.054	4.46E-10	<i>RP11-412D9.4/TMEM263</i>	unknown	novel
rs62078811	17q22	55031815	A/G	0.218	-0.369	0.065	1.158E-08	<i>STXBP4</i>	intron variant	yes	
Hannum-EAA	rs1005277	10p11.21	37929331	A/C	0.301	0.533	0.070	2.173E-14		unknown	yes

221

222 Genome-wide significance defined as having a *P*-value of $P < 5 \times 10^{-8}$. A1 and A2 refer to the reference allele and non-reference allele for the index SNP, respectively. Freq (allele
 223 frequency), Beta (effect size), and SE (standard error of effect size) columns pertain to the reference allele, A1. Chromosome and position (in Mb) denote the location of the index
 224 SNP, and are given with regards to the GRCh38 assembly.

225 ^a Genes are listed if located within +/- 10 kb of a listed SNP.

226

227 The Hannum-EAA GWAS meta-analysis identified 324 genome-wide significant ($P < 5 \times 10^{-8}$)
228 associated variants mapping to a single genomic locus at 10p11.21 with one index SNP (**Fig 1**,
229 **Table 1**, full details of index SNP in **Table E of S1 Data**). *ZNF25*, a transcription factor associated
230 with osteoblast differentiation of human skeletal stem cells (20), is the closest gene to this variant,
231 at a distance of 20 Kb. At this Hannum-EAA-related locus, the risk allele conferred 0.53
232 (SE=0.070) years higher Hannum-EAA. We replicated two of the three variants significantly
233 associated with Hannum-EAA in the Lu et al. study; however, based on our clumping criteria with
234 $r^2 < 0.1$, we report only one as an independent significant SNP. Conditional analysis revealed no
235 secondary signal at this locus. The third locus reported in the previous study was not associated at
236 genome wide significance in this larger sample ($P = 3.74 \times 10^{-3}$). A regional association plot for
237 10p11.21 is shown in **Fig M in S2 Text**.

238

239 Of the ten independent variants associated with Horvath-EAA, nine exhibited sign-consistent
240 associations with Hannum-EAA, of which five attained at least nominal significance with
241 association P -values less than 0.05 (most significant $P = 6.9 \times 10^{-5}$) (**Table G in S1 Data**). The single
242 independent SNP associated with Hannum-EAA also exhibited a nominal and sign-consistent
243 association with Horvath-EAA ($P = 0.011$). Across all SNPs, however, there was little correlation
244 between the SNP association P -values for the Horvath-based and Hannum-based epigenetic age
245 acceleration measures ($r = 0.104$, SE=0.0004, **Fig N in S2 Text**).

246

247 **Heritability**

248 Using univariate LD score regression, the SNP-based heritabilities of Horvath-EAA and Hannum-
249 EAA were estimated to be 0.154 (SE=0.042) and 0.194 (SE=0.040) respectively (**Table D in S1**
250 **Data**), comparable to previous SNP-based heritability estimates but lower than estimates based on
251 pedigree relationships (19).

252

253 **SNP functional annotation**

254 We used FUMA to functionally annotate SNPs in LD ($r^2 \geq 0.6$) with the independent significant
255 SNPs for each of the epigenetic age acceleration measures. For Horvath-EAA, this resulted in
256 functional annotation of 825 SNPs (**Table H in S1 Data**). The vast majority of the SNPs were
257 intergenic (44.85%) or intronic (47.88%), with only five (0.61%) exonic SNPs. 25 SNPs had
258 CADD scores greater than 12.37, surpassing the suggested threshold to be considered deleterious
259 and thus providing evidence of pathogenicity (21). The highest CADD scores were found in three
260 exonic SNPs: rs1800460 and rs1142345 of *TPMT* and rs10949483 of *NHLRC1* (CADD scores
261 28.40, 28.30 and 18.92 respectively), indicating potentially deleterious protein effects. Six SNPs
262 (rs413147, rs12631035, rs9851887, rs12189658, rs6915893, rs12199316) had RegulomeDB scores
263 of 1f, suggesting that variation at these SNPs is likely to affect gene expression. Almost all SNPs
264 (98.18%) were in open chromatin regions.

265
266 For Hannum-EAA, functional annotation of 1,382 candidate SNPs indicated a high proportion of
267 intergenic SNPs (60.49%), while 11.79% were intronic and only three SNPs were located in exons
268 (**Table I in S1 Data**). 14 SNPs had CADD scores above 12.37, indicating that variation at these
269 SNPs is potentially deleterious. Although 42.04% of the SNPs were located in open chromatin
270 regions, there is little evidence that the Hannum-EAA-associated locus contains regulatory regions,
271 as analysis using RegulomeDB, which integrates a larger collection of regulatory information
272 encompassing protein binding, motifs, expression quantitative trait loci (eQTLs), and histone
273 modifications as well as chromatin structure, revealed only one SNP (rs2474568) with a score
274 below 2.

275

276 **Tissue Expression analysis**

277 MAGMA (Multi-marker Analysis of GenoMic Annotation) gene property analysis linking
278 differences in epigenetic age acceleration with differences in gene expression in various tissue

279 types, or in brain samples of different ages and developmental stages, revealed no significant
280 relationships after correcting for multiple tests (**Tables J-Q in S1 Data**).

281

282 **Identification of expression quantitative trait loci**

283 For the independent SNPs associated with Horvath-EAA and Hannum-EAA, evidence of eQTLs
284 was explored using the Genotype-Tissue expression (GTEx) v7 database. Seven of the ten
285 independent significantly associated SNPs for Horvath-EAA, and the single independent significant
286 Hannum-EAA-associated SNP were identified as potential eQTLs (**Table R in S1 Data**). Notably,
287 rs388649 is associated with expression of *ESYT3*, which has a role in lipid transport and
288 metabolism pathways (22,23), expression of *FAIM*, which is associated with apoptosis and
289 autophagy (24), in a number of skin and brain tissues, and *PIK3CB*, which regulates vital cell
290 functions including proliferation and survival (25,26). rs76244256, the variant most strongly
291 associated with Horvath-EAA, shows eQTL evidence for *NHLRC1* expression, which is associated
292 with glycogen metabolism (27), across multiple tissues. The Hannum-EAA-associated SNP,
293 rs1005277, affects the expression of several zinc finger proteins involved in transcriptional
294 regulation (28).

295

296 **Gene-based analysis**

297 MAGMA v1.6 was used to identify gene-level associations with each EAA measure. SNPs were
298 mapped to 17,798 protein coding genes, with genome-wide significance defined at
299 $P=0.05/17,798=2.809 \times 10^{-6}$. A total of 21 genes attained genome-wide significance for association
300 with Horvath-EAA (**Table 2**, full details in **Table S in S1 Data**). As expected, many of these genes
301 were located in the same regions as the lead SNPs. Three genes at 6p22.3, *NHLRC1*, *TPMT*, and
302 *KDM1B*, had the lowest P -values of 1.251×10^{-23} , 4.639×10^{-23} , and 7.68×10^{-11} respectively; all these
303 genes are involved in metabolism-related pathways (27,29,30). Although containing no genome-
304 wide significant SNPs, 3q25.33 appears to be an important genomic region for Horvath-EAA, with

305 four significantly associated genes including *TRIM59* and *KPNA4*, which play roles in the immune
306 system (31,32). Two further significant genes are *FAIM* and *TERT*, whose functions include
307 apoptosis and autophagy (24), and telomere length-associated ageing and apoptosis (33,34)
308 respectively. Twelve genes were significantly associated with Hannum-EAA (**Table 2, Table S in**
309 **S1 Data**). Genes of interest include *MTRNR2L7*, a neuroprotective and anti-apoptotic factor
310 (35,36), and *TRIM46* and *MUC1*, both located at 1q22, and which are involved with innate immune
311 system pathways (31,37). The 4q24 cytogenetic band houses several genes significantly associated
312 with Hannum-EAA: *MANBA* and *UBE2D3* have metabolic and innate immune system functions
313 (23,38) while *CISD2* regulates autophagy and is involved in life span control (39,40). Comparing
314 the results of the gene-based association analyses of Horvath-based and Hannum-based EAA, there
315 was no overlap, and the correlation between gene-based association *P*-values for Horvath-EAA and
316 Hannum-EAA was low ($r=0.117$, $SE=0.007$, **Fig O in S2 Text**). Manhattan plots and QQ plots for
317 the gene-based analysis of both epigenetic age acceleration measures are shown in **Figs P and Q in**
318 **S2 Text**.

319 **Table 2. Results of MAGMA gene-based association analysis for Horvath-based and Hannum-based epigenetic age acceleration.**

320

Phenotype	Gene	Chr	N_SNPs	P-value	Function/related pathways
Horvath-EAA	<i>SELP</i>	1	148	1.6883E-07	Immunoglobulin E responsiveness
	<i>EDARADD</i>	1	516	4.2627E-07	Innate immune system, cytokine signalling in immune system
	<i>GATA2</i>	3	72	1.0663E-07	Stem cell maintenance and hematopoietic development
	<i>ESYT3</i>	3	93	6.5973E-07	Metabolism, lipid transport
	<i>CEP70</i>	3	164	1.0891E-06	Organelle biogenesis and maintenance
	<i>FAIM</i>	3	49	2.4177E-08	Apoptosis and autophagy; regulates B-cell signalling and differentiation
	<i>PIK3CB</i>	3	175	2.52E-08	Coordinates cell functions e.g. proliferation, survival, migration
	<i>IFT80</i>	3	150	1.2622E-07	Organelle biogenesis and maintenance; intraflagellar transport
	<i>SMC4</i>	3	77	9.8909E-07	Changes in chromosome structure during mitotic segregation
	<i>TRIM59</i>	3	105	1.7737E-07	Multifunctional regulator for innate immune signalling pathways
	<i>KPNA4</i>	3	104	2.9437E-07	Cytokine signalling in immune system; protein transporter activity
	<i>TERT</i>	5	90	4.0455E-08	Roles in ageing and apoptosis; regulation of telomerase.
	<i>NHLRC1</i>	6	76	1.2512E-23	Clearance of toxic polyglucosan and protein aggregates; metabolism pathways
	<i>TPMT</i>	6	151	4.6385E-23	Drug metabolism - cytochrome P450; thiopurine S methyltransferase activity
	<i>KDM1B</i>	6	248	7.6758E-11	Metabolism of proteins, regulates histone lysing methylation
	<i>SCGN</i>	6	202	3.8379E-10	Calcium binding protein; neuroscience, Ca, cAMP and lipid signalling pathways
	<i>TMEM72</i>	10	123	1.1154E-06	Transmembrane protein
	<i>RFX4</i>	12	299	9.4786E-07	Transcriptional regulatory network in embryonic stem cell
	<i>RIC8B</i>	12	155	1.0988E-06	Can activate some G-alpha proteins; odorant signal transduction.
	<i>C12orf23/TMEM263</i>	12	98	6.321E-09	Transmembrane protein
	<i>ZNF70</i>	22	79	2.7934E-06	Transcriptional regulation; gene expression pathways
Hannum-EAA	<i>TRIM46</i>	1	27	2.66E-06	Innate immune system; cytokine signalling in immune system
	<i>MUC1</i>	1	15	7.33E-07	Cytokine signalling in immune system; bacterial infections in CF airways
	<i>MANBA</i>	4	190	1.31E-06	Glycosaminoglycan metabolism; innate immune system
	<i>UBE2D3</i>	4	154	1.19E-06	Metabolism of proteins; innate immune system
	<i>CISD2</i>	4	54	1.18E-06	Regulator of autophagy; life span control; glucose/energy metabolism pathways

<i>SLC9B1</i>	4	217	2.56E-06	Sperm motility and fertility, ion channel transport
<i>MTRNR2L7</i>	10	52	5.20E-07	Neuroprotective and antiapoptotic factor
<i>ZNF248</i>	10	204	2.22E-07	Transcriptional regulation; gene expression pathways
<i>ZNF25</i>	10	99	1.23E-08	Transcriptional regulation; gene expression pathways
<i>ZNF33A</i>	10	159	8.29E-09	Transcriptional regulation; gene expression pathways
<i>ZNF37A</i>	10	146	3.79E-10	Transcriptional regulation; gene expression pathways
<i>DNTT</i>	10	131	2.51E-07	DNA double-strand break repair; hematopoietic cell lineage

321

322 Genome-wide significant results after Bonferroni correction for multiple testing ($P < 2.809 \times 10^{-6}$) are reported. N_SNPs is the number of SNPs in the gene.

323 **Gene-set and pathway analysis**

324 Using a competitive test of enrichment implemented in MAGMA v1.6, we did not identify any gene
325 sets that were significantly associated with either Horvath-EAA or Hannum-EAA after Bonferroni
326 correction for multiple testing. **Tables T and U in S1 Data** show the top 100 gene-sets for Horvath-
327 EAA and Hannum-EAA respectively.

328

329 **Genetic correlations**

330 The SNP-based genetic correlation between Horvath-EAA and Hannum-EAA in the meta-analysis
331 dataset, determined using LD score regression, was 0.571 (SE=0.132, $P=1.605 \times 10^{-5}$), suggesting a
332 moderate overlap in the genetic factors influencing these two measures of epigenetic age
333 acceleration. We also explored genetic correlations between Horvath-EAA/Hannum-EAA and 218
334 other health and behavioural traits using LD score regression analysis of summary-level data,
335 implemented in the online software LD Hub (41). None of these phenotypes had a significant
336 genetic correlation ($P_{FDR} < 0.05$) with either Horvath-EAA or Hannum-EAA after applying false
337 discovery rate correction (most significant correlation with Horvath-EAA: father's age at death,
338 $P_{FDR}=0.160$; with Hannum-EAA: waist-to-hip ratio, $P_{FDR}=0.065$). This correction, however, may be
339 overly conservative, as not all the tested traits are independent, with several being identical or
340 highly correlated, and nominally significant correlations ($P_{uncorrected} < 0.05$) were found with a
341 number of traits (**Table 3**).

342
343
344

Table 3. Nominally significant genetic correlations ($P_{uncorrected} < 0.05$) between Horvath-EAA/Hannum-EAA and other health and behavioural traits.

Phenotype	Trait	Genetic Correlation	SE	P-value	
Horvath-EAA	Fathers age at death	-0.472	0.144	0.001	
	Urate	0.278	0.089	0.002	
	Waist-to-hip ratio	0.194	0.064	0.002	
	Waist circumference	0.178	0.064	0.005	
	ICV	-0.403	0.163	0.013	
	Forced expiratory volume in 1 second (FEV1)/Forced Vital capacity(FVC)	-0.170	0.078	0.030	
	Extreme waist-to-hip ratio	0.306	0.146	0.036	
	Child birth weight	-0.274	0.131	0.037	
	Childhood IQ	-0.317	0.152	0.037	
	Leucine	0.450	0.222	0.043	
	Glycoprotein acetyls; mainly a1-acid glycoprotein	0.360	0.183	0.049	
	Hannum-EAA	Waist-to-hip ratio	0.225	0.062	0.0003
		Waist circumference	0.210	0.067	0.002
		Parents age at death	-0.455	0.148	0.002
Type 2 Diabetes		0.331	0.114	0.004	
Years of schooling 2013		-0.231	0.083	0.005	
Years of schooling 2016		-0.162	0.058	0.006	
Birth weight		0.211	0.079	0.007	
HDL cholesterol		-0.210	0.082	0.010	
Former vs Current smoker		-0.330	0.130	0.011	
Forced expiratory volume in 1 second (FEV1)		-0.239	0.095	0.012	
Forced expiratory volume in 1 second (FEV1)		-0.371	0.149	0.013	
Hip circumference		0.163	0.066	0.013	
Intelligence		-0.169	0.070	0.016	
Cigarettes smoked per day		0.326	0.138	0.018	
Ever vs never smoked		0.202	0.088	0.022	
College completion		-0.195	0.086	0.023	

Age of first birth	-0.156	0.070	0.026
HOMA-B	0.305	0.137	0.026
Fasting insulin main effect	0.237	0.107	0.027
HbA1C	-0.277	0.126	0.028
Childhood IQ	-0.286	0.130	0.028
Fathers age at death	-0.287	0.131	0.028
Triglycerides	0.136	0.065	0.036
Phospholipids in medium LDL	-0.410	0.200	0.040
Free cholesterol in large LDL	-0.485	0.237	0.041
Anorexia Nervosa	-0.152	0.074	0.041
Amyotrophic lateral sclerosis	0.363	0.178	0.042
Obesity class 1	0.135	0.067	0.042
Years of schooling (proxy cognitive performance)	-0.171	0.084	0.042
Phospholipids in large LDL	-0.471	0.232	0.043
Phospholipids in very small VLDL	-0.373	0.184	0.043
Free cholesterol in IDL	-0.439	0.220	0.046
Celiac disease	-0.265	0.134	0.047
Extreme waist-to-hip ratio	0.285	0.145	0.048
Total cholesterol in large LDL	-0.430	0.219	0.049

345

346

Genetic correlations were determined using bivariate Linkage Disequilibrium score regression implemented in the online software LD Hub. SE is the standard error of the genetic

347

correlation estimate; *P*-value is the association *P*-value for the genetic correlation estimate; ICV – intracranial volume; LDL – low density lipoprotein; IDL – intermediate density

348

lipoprotein; VLDL – very low density lipoprotein.

349

350 Both epigenetic age acceleration measures had nominally significant positive genetic correlations
351 with a range of traits pertaining to adiposity, and negative correlations with father's age at death and
352 childhood IQ. Nominally significant genetic correlations were observed between Hannum-EAA, but
353 not Horvath-EAA, and a wide range of traits including measures relating to education, smoking
354 behaviour, various lipid- and cholesterol-related measures, diabetes and related glyceic measures,
355 and parent's age at death. Some of these results have previously been reported (19), but many are
356 novel. The current study did, however, fail to replicate a number of previously reported correlations,
357 including with age at menopause (19). Details of the genetic correlations of all the tested traits with
358 Horvath-EAA and Hannum-EAA are given in **Tables V and W in S1 Data**, respectively.

359

360

361 **Discussion**

362

363 This study investigated genetic markers of epigenetic ageing in a sample of 13,493 individuals of
364 European ancestry. We examined genetic determinants of both Horvath-based (adjusted for the
365 composition of age-related blood cells) and Hannum-based (immune system-associated) epigenetic
366 age acceleration, sometimes referred to as 'intrinsic' and 'extrinsic' epigenetic age acceleration, to
367 gain insight into the regulation of epigenetic ageing. We report several novel findings in addition to
368 replicating a sub-set of previous results. The meta-analysis of Horvath-EAA identified ten
369 independent associated SNPs, doubling the number reported to date, and highlighted 21 genes
370 involved in Horvath-based epigenetic ageing. A single genome-wide significant variant was
371 identified for Hannum-EAA, along with 12 implicated genes. We uncovered limited evidence of
372 functionality within some associated genomic loci, with many SNPs located in regions of open
373 chromatin and a smaller number in regulatory regions. Some loci also contained regions where
374 genetic variation is predicted to be deleterious.

375

376 A number of the genes significantly associated with Horvath-EAA are related to metabolism
377 (*NHLRC1*, *TPMT*, *KDM1B*, and *ESYT3*), consistent with several studies reporting phenotypic
378 associations between Horvath-based EAA and metabolic syndrome characteristics and supporting
379 the suggestion of a role in tracking metabolic ageing (14,18). Others are involved in immune system
380 pathways (*TRIM59*, *KPNA4*, *EDARADD*), while several have roles in cellular processes linked to
381 ageing: apoptosis and autophagy (*FAIM*), ageing and autophagy (*TERT*), and coordinating vital cell
382 functions (*PIK3CB*). *PIK3CB* plays a role in the signal transduction of insulin and insulin-like
383 pathways (42), and genetic variants at this locus have been related to insulin-like growth factor
384 levels in plasma, and human longevity (43).

385
386 Genes associated with Hannum-based EAA, often referred to as immune system ageing, include
387 several involved in innate immune system pathways (e.g. *TRIM46* and *MUC1*) or with metabolic
388 and immune system functions (*MANBA*, *UBE2D3*). Other associated genes of interest include those
389 with roles relating to ageing and longevity: *MTRNR2L7* is a neuroprotective and anti-apoptotic
390 factor, and *CISD2* regulates autophagy and is a fundamentally important regulator of lifespan.
391 Mouse studies indicate that *CISD2* ameliorates age-associated degeneration of skin, skeletal muscle,
392 and neurons, protects mitochondria from age-related damage and functional decline, and attenuates
393 age-associated reduction in energy metabolism (44), while *CISD2* deficiency leads to a number of
394 phenotypic features suggestive of premature ageing (45).

395
396 Our LD score regression analysis replicated the positive genetic correlations with central adiposity
397 reported by Lu et al. (2018) at nominal significance levels, supporting the suggestion that observed
398 phenotypic associations (14,18) may result in part from a shared genetic aetiology. We did not,
399 however, replicate previously reported correlations between Horvath-EAA and metabolic disease-
400 related traits or diabetes, and found these traits to be correlated with Hannum-EAA at only nominal
401 significance levels in our larger sample (19). We also found no correlation between epigenetic age

402 acceleration and age at menopause. Nominally significant genetic correlations between Hannum-
403 based, but not Horvath-based, epigenetic age acceleration, and lifestyle factors such as smoking
404 behaviour and education level, provide some evidence for a genetic basis underlying the phenotypic
405 results we reported previously (18), and provide tentative support to the hypothesis that Hannum-
406 based epigenetic ageing is relatively sensitive to changes in environment and lifestyle. Father's age
407 at death, a rough proxy for lifespan (46), was nominally significantly correlated with both EAA
408 measures, and parents' age at death was additionally correlated with Hannum-EAA, consistent with
409 a body of work demonstrating robustly that EAA predicts life span (10,11). Aside from these,
410 genetic correlations with age-related traits were surprisingly few: it is possible that this could reflect
411 an overly conservative correction for the multiple tests carried out, or low statistical power, rather
412 than a genuine lack of correlations (**Table D in S1 Data**). While the mean χ^2 values (1.059 and
413 1.054 for Horvath-EAA and Hannum-EAA respectively) indicate a sufficient level of polygenicity
414 within the dataset for use with LD score regression, the heritability Z-scores for Horvath-EAA and
415 Hannum-EAA are 3.69 and 4.91 respectively. The recommendation is that genetic correlation
416 analysis should be restricted to GWAS with a heritability Z-score of 4 or more, on the grounds of
417 interpretability and power (41), so the Horvath-based results particularly should be interpreted with
418 caution.

419

420 This study of epigenetic age acceleration benefits from having a large sample size. Increasing
421 GWAS sample size increases the power to detect associated loci, and is often achieved, as in this
422 case, by combining smaller studies in a meta-analysis. Meta-analytic GWAS are, however,
423 sometimes hampered by differences in how a trait is measured between individual studies. In this
424 instance, use of the online calculator to calculate the EAA measures and using the same algorithm
425 and output columns for each study, mitigates this. The current study comprises only individuals of
426 European ancestry, which confers a further advantage as epigenetic ageing rates have been shown

427 to differ between ethnicities (47). It should be noted, however, that although large for these
428 phenotypes, the size of the sample studied here is still small in terms of GWASs of polygenic traits.
429
430 Despite the large sample overlap, some results of this study differ from those reported by Lu et al.
431 (2018). One reason for this could be that only European-ancestry individuals were included in this
432 analysis whereas the Lu study reports results from a mixed ancestry sample. Another likely
433 contributing factor is the age ranges involved: the GS cohort, not included in Lu's analysis but
434 which makes up 38% of the total sample in the current study, has a mean age of 48.5 years, 14.4
435 years younger than the mean age of the remaining cohorts. Given that epigenetic age changes over
436 the life course, although not necessarily in parallel with chronological age, this could help explain
437 the discrepancies between the studies.
438
439 Horvath-based and Hannum-based epigenetic age acceleration are thought to represent different
440 aspects of ageing. Hannum-EAA has been described as a biomarker of immune system ageing, and
441 has been found to be associated with a wide range of traits (14,18), indicating a sensitivity to
442 variations in environment and lifestyle. By contrast, Horvath-EAA is considered to be a
443 fundamental, intrinsic cellular ageing process, largely unrelated to lifestyle factors, although
444 associations with a range of metabolic syndrome characteristics suggest a role in tracking metabolic
445 ageing processes. Our results reflect this to a large degree, with more nominally significant genetic
446 correlations found with Hannum-EAA than Horvath-EAA, including items relating to education,
447 smoking, intelligence, and various cholesterol measures. Meanwhile the greater number of
448 significant variants, genomic loci, and genes associated with Horvath-EAA are consistent with the
449 hypothesis that this measure of 'cell-intrinsic' ageing is less related to lifestyle and more under
450 genetic control, and thus more likely to remain relatively stable. Despite these differences, however,
451 our results indicate some common features. The significant genetic correlation of 0.57 between the
452 two measures suggests a moderate overlap in the genetic factors influencing the two phenotypes

453 despite the biomarkers being based on almost entirely distinct CpG sets. Both also appear to be
454 influenced by genes associated with metabolic and immune system pathways, although the specific
455 genes involved are different.

456

457 **Conclusions**

458 This study provided insight into the genetic determinants of differential biological ageing through
459 the identification of genes and genetic variants associated with epigenetic age acceleration. We
460 doubled the number of SNPs associated with Horvath-EAA reported to date, and report 21 genes
461 significantly associated with this phenotype, including *PIK3CB*, linked to human longevity. We
462 identified 12 Hannum-EAA-associated genes, one of which, *CISD2*, has a fundamental role in
463 lifespan control. Our results also highlighted differences in the genetic architecture of the Horvath-
464 based and Hannum-based EAA measures, with no genome-wide significant SNPs or genes common
465 to the two, providing substantial support for the hypothesis that they represent different aspects of
466 ageing.

467

468 While the genetic information coded by our DNA sequence remains largely fixed throughout the
469 lifetime, the expression of our genes is primarily regulated by epigenetic factors, which change over
470 time. Epigenetic age increases with, but not in parallel with, chronological age; individual
471 differences in the rate of epigenetic ageing potentially explain why trajectories of ageing differ
472 between individuals. Understanding what causes these differences could potentially inform
473 therapeutic interventions to delay the onset of age-related decline and improve ageing outcomes.

474

475

476 **Methods**

477

478 **Generation Scotland cohort**

479 We carried out genome-wide association analyses of Horvath-EAA and Hannum-EAA in a subset
480 of individuals (n=5,100) from the Generation Scotland: Scottish Family Health Study (GS) for
481 whom both genetic and DNA methylation data were available. GS is a family- and population-
482 based cohort recruited via general medical practices across Scotland; the recruitment protocol and
483 sample characteristics are described in detail elsewhere (48,49). In brief, the full cohort comprises
484 23,960 individuals aged between 18 and 98 years. Pedigree information was available for all
485 participants, detailed socio-demographic and clinical data were collected, and biological samples
486 were taken for genotyping.

487

488 **DNA methylation and derivation of epigenetic age acceleration variables in GS**

489 DNA methylation data were obtained from peripheral blood (n=5,091) or saliva (n=10) samples for
490 5,101 individuals from GS, with quality control checks carried out using standard methods outlined
491 in **S1 Text**, and described in full elsewhere (18). After QC, the dataset comprised beta-values for
492 860,928 methylation loci. Methylation-based age estimates (DNAm age) and epigenetic age
493 acceleration variables (Horvath-EAA and Hannum-EAA, described in **S1 Text**) were obtained from
494 the online DNA Methylation Age Calculator (<https://dnamage.genetics.ucla.edu/>) developed by
495 Horvath (8). Normalised DNA methylation beta-values were submitted to the calculator, using the
496 'Advanced Analysis for Blood Data' option, and undergoing further normalisation within the
497 calculator algorithm to make the data comparable to the training data of the epigenetic clock. One
498 individual was flagged by the calculator as having a gender mismatch, and was therefore omitted
499 from downstream analysis, leaving a total of 5,100 individuals for the GWAS of Horvath-EAA and
500 Hannum-EAA in GS. Blood cell abundance measures were also estimated by the online calculator,
501 based on DNA methylation levels, as described previously (50).

502

503 **Genotyping, imputation, and quality control in GS**

504 An overview of biological sample collection, DNA extraction, genotyping, imputation using the
505 Haplotype Research Consortium reference panel (v1.1), and quality control for GS is included in **S1**
506 **Text**; full details have been described previously (51). A total of 20,032 individuals passed all
507 quality control thresholds. Following the removal of monomorphic or multiallelic variants and
508 SNPs with a low imputation quality or a minor allele frequency below 1%, an imputed dataset with
509 8,633,288 hard called variants remained to be used in the genome-wide association analysis.

510

511 **GWAS of Horvath-EAA and Hannum-EAA in GS**

512 GWAS of Horvath-EAA and Hannum-EAA in GS were conducted using mixed linear model based
513 association (MLMA) analysis (52), implemented in GCTA (v1.25) (53), and adjusting for sex to
514 account for the higher epigenetic age acceleration in men than in women (7,11,47). In order to
515 account for population stratification, it is common to conduct ancestry-informative principal
516 components analysis on the population in question, and use a number of the top-ranking PCs from
517 this analysis as covariates in the GWAS. However, as GS is a family-based sample, we employed a
518 different approach to capture population structure. In place of PCs, two genomic relationship
519 matrices (GRMs) were included in the GWAS, as this method has been shown to account for
520 potential upward biases due to excessive relationships, and thus allows the inclusion of closely and
521 distantly related individuals in genetic analyses (54). The first GRM included pairwise relationship
522 coefficients for all individuals, while the second had off-diagonal elements <0.05 set to 0; full
523 details of the methods involved and construction of the GRMs is given elsewhere (55). The results
524 of univariate LD score regression analysis (56) (**Table D in S1 Data**) indicate that the two GRMs
525 adequately accounted for population stratification, so it was not necessary to include ancestry-
526 informative PCs in the GWAS.

527

528 **GWAS meta-analysis of Horvath-EAA and Hannum-EAA**

529 We obtained summary statistics from the largest European-ancestry analysis of epigenetic age
530 acceleration to date (n=8,393, Lu et al., 2018, summary information in **Table X in S1 Data**), and
531 meta-analysed these with GS (details above). We chose not to include available data from non-
532 European samples, despite the advantages of increased sample size, as different ethnicities have
533 been shown to have different epigenetic ageing rates (47). Association summary statistics from the
534 GWAS of the two EAA phenotypes in GS and the Lu et al. study were meta-analysed using the
535 inverse variance-weighted approach, which weights effect sizes by sampling distribution. This
536 analysis was implemented in METAL (57), conditional on each variant being available in both
537 samples. As SNPs which co-located with CpGs from the Hannum- or Horvath-based DNAm age
538 predictors had already been excluded from Lu et al.'s analysis, it was not necessary to repeat this
539 step. This resulted in 5,932,107 genetic variants for Horvath-EAA and 5,931,171 variants for
540 Hannum-EAA, in a meta-analysis dataset containing 13,493 participants.

541
542 The meta-analytic summary statistics produced by METAL were uploaded to FUMA
543 (fuma.ctglab.nl) (58), which identified index SNPs and genomic risk loci related to epigenetic age
544 acceleration. FUMA selects independent significant SNPs based on their having a genome-wide
545 significant P -value ($P < 5 \times 10^{-8}$) and being independent from each other ($r^2 < 0.6$ by default) within a
546 250kb window. The European subset of the 1000 Genomes phase 3 reference panel (59) was used
547 to map LD. SNPs in LD with these independent significant SNPs ($r^2 \geq 0.6$) within a 250kb window,
548 and which have a minor allele frequency (MAF) $> 1\%$ within the 1000 Genomes reference panel,
549 were included for further annotation and used for gene prioritization. A subset of the independent
550 significant SNPs, those in LD with each other at $r^2 < 0.1$ within a 250kb window, were identified as
551 lead SNPs. Genomic risk loci, including all independent signals that were physically close or
552 overlapping in a single locus, were identified by merging any lead SNPs that were closer than
553 250kb apart (meaning that a genomic risk locus could contain multiple lead SNPs, with each locus
554 represented by the lead SNP with the lowest P -value in that locus).

555

556 Conditional analysis was implemented using GCTA software (53) to ascertain whether associated
557 genetic loci harboured more than one independent causal variant, conditioning on the lead SNP at
558 the locus and using GS as the reference panel for inferring the LD pattern. SNPs which remained
559 significantly associated ($P < 5 \times 10^{-8}$) with the phenotype after conditioning on the lead SNP were
560 considered to be further independent associated variants.

561

562 Manhattan plots and quantile-quantile plots were generated in R version 3.2.3 using the 'qqman'
563 package, and regional SNP association results were visualised with LocusZoom (60). SNPs which
564 surpassed the threshold for genome-wide significance in our meta-analyses were checked against
565 the NHGRI-EBI catalog of published GWAS (61,62) (www.ebi.ac.uk/gwas/) to determine whether
566 they had previously been observed in association analysis.

567

568 **Heritability analysis**

569 To estimate the SNP-based heritability for Horvath-EAA and Hannum-EAA, univariate Linkage
570 Disequilibrium score regression (56) was applied to the GWAS summary statistics for both
571 measures. This method also provides metrics to evaluate the proportion of inflation in the test
572 statistics caused by confounding biases such as residual population stratification, relative to genuine
573 polygenicity. We used pre-computed LD scores, estimated from the European-ancestry samples in
574 the 1000 Genomes Project (63).

575

576 **SNP functional annotation**

577 Functional annotation, using all SNPs located within the genomic risk loci which were nominally
578 significant ($P < 0.05$), had a $MAF \geq 1\%$, and were in LD of $r^2 \geq 0.6$, was carried out in FUMA v1.3.0
579 (58). In order to investigate the functional consequences of variation at these SNPs, they were first

580 matched (based on chromosome, base pair position, reference and non-reference alleles) to a
581 database containing functional annotations from a number of repositories:

- 582 • ANNOVAR categories (64), used to identify a SNP's function and determine its position
583 within the genome.
- 584 • Combined Annotation Dependent Depletion (CADD) scores (21), a measure of the
585 deleteriousness of genetic variation at a SNP to protein structure and function, with higher
586 scores indicating more deleterious variants.
- 587 • RegulomeDB (RDB) scores (65), based on data from expression quantitative trait loci
588 (eQTLs) as well as chromatin marks, with lower scores given to variants with the greatest
589 evidence for having regulatory function.
- 590 • Chromatin states (66–68), indicating the level of accessibility of genomic regions, described
591 on a 15 point scale, where lower chromatin scores indicate a greater level of accessibility to
592 the genome at that site; generally, between 1 and 7 is considered an open chromatin state.

593

594 **Gene-based analysis**

595 Gene-based analysis was performed for each phenotype using the results of our association analysis,
596 using default settings in MAGMA (Multi-marker Analysis of GenoMic Annotation) v1.6 (69),
597 integrated within the FUMA web application. Summary statistics of SNPs located within protein-
598 coding genes were aggregated to assess the simultaneous effect of all SNPs in the gene on the
599 phenotype. The European panel of the 1000 Genomes phase 3 data was used as a reference panel to
600 account for LD (59). Genetic variants were assigned to protein-coding genes obtained from
601 Ensembl build 85, resulting in 17,798 genes being analysed. After Bonferroni correction
602 ($\alpha=0.05/17,798$), a threshold for genome-wide significant genes was defined at $P<2.809\times 10^{-6}$.

603

604 **Tissue Expression analysis**

605 To determine whether differential expression levels of a gene in specific tissues relate to the

606 association of that gene with EAA, gene-property analysis was conducted using MAGMA,
607 integrated within the FUMA web application, using average expression of genes per tissue type as a
608 gene covariate. Four types of tissue expression analysis were performed separately, for 30 general
609 tissue types, 53 specific tissue types (both taken from the GTEx v7 RNA-seq database (70,71)), 29
610 different ages of brain samples, and 11 developmental stages of brain samples (from BrainSpan
611 (72)) , with Bonferroni correction over 30, 53, 29 and 11 tests respectively to control for multiple
612 testing.

613

614 **eQTL analysis**

615 The independent genome-wide significant variants identified for Horvath-EAA and Hannum-EAA
616 in the GWAS meta-analysis were assessed to determine whether they were potential expression
617 quantitative trait loci (eQTLs), using the Genotype Tissue Expression Portal (GTEx) v7 (71), which
618 used gene expression data from multiple human tissues linked to genotype data to provide
619 information on eQTLs. eQTL mapping carried out within FUMA maps SNPs to genes which likely
620 affect expression of those genes within 1Mb, i.e. *cis*-eQTLs.

621

622 **Gene-set analysis**

623 To assess whether the Horvath-EAA and Hannum-EAA GWAS meta-analysis results are enriched
624 for various gene-sets and provide insight into the involvement of specific biological pathways in the
625 genetic etiology of the phenotype, the gene-based analysis results were used to perform competitive
626 gene-set and pathway analysis using default parameters in MAGMA v1.6, integrated within FUMA.
627 The reference genome was 1000 genomes phase 3. This analysis used gene annotation files from the
628 Molecular Signatures Database v5.2 for "Curated gene sets", covering chemical and genetic
629 perturbations, and Canonical pathways, and "GO terms", covering three ontologies: biological
630 process, cellular components, and molecular function. A total of 10,894 gene-sets were examined
631 for enrichment in Horvath-EAA and Hannum-EAA, with a Bonferroni correction applied to control

632 for multiple testing. Thus genome-wide significance was defined at $P=0.05/10,894=4.59 \times 10^{-6}$.

633

634 **Genetic correlations**

635 Cross trait LD score regression (73) was used to calculate genetic correlations between Horvath-
636 based and Hannum-based EAA in our meta-analysis, and then between Horvath-EAA/Hannum-
637 EAA and 218 other behavioural and disease-related traits for which GWAS summary data were
638 available through LD Hub (41); traits derived from non-Caucasian or mixed ethnicity samples were
639 removed prior to analysis. This method exploits the correlational structure of SNPs across the
640 genome and uses test statistics provided from GWAS summary estimates to calculate the genetic
641 correlations between traits (73). We checked whether our meta-analysis datasets had sufficient
642 evidence of a polygenic signal, indicated by a heritability Z-score of >4 and a mean χ^2 statistic
643 of >1.02 (73). By default, a MAF filter of $>1\%$ was applied, and indels and strand ambiguous SNPs
644 were removed. We filtered to HapMap3 SNPs, and SNPs whose alleles did not match those in the
645 1000 Genomes European reference sample were removed. LD scores and weights for use with
646 European populations were downloaded from (http://www.broadinstitute.org/~bulik/eur_ldscores/).
647 We did not constrain the intercepts in our analysis, as we could not quantify the exact amount of
648 sample overlap between cohorts. False discovery rate correction was applied across the 218 traits to
649 correct for multiple testing (74).

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651 **Ethics Statement**

652 Generation Scotland received ethical approval from the NHS Tayside Committee on Medical
653 Research Ethics (REC Reference Number: 05/S1401/89). GS has also been granted Research Tissue
654 Bank status by the Tayside Committee on Medical Research Ethics (REC Reference Number:
655 10/S1402/20), providing generic ethical approval for a wide range of uses within medical research.
656 All participants provided written informed consent. Details of ethics approval and consent to
657 participate for the cohorts included in the Lu et al. (2018) study can be found in their publication.

658

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660

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684 **Fig 1. Manhattan plots for genome-wide meta-analyses (n=13,493) of Horvath-based and**
685 **Hannum-based epigenetic age acceleration.**

686 SNP-based Manhattan plots for Horvath-EAA and Hannum-EAA, with $-\log_{10}$ transformed P -values for each SNP
687 plotted against chromosomal location. The red line indicates the threshold for genome-wide significance ($P < 5 \times 10^{-8}$)
688 and the blue line for suggestive associations ($P < 1 \times 10^{-5}$).

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691 **Fig 2. QQ plots for the meta-analyses of Horvath-based and Hannum-based epigenetic age**
692 **acceleration.**

693 Quantile-quantile plots for the genome-wide meta-analyses of Horvath-EAA and Hannum-EAA, showing the expected
694 distribution of GWAS test statistics, $-\log_{10}(p)$, versus the observed distribution.

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956 **Supporting Information**

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958 **S1 Text: Supplementary Information**

959 S1 Text contains further information on the Hannum and Horvath epigenetic clocks, measures of
960 epigenetic age and epigenetic age acceleration, DNA methylation in GS, derivation of epigenetic
961 age and epigenetic age acceleration variables in GS, genotyping, imputation, and quality control in
962 GS.

963

964 **S1 Data: Supplementary Tables**

965 **Table A:** Summary of age and estimated epigenetic age variables in Generation Scotland

966 **Table B:** Independent variants with a genome-wide significant association ($P < 5 \times 10^{-8}$) with
967 epigenetic age acceleration in the Generation Scotland cohort

968 **Table C:** Independent variants with a P -value $< 5 \times 10^{-8}$ for association with Horvath-
969 EAA/Hannum-EAA in the Lu et al. sample, and their corresponding effect size and
970 significance in the Generation Scotland cohort

971 **Table D:** Estimated polygenicity and SNP-based heritability using LD score regression

972 **Table E:** Full details of independent variants with a genome-wide significant association
973 ($P < 5 \times 10^{-8}$) with Horvath-based or Hannum-based epigenetic age acceleration

974 **Table F:** Independent variants with a P -value $< 5 \times 10^{-8}$ for association with Horvath-
975 EAA/Hannum-EAA in the meta-analysis, and their corresponding effect size and
976 significance in the Generation Scotland and Lu samples

977 **Table G:** Summary of the independent variants significantly associated with either Horvath-
978 EAA or Hannum-EAA, and their association with both epigenetic age acceleration measures

979 **Table H:** Functional annotation of all SNPs in LD ($r^2 \geq 0.6$) with FUMA-identified
980 independent significant SNPs for Horvath-EAA

981 **Table I:** Functional annotation of all SNPs in LD ($r^2 \geq 0.6$) with FUMA-identified
982 independent significant SNPs for Hannum-EAA

983 **Table J:** MAGMA gene property analysis (30 general tissue types) for the meta-analysis of
984 Horvath-EAA

985 **Table K:** MAGMA gene property analysis (53 specific tissue types) for the meta-analysis of
986 Horvath-EAA

987 **Table L:** MAGMA gene property analysis (29 different ages of brain samples) for the meta-
988 analysis of Horvath-EAA

989 **Table M:** MAGMA gene property analysis (11 different developmental stages of brain
990 samples) for the meta-analysis of Horvath-EAA

991 **Table N:** MAGMA gene property analysis (30 general tissue types) for the meta-analysis of
992 Hannum-EAA

993 **Table O:** MAGMA gene property analysis (53 specific tissue types) for the meta-analysis of
994 Hannum-EAA

995 **Table P:** MAGMA gene property analysis (29 different ages of brain samples) for the meta-
996 analysis of Hannum-EAA

997 **Table Q:** MAGMA gene property analysis (11 different developmental stages of brain
998 samples) for the meta-analysis of Hannum-EAA

999 **Table R:** Expression quantitative trait loci identified by analysis of independent significant
1000 variants for Horvath-EAA and Hannum-EAA and the significance of their expression in the
1001 specified tissues

1002 **Table S:** Genome-wide significant gene-based results ($P < 2.809 \times 10^{-6}$) obtained by MAGMA
1003 gene-based association analyses of Horvath-EAA and Hannum-EAA

1004 **Table T:** Most associated gene sets for the GWAS meta-analysis of Horvath-EAA

1005 **Table U:** Most associated gene sets for the GWAS meta-analysis of Hannum-EAA

1006 **Table V:** Genetic correlations between Horvath-EAA and 218 other health and behavioural
1007 traits

1008 **Table W:** Genetic correlations between Hannum-EAA and 218 other health and behavioural
1009 traits

1010 **Table X:** Overview of study datasets

1011

1012 **S2 Text: Supplementary Figures**

1013 **Fig A:** SNP-based Manhattan plot for the GWAS analysis of Horvath-based epigenetic age
1014 acceleration and Hannum-based epigenetic age acceleration in the GS cohort

1015 **Fig B:** QQ plots for the GWAS of Horvath-EAA and Hannum-EAA in GS

1016 **Figs C-L:** Regional association plots for the independent SNPs that are significantly
1017 associated with Horvath-EAA

1018 **Fig M:** Regional association plot for the independent significantly associated SNP with
1019 Hannum-EAA

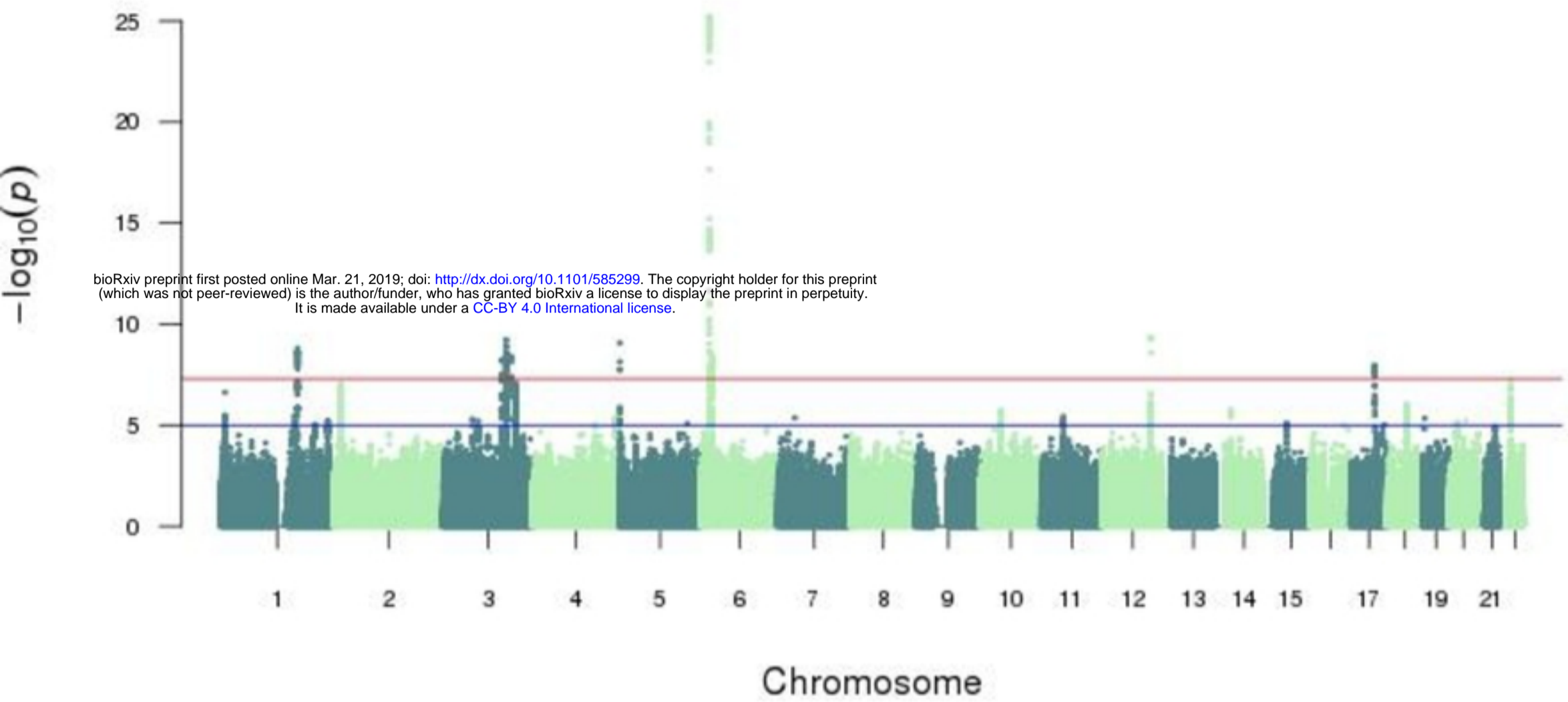
1020 **Fig N:** Scatter plot of $-\log_{10}(\text{association } P\text{-value})$ for SNP-based GWAS of Horvath-EAA vs
1021 $-\log_{10}(\text{association } P\text{-value})$ for SNP-based GWAS of Hannum-EAA

1022 **Fig O:** Scatter plot of $-\log_{10}(\text{association } P\text{-value})$ for gene-based GWAS of Horvath-EAA
1023 vs $-\log_{10}(\text{association } P\text{-value})$ for gene-based GWAS of Hannum-EAA

1024 **Fig P:** Manhattan plots for the MAGMA gene-based association analysis for the GWAS
1025 meta-analysis of Horvath-based epigenetic age acceleration and Hannum-based epigenetic
1026 age acceleration

1027 **Fig Q:** QQ plots for the gene-based association analyses of Horvath-EAA and Hannum-EAA

Manhattan plot for Horvath-EAA



Manhattan plot for Hannum-EAA

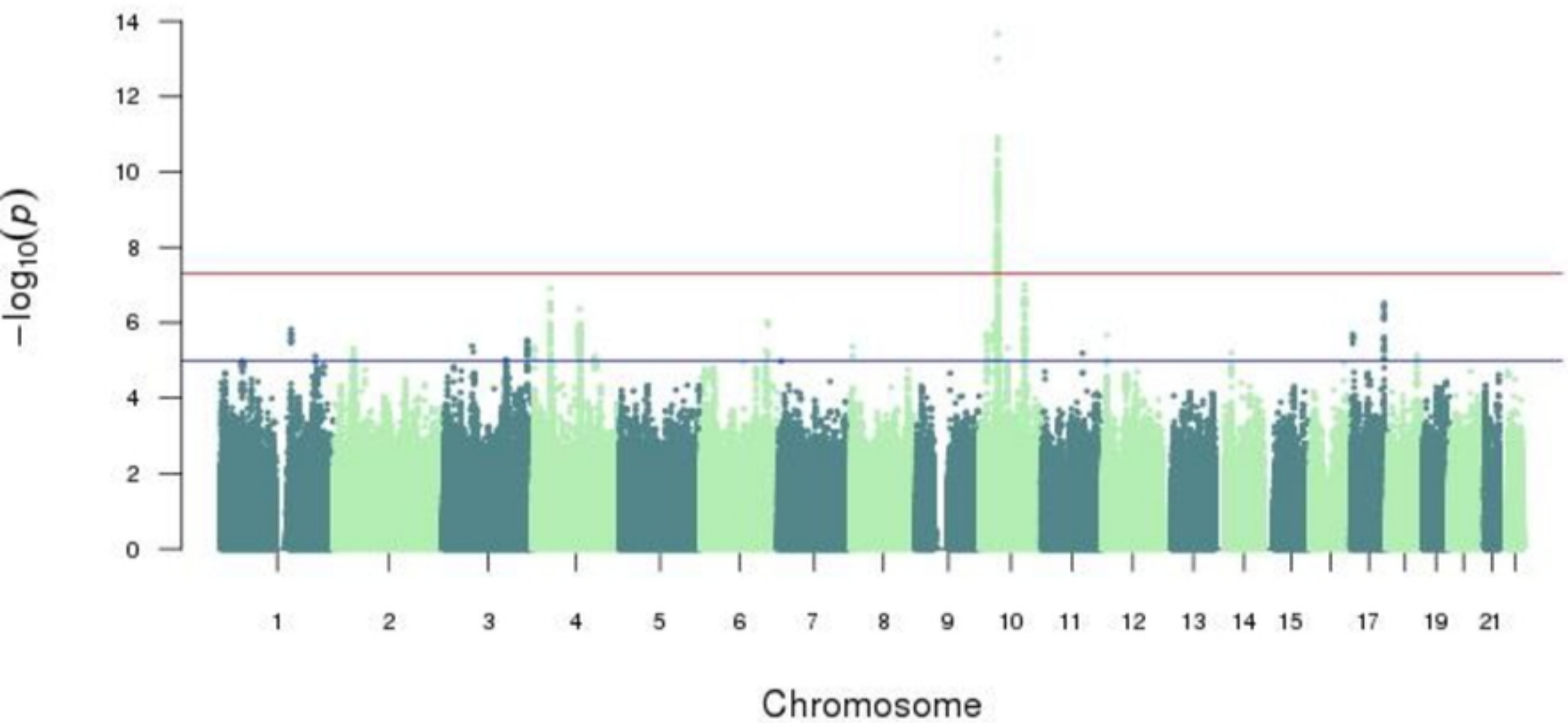
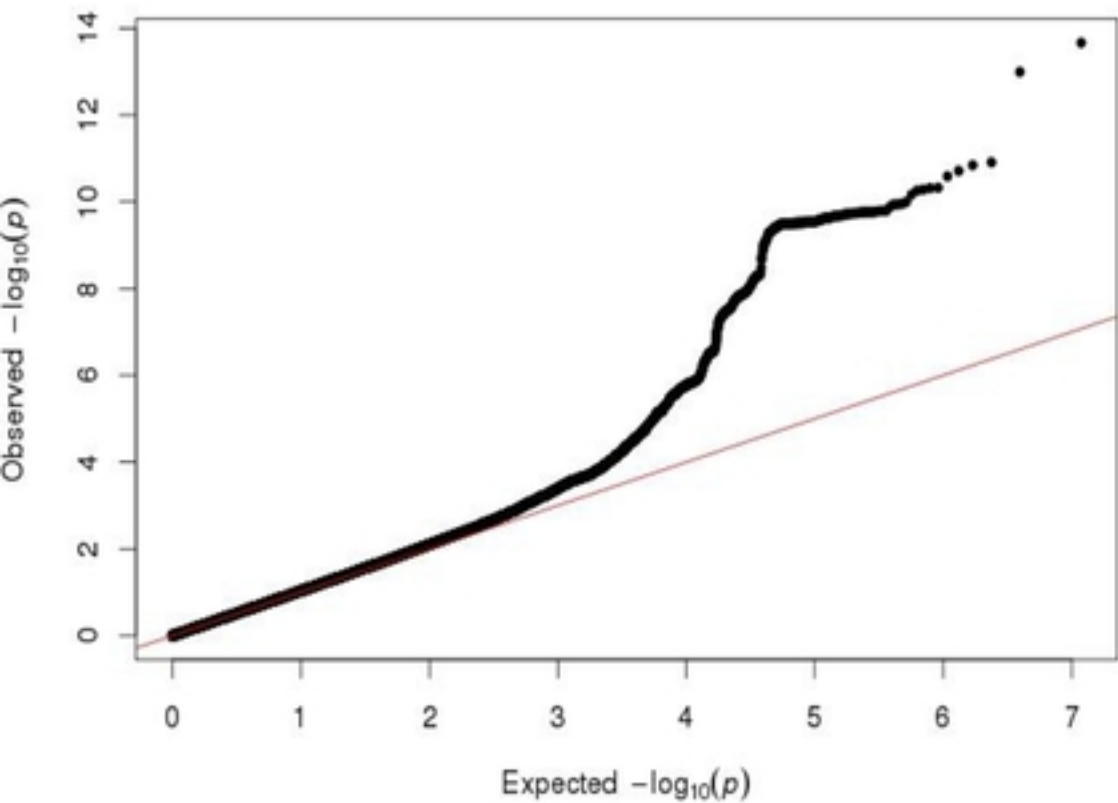


Figure 1

Q-Q plot of Hannum-EAA GWAS p-values



Q-Q plot of Horvath-EAA GWAS p-values

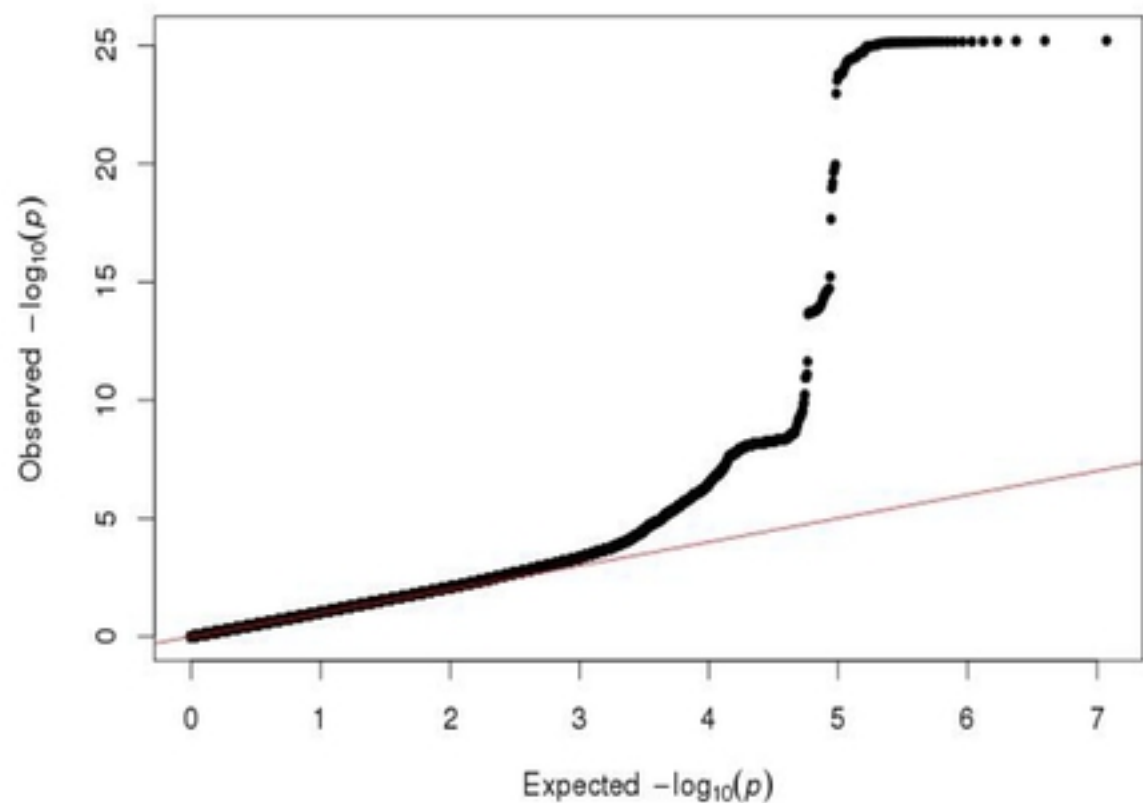


Figure 2