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A GWAS in Latin Americans highlights the convergent evolution of lighter skin pigmentation in Eurasia

Kaustubh Adhikari et al.#

We report a genome-wide association scan in >6,000 Latin Americans for pigmentation of skin and eyes. We found eighteen signals of association at twelve genomic regions. These include one novel locus for skin pigmentation (in 10q26) and three novel loci for eye pigmentation (in 1q32, 20q13 and 22q12). We demonstrate the presence of multiple independent signals of association in the 11q14 and 15q13 regions (comprising the GRM5/TYR and HERC2/OCA2 genes, respectively) and several epistatic interactions among independently associated alleles. Strongest association with skin pigmentation at 19p13 was observed for an Y182H missense variant (common only in East Asians and Native Americans) in MFSD12, a gene recently associated with skin pigmentation in Africans. We show that the frequency of the derived allele at Y182H is significantly correlated with lower solar radiation intensity in East Asia and infer that MFSD12 was under selection in East Asians, probably after their split from Europeans.
Hundreds of genes involved in pigmentation have been identified in animal models (http://www.espcr.org/micecut/) and mutations at some of these have been shown to cause rare human pigmentation disorders. Extensive association analyses have robustly identified polymorphisms at tens of pigmentation genes impacting on variation of skin, eye or hair color in humans, the great majority of these variants have been identified in European-derived populations. Recent analyses of non-European populations have suggested the existence of additional pigmentation variants, emphasizing the importance of a wider population characterization in order to obtain a fuller picture of the genetic architecture of pigmentation variation in humans. Since Darwin’s original proposal, it has been suggested that the evolution of pigmentation in humans (and other organisms) could have been shaped by some form of selection. In particular, the observation of a decrease in human skin pigmentation at increasing distance from the Equator has been interpreted as resulting from an adaptation to lower levels of ultraviolet radiation, consistent with the tanning response being a physiological skin-protection mechanism. As a corollary, it has been suggested that variation in eye and hair color in Western Eurasians could represent a by-product of natural selection on skin pigmentation. Alternatively, it has been proposed that variation in human pigmentation could have been affected by sexual selection, or a form of frequency-dependent selection, as appears to be the case in many other animals.

In agreement with these evolutionary scenarios, analyses of patterns of human genome diversity have found signals of selection at certain pigmentation loci. Interestingly, these signals were observed to only partially overlap between Europeans and East Asians, leading to the suggestion that variation in skin pigmentation could have evolved somewhat independently in Western and Eastern Eurasia. Among the genomic regions affecting pigmentation in Europeans, variants in OCA2 and MCIR restricted to East Asia have been shown to impact on skin pigmentation in populations from this geographical area. The fact that different alleles at these two genes impact on skin pigmentation in Western and Eastern Eurasia agrees with the evolutionary convergence of lighter skin color in these two regions. Thus, further analyses of pigmentation in East Asian-derived populations are of special interest for examining the genetic architecture and evolution of lighter skin pigmentation in Eurasia.

To this end, here we report a genome-wide association study (GWAS) of pigmentation in over 6000 Latin Americans, most with high Native American ancestry. It is well established that Native Americans are closely related to East Asians, the initial settlement of the New World starting some 15,000 years ago, through migration from Eastern Siberia into North America. We identified four novel associated regions involving skin or eye pigmentation. Follow-up analyses conditioned on six well-established pigmentation variants, emphasizing the importance of these two traits with skin pigmentation (blue/gray and green) were more common in Brazil (~40%) than in the other countries (~10%). In addition to eye color categories, we obtained quantitative variables related to perceived eye color from the analysis of digital photographs, using the HCL color space (hue, chroma, lightness). The frequency distributions of these variables are shown in Supplementary Figure 4. In contrast to the eye color categories, these quantitative color variables capture variation not only in the blue/gray to brown spectrum (mainly captured by H and L), but also variation within the brown spectrum (mainly captured by C). As H is a circular variable, it was standardized and converted to cos(H) before testing for association (see Methods). In what follows we contrast results for all the pigmentation phenotypes examined in the CANDELA individuals.

All the pigmentation phenotypes examined are significantly correlated (Supplementary Table 2A). Strongest correlation was observed between hair and categorical eye color (r = 0.50), while there is lower correlation of these two traits with skin pigmentation (r = 0.30 and r = 0.31, respectively). Lighter pigmentation of hair, skin and eyes is also significantly correlated with the genetic estimates of European ancestry (r ranging between 0.31 and 0.39, Supplementary Table 2B). Categorical eye color was strongly correlated with the L digital eye color variable (r = −0.78), but moderately correlated with cos(H) and almost uncorrelated with C (r of 0.40 and −0.08, respectively), highlighting the considerable amount of variation in the quantitative variables not captured by the eye color categories.

Results

Pigmentation features examined. Our study sample is part of the CANDELA cohort ascertained in five Latin American countries (Brazil, Colombia, Chile, Mexico and Peru; Supplementary Table 1). Information on skin, hair and eye color (iris) pigmentation (Figs. 1 and 2) was obtained for 6357 individuals. Skin pigmentation, measured using reflectometry by the melanin index (MI), showed extensive variation. The MI ranged from 20 to 65 (mean = 34.98 and SD = 5.34). The lightest mean pigmentation was observed in Brazil (32.04) and the darkest mean pigmentation in Mexico (36.32) (Fig. 1a). We have previously reported genome-wide association analyses of categorical hair color in the CANDELA sample. The most prevalent colors were black and brown, which account for ~80% of this sample. These are also the most prevalent categories across countries, except in Brazil where ~50% of individuals had dark blond/light brown or blond hair (Fig. 1b). Eye color was classified into 5 ordinal categories (1-blue/gray, 2-honey, 3-green, 4-light brown, 5-dark brown/black) by direct observation of the volunteers. The most common categories were dark brown/black and light brown, comprising ~85% of the sample (Fig. 1c). The lighter eye color categories (blue/gray and green) were more common in Brazil (~40%) than in the other countries (~10%).
Individuals were genotyped on Illumina Omni Express BeadChip. After quality control, we retained 674,971 single-nucleotide polymorphisms (SNPs) and 6236 individuals for the genetic analyses. Average continental admixture proportions in these individuals were estimated as: 48% European, 46% Native American and 6% African (Supplementary Figure 5). Based on a kinship matrix obtained from the SNP data, we estimated a narrow-sense heritability for skin color of 0.85 (SE 0.05) and of 1 (SE 0.05) for both hair and eye color. Similarly, quantitative eye color variables showed high heritability estimates (between 0.79 and 1.00, SE 0.06) (Supplementary Table 3). High heritabilities for pigmentation traits have also been estimated from family data.

Association analyses. The primary genome-wide association tests (Table 1) (using 8,896,142 genotyped and imputed SNPs) were performed using multivariate linear regression, as implemented in PLINK v1.9. We used an additive genetic model adjusting for age, sex and the first six principal components (PCs; Supplementary Figure 6A) obtained from genome-wide SNP data. Following up the primary GWAS results, and to account for phenotypic variation explained by known pigmentation loci, we...
performed GWAS analyses conditioned on six well-established pigmentation SNPs, which explain a large proportion of the phenotypic variance seen in our sample (Supplementary Table 5 and Methods): rs16891982 (SLC45A2), rs12203592 (IRF4), rs10809826 (TYRP1), rs1800404 (OCA2), rs12913832 (HERC2) and rs1426654 (SLC24A5). The association statistics showed no evidence of residual population stratification, except for skin pigmentation (genomic inflation factor $\lambda = 1.11$) (Supplementary Table 4A and Supplementary Figure 6B). We interpret this as resulting from a relatively high polygenicity of skin pigmentation, rather than from residual population stratification, as has been suggested by other studies. Consistent with this view, an analysis based on the Tail Strength statistic indicates modest but significant polygenicity for all the traits examined, with the highest values being observed for skin pigmentation (see Supplementary Table 4A and Methods).

Across all traits, we detected genome-wide significant association ($P$ values $< 5 \times 10^{-8}$) at SNPs in 12 genome regions (Table...
### Table 1 Features of index SNPs in genome regions associated with pigmentation traits in the CANDELA sample

<table>
<thead>
<tr>
<th>Region</th>
<th>SNP</th>
<th>Candidate gene</th>
<th>SNP annotation</th>
<th>Trait/Association (P value)</th>
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<tr>
<td></td>
<td></td>
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<td></td>
<td>Skin</td>
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<tr>
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</tr>
</tbody>
</table>

**Note:**
- Regional genomic significance is marked in bold. Genome-wide significant P-values (<5 × 10^{-8}) are in bold.
- MI: min misc, L: Lighness, C: Chroma, H: Hue.
- **a:** These SNPs were obtained through imputation. Their imputation quality info metric was >0.975, the median value being 0.993. The other SNPs were obtained from chip genotyping, and their concordance metric was >0.9, the median value being 0.981.
- **b:** These SNPs have been robustly associated with pigmentation traits in previous studies, and they explain a large proportion of the phenotypic variance in our sample (see Methods). These six SNPs were therefore used to condition the GWAS in subsequent analyses.
- **c:** The independence of association signals of these SNPs from the main index SNPs in the same regions was confirmed by conditioned analyses.

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Fig. 3 and Supplementary Figure 7). As expected from the gain of power provided by conditioning on known pigmentation loci with large effects in our sample, P values from the conditioned analyses (Supplementary Table 5) are smaller for each locus than those obtained in the unconditioned analyses (Table 1). This includes well-established pigmentation SNPs not used in conditioning (rs1042602 in TYR, rs885479 in MCIR; Table 1, Supplementary Table 5), which are expected to represent confirmed associations (the association P value for rs885479 in MCIR with skin pigmentation was only suggestive in the unconditioned analyses but became genome-wide significant in the conditioned analyses). Furthermore, in the unconditioned analysis the novel association in DSYTK was genome-wide significant only with eye color variable L, but in the conditional analysis this association is also genome-wide significant for eye color variable L.

Altogether, skin pigmentation showed association with SNPs in eight regions, of which: (i) five have been robustly replicated in previous studies in Europeans or East Asians26-29; (ii) one (19p13) has recently been associated with skin pigmentation in Africans5, but at different SNPs than seen here; and (iii) one (10q26) has not been previously reported. SNPs at four of the skin pigmentation regions were also found to be significantly associated with eye and hair color (in 5p13, 6p25, 15q3 and 15q21; Table 1). In addition, eye color shows association with SNPs in four other regions (in 1q32, 9p23, 20q13 and 22q12), of which three (in 1q32, 20q13 and 22q12) have not previously been reported. The genomic regions associated with categorical eye color showed stronger association with the quantitative eye color variables (Table 1), consistent with the greater statistical power for association testing of the quantitative color variables extracted from the digital photographs, compared with the categorical variables.

Other than these primary genome-wide SNP association tests, we performed two types of secondary analyses. Firstly, we examined association for each index SNP in the newly associated regions (i.e., the variant with the lowest P value within a region) in each country sample separately, and combined results as a meta-analysis (Supplementary Figure 8). For all SNPs, significant effects were in the same direction in all country samples, the variability of effect reflecting sample size. Secondly, we combined all phenotypes in a single multivariate association analysis, seeking to exploit the correlation between traits (Supplementary Table 6). As expected, index SNPs with effects across phenotypes were found to be significantly associated in this combined analysis (P value < 5 × 10^{-8}), whereas SNPs that only affected one trait were not associated at genome-wide significance, consistent with a reduced power under this scenario^{40}.

We evaluated the presence of multiple, independent, signals of association at each genomic region highlighted in the primary GWAS by performing step-wise regression (using the same model as in the primary analyses), conditioning on the index SNP at each region (Table 1). Evidence of genome-wide significant association was abolished for all regions except 11q14 and 15q13, where a total of three and five independent signals were detected, respectively (Table 1). These two regions include, respectively, the GRM5/TYR and OCA2/HERC2 genes. SNPs in these regions have been robustly associated with pigmentation traits by previous analyses, including a number of GWAS and candidate gene studies^{42,27,31}. However, since the SNPs examined in these reports often differ, the independence of these SNPs’ effects has not been systematically evaluated. Consistent with our findings, two independent signals of association in 11q14 have been reported in a GWAS for skin pigmentation in the African/European admixed population of Cabo Verde^{32}. Seven of the eight independently associated SNPs detected here impact on skin pigmentation (the exception being rs4778249 in 15q13). In addition to the effect on skin pigmentation of the three associated SNPs in GRM5/TYR, two (rs1042602 and rs7186777) were also associated with hair pigmentation, and one (rs1126809) with eye color (Table 1). The five independently associated SNPs in OCA2/HERC2 impact on eye color variation, with one of these SNPs also impacting on hair color (rs12913832). Genome
Fig. 3 Summary of GWAS findings. Results are presented for six pigmentation traits: skin melanin index (MI, quantitative), categorical hair color, categorical eye color, and three quantitative eye color variables extracted from digital photographs: L (lightness/brightness), C (chroma/saturation) and cos H (cos hue/tone). These traits are represented on the right. The HCL color space with the three axes of variation is shown in the inset. To provide a global summary of the results, a composite Manhattan plot is presented at the bottom combining significant signals for all the traits. Horizontal lines indicate the suggestive (blue line, \( P \text{ value} = 1 \times 10^{-5} \)) and significant (red line, \( P \text{ value} = 5 \times 10^{-8} \)) thresholds. The y-axis was truncated at \(-\log_{10}(P \text{ value}) = 14\). Index SNPs in each region are listed above the Manhattan plot. The association of these SNPs with specific traits is represented by colored boxes at the top: a box is shown if a SNP is associated with that trait (Table 1). Box colors correspond to colors assigned to each chromosome in the Manhattan plot, with slight variation when multiple independent hits were observed on the same chromosome. Novel genomic regions are marked with an asterisk.
annotations suggest that these eight independently associated SNPs could have separate functional relevance (Table 1). Four occur in exons, of which three result in non-conservative amino-acid substitutions and one (rs1800404) encodes a synonymous substitution (in exon 10 of OCA2) and is located in a conserved binding site for transcription factor YY1 (known to regulate pigmentation in animal models). The allele associated with lighter skin pigmentation at rs1800404 has also been associated with a shorter OCA2 gene transcript that is missing exon 10 and codes for a protein missing a transmembrane region. The other four independently associated SNPs are located in introns of GRM5/TYR or OCA2/HERC2. For one of these (rs12913832), intronic within HERC2, there is strong experimental evidence indicating that it regulates transcription of the neighboring OCA2 gene.

Figure 4 summarizes the allelic effects and derived population allele frequencies for the 18 index SNPs identified here. Most of these show large differences between continental populations, with the frequency in the CANDELA sample being intermediate.
Fig. 5 Heatmaps of statistical interactions between the 18 index SNPs identified here. Each panel corresponds to a different trait. The lower left triangle represents $-\log_{10} P$ values for the interaction term included in the regression model (with the color scale shown at the top). The upper right triangle represents regression beta-coefficients for each interaction term, colored from blue (negative effect) to white (no effect) to red (positive effect). As the scale for each trait is different, separate scales for effect sizes are shown next to each panel. Interactions that are significant (after Bonferroni correction) are marked with a black dot.
Fig. 6 Regional association (LocusZoom) plots for SNPs in the five genomic regions showing novel genome-wide significant associations to pigmentation traits. Chromosomal location and trait are specified in the title of each panel. In each region, index SNPs (Table 1) are highlighted with a purple diamond. Colors for other SNPs represent the strength of LD between that SNP and the index SNP (in the 1000 Genomes AMR data). Local recombination rate in the genomic coordinates (in Mb, using the NCBI human genome sequence, Build 37, as reference) are shown in the middle of each panel. At the bottom is shown a pairwise LD heatmap across all SNPs in a region (using r², ranging from red indicating r² = 1 to white indicating r² = 0).

Interaction of SNPs independently associated with pigmentation. We examined interaction between the index SNPs of Table 1 by testing regression models including all possible pairs of SNPs, adjusting for age, sex and the first six PCs, as in our primary association analysis. A number of significant interactions were detected at a multiple-testing corrected P value threshold of 3.3 x 10⁻⁴ (Fig. 5). A different pattern of interactions was observed for skin, relative to hair or eye pigmentation. In the case of skin pigmentation, significant interactions were seen mainly between SNPs that, individually, have strong effects (in SLC45A2, SLC24A5, HERC2/OCA2 and TYR/GRM5). By contrast, for hair and eye color, SNPs in the regions with strongest individual effects (SLC45A2, SLC24A5 and HERC2/OCA2) showed significant interaction with SNPs at most other pigmentation-associated regions. This included regions that individually do not have a significant effect on a particular trait (e.g., MC1R and MFSD12 with hair or eye pigmentation, respectively). These results are in line with other analyses of epistasis for pigmentation traits.

Candidate genes in genome regions showing novel association signals. The 10q26 region that is newly associated with skin pigmentation shows genome-wide significant association with a linkage disequilibrium (LD) block of SNPs spanning ~100 Kb, within an intergenic region of ~400 Kb (Fig. 6). Genome annotations indicate that this region overlaps an open chromatin segment that is highly conserved evolutionarily and includes several transcription factor binding sites (Supplementary Figure 9). The derived allele for the index SNP (rs11198112) is associated with darker skin pigmentation, in contrast to the effect of the majority of variants associated with skin pigmentation (Fig. 4). The derived allele is segregating at low to moderate frequency across many populations, but reaches its highest frequency (>50%) in Native Amazonians and Melanesians (Supplementary Figure 10). The index SNP is included in the binding site for transcription factor EBF1 (early B-cell factor). If the effect of this SNP is mediated through regulation of nearby genes, of potential interest is the gene encoding for the transcription factor (empty spiracles homeobox 2), which flanks the associated...
relative to other cell types, and is also expressed in human skin (Supplementary Figure 12C), we examined the cellular expression of MFSD12 in normal human skin using immunohistochemistry. MFSD12 was detected in the cytoplasm of a subpopulation of melanocytes in the epidermis (Fig. 7), possibly reflecting expression of this protein at a particular maturation stage of skin melanocytes. By contrast, no expression was detected in hair bulb melanocytes of anagen scalp hair follicles.

Of the three novel regions associated with quantitative digital eye color variables, the one in 1q32 is characterized by substantial LD over a region of ~300 Kb (Fig. 6) and is associated with the L and C variables (Table 1 and Fig. 4). Strongest association is seen for markers overlapping the DSTYK gene (dual serine/threonine and tyrosine protein kinase), the index SNP (rs3795556) being located in the 3′ untranslated region of the DSTYK transcript. Expression studies have shown that MITF regulates the expression of DSTYK in melanocytes. The 20q13 region associated with the cos(H) variable shows strong LD over a region of ~200 Kb. Strongest association is seen for SNPs overlapping the WDFCS (WAP Four-Disulphide Core Domain 5, Fig. 6), with the index SNP (rs17422688) leading to a histidine for tyrosine substitution (H97Y) in a highly conserved region (based on GERP and Siph conservation metrics). This amino-acid change is predicted to affect protein function, as implied by low SIFT (0.03) and high PolysPhen2 (0.81) scores. WDFCS is highly expressed in skin tissues (Supplementary Figure 12D). Several WAP Four-Disulphide Core Domain genes have been shown to be expressed in the human iris. SNPs in 22q12 associated with the C variable show LD over a region of ~100 Kb (Fig. 6). The index SNP (rs5756492) is located in the second intron of the gene encoding Mercaptopteryridine Sulfurtransferase (MPST), an enzyme playing a role in cyanide detoxification and cellular redox regulation. MPST is expressed in the skin (Supplementary Figure 12E) and the human iris.

![Fig. 7 Immunohistochemical analysis of MFSD12 protein expression in the epidermis of human scalp. MFSD12 expression (green fluorescence) was detected in multiple skin cell types (a, b). MFSD12 expression levels were higher in melanocytes (identified with an anti-melanocyte antibody in red fluorescence) than in adjacent keratinocytes (green only). Co-localization of both MFSD12 and the melanocyte-specific protein gp100 expression can be seen in yellow/orange fluorescence (arrow). Insets show higher magnification views of arrowed MFSD12-expressing melanocytes in skin epidermis. c A proportion of keratinocytes in scalp hair follicle from the same tissue also expressed MFSD12 (green only). By contrast with the skin, MFSD12 expression was not detected in hair melanocytes (i.e., seen as red fluorescence only indicating gp100 protein expression). d Positive control (human kidney). Note MFSD12 expression in kidney tubular cells (arrow). Scale bars: a, b = 50 μm. c = 15 μm, d = 30 μm

region (Fig. 6). Mouse experiments have shown that Emx2 regulates the expression of Mitf (a key regulator of melanocyte development and survival) as well as of Tyr and Tyrp-1 (two melanocyte-specific genes responsible for melanin production). In addition, this gene has been recently associated to tanning response in Europeans.

SNPs showing genome-wide significant association in the 19p13 region span ~100 Kb and show strongest association for SNP rs2240751 located in the third exon of the major facilitator superfamily domain containing 12 (MFSD12) gene (Table 1, Fig. 6). Variants in this region have recently been associated with skin pigmentation in Sub-Saharan Africans. The index SNP in the CANDELA data (rs2240751) leads to a tyrosine for histidine substitution at amino-acid 182 of MFSD12 (Y182H), which is common in East Asians and Native Americans but rare elsewhere (Fig. 4, Supplementary Table 7, Supplementary Figure 11). This variant occurs in a highly conserved sequence (as indicated by Genomic Evolutionary Rate Profiling (GERP) and Site-specific Phylogenetic (SiPhy) metrics) and the replacement of a polar for a basic amino acid could affect the function of the protein, as indicated by low Sorting Intolerant from Tolerant (SIFT; <0.01) and high Polymorphism Phenotyping v2 (PolyPhen2; >0.99) scores. Functional analyses indicate that MFSD12 is involved in lysosomal biology and that it can alter pigmentation coloration in animal models. Since MFSD12 is highly expressed in melanocytes

Evidence for selection at pigmentation-associated regions. Previous studies have detected signatures of selection around several pigment genes. In agreement with those analyses, we found strong signals of selection in Europeans (CEU) and East Asians (CHB) from the 1000 Genomes (1KG) Project at most of the pigmentation-associated regions replicated here (Supplementary Figure 13 and Supplementary Table 8). Often the associated SNPs do not show the strongest selection signals, which suggests that selection may have acted on other nearby SNPs (Supplementary Figure 13). Highly significant signals of selection were also detected in three of the five novel pigmentation regions identified here, with the strongest signals being observed in the MFSD12 region in East Asians (Fig. 8a). More generally, we also detected a significant enrichment of maximum Population Branch Statistic (PBS) and Integrated Haplotype Score (iHS) scores at genomic regions showing at least suggestive association (i.e., those including SNPs with P values < 10^{-5}) compared to the rest of the genome (Supplementary Table 9).

Selection for skin pigmentation has been proposed to relate to adaptation to solar radiation. Consistently, a correlation between allele frequencies at certain skin pigmentation-associated SNPs with solar radiation levels has been reported in the Human Genome Diversity Project (HGDP) population panel. We re-evaluated this correlation for the index SNPs of Table 1 in a dataset we compiled including 64 native populations from around the world (excluding the HGDP panel; Supplementary Table 10). Allele frequencies at four SNPs showed a significant correlation with solar radiation (Supplementary Table 11). Three of these SNPs are in gene regions replicated in the CANDELA sample (rs12913832 and rs1800404 in the HERC2/OCA2 gene region and rs885479 in MCIR). The fourth is the index SNP at MFSD12
which showed a strong correlation with solar radiation in Eastern Eurasia ($\log_{10}(BF) = 2.32$, $P$ value = 0.004; $\rho = -0.28$, $P$ value = 0.047) (Fig. 8b, c).

Considering the evidence for selection in the MFSD12 region in Eastern Eurasians, we estimated the time since the start of selection and the selection coefficient for this region in the CHB dataset from 1KG using an approximate Bayesian computation (ABC) approach (Supplementary Figure 14, 15 and 16 and Methods). We obtained a median estimate for the selection coefficient of 1.15% (95% credible interval 0.08%–4.4%) and a median age for the start of selection of 10,834 year ago (95% credible interval of 5266–33,801 years ago).

Discussion

The analyses presented here highlight the complex genetic architecture of pigmentation variation in Latin Americans, with multiple gene regions as well as multiple independent variants at the OCA2/HERC2 and GRM5/TYR regions, and several epistatic interactions, affecting pigmentation variation. Since the history of the New World involved the extensive admixture of Native Americans, Europeans and Africans, it is to be expected that variants impacting on pigmentation in those continental populations are segregating in Latin America. Further, since Native Americans trace their ancestry to East Asia, it is likely that certain pigmentation variants present in Latin Americans should be shared with East Asians. Consistent with this scenario, we replicate 7 allelic variants that have been previously associated with pigmentation phenotypes in Europeans and one variant previously reported in East Asians (rs885479 in MC1R). It seems likely that we did not detect some of the other variants previously associated with pigmentation variation in Old World populations due to a combination of factors affecting power across studies. For instance, some of the reported variants could have high frequency in Old World populations that did not contribute to admixture in Latin America. Dissimilarities in phenotype assessment approaches and in trait definitions are also likely to explain some of the differences in association results across studies. For example, GWAS carried out in Europeans have mostly focused on variation in the brown to blue color spectrum. By contrast, the C (saturation) color component examined here, with which two new loci have been associated, captures variation within brown eyes (Fig. 2b) and the index SNPs at these loci have highest derived allele frequencies in East Asians (Fig. 4).

The convergent evolution of lighter skin pigmentation in Western and Eastern Eurasia stems partly from allelic heterogeneity at two well-established pigmentation genes initially identified in Europeans: OCA2 and MC1R. In addition to allelic heterogeneity at these two genes, here we identify rs224071 at
MFSD12 as another pigmentation variant specific to populations of East Asian/Native American ancestry. This gene region has been recently implicated in a study of skin pigmentation variation in Sub-Saharan Africans. Strongest association in that study was seen for synonymous and intronic SNPs in MFSD12, variable only in Africans, and in an upstream regulatory region, variable in Africans and South and South East Asians, but not in Europeans or East Asians. By contrast, we found that in our sample the strongest association with skin pigmentation is seen for the Y182H amino-acid substitution in MFSD12, a variant seen at high frequency only in East Asians and Native Americans. It is thus likely that this variant rose in frequency in East Asia and was carried into the Americas during Native American migrations. This establishes MFSD12 as an additional gene involved in the convergent evolution of lighter skin pigmentation in Eurasians.

Furthermore, consistent with what is observed at several other pigmentation gene regions, we observe a strong signal of selection in this gene region in East Asians (dated after their split from Europeans), and a correlation of the frequency of the MFSD12 Y182H variant with solar radiation levels in East Asia (Fig. 8). The pattern of variation at MFSD12 is thus reminiscent of what is observed for certain pigmentation genes in Europeans (e.g., OCA2 or SLC45A2). Associated SNPs at those genes are polymorphic mainly in Europeans, show strong signals of selection and a correlation of derived allele frequencies with latitude.

Our estimate of the selection coefficient for MFSD12 is best viewed in the context of estimates for other pigmentation loci. Beleza et al. used forward Monte Carlo simulations coupled with a rejection algorithm to estimate the selection coefficient at four pigmentation genes. Under an additive model, the selection coefficient for KITLG (rs642742 G allele) in Europe and East Asia was estimated to be 0.02, whereas the coefficients for TYR (rs2733831 G allele), SLC45A2 (rs16891982 G allele) and SLC24A5 (rs13426654 A allele) were estimated to be 0.03, 0.04 and 0.08, respectively. López et al. estimated the selection coefficient of SLC45A2 (rs16891982 G allele) to be 0.01 to 0.02 in a South European population. Similarly, using an ancient DNA forward simulation approach restricted to European populations, Wilde et al. estimated the selection coefficient of SLC45A2 (rs16891982 G allele), TYR (rs1042602 A allele) and HERC2 (rs12913832 G allele) to be 0.03, 0.03 and 0.04, respectively. The selection coefficient that we estimated (0.01) for MFSD12 thus lies at the lower end of those estimated for other pigmentation genes that appear to have been under selection. This result is in line with the relatively weaker phenotypic effect of MFSD12, relative to genes such as SLC45A2 and SLC24A5. Our estimate for the age since the start of selection (10,833 ya (95% CI of 5266–33,801 ya)) suggests that it would have started long after the split of proto-East Asians from proto-Europeans.

Considering the evidence for solar radiation having contributed to shape the diversity of certain genomic regions in Old World populations, it is interesting that we do not detect pigmentation variants private to the Americas in the CANDELA sample (with the caveat that we might be unable to detect the effects of rare local variants). The American continent shows extensive variation in solar radiation levels as its territory extends along a North–South axis encompassing circumpolar and Equatorial latitudes (Fig. 8c). However, Native Americans do not exhibit a variation in skin pigmentation like that seen in Old World populations living at similar latitudes. It has been suggested that this difference between continents might relate to cultural adaptations, environmental factors, or to another mechanism of biological adaptation, such as a better tanning ability.

It is possible that the lack of novel genetic adaptations to solar radiation levels in the Americas could relate to the relatively recent settlement of the New World, which started about 15,000 years ago. This recent settlement limits the time-span over which new genetic variants could have arisen and changed in frequency in response to selection pressures, particularly considering the magnitude of the selection coefficients that have been estimated for pigmentation associated loci.

**Methods**

**Study subjects.** We analyzed data for 6557 individuals from the CANDELA dataset (Brazil, Colombia, Mexico and Peru) (Supplementary Table 1, http://www.ucf.ac.uk/silva/canelda). All volunteers provided written informed consent. Ethics approval was obtained from: Universidad Nacional Autónoma de México (México), Universidad de Antioquia (Colombia), Universidad Peruvian Cayetano Heredia (Perú), Universidad de Tarapacá (Chile), Universidade Federal do Rio Grande do Sul (Brazil) and University College London (UK).

**Phenotype data.** A physical examination of each volunteer was carried out using the same protocol and instruments at all recruitment sites. Eye color was recorded in five categories (1-blue/grey, 2-honey, 3-green, 4-light brown, 5-dark brown/black). Hair color was recorded in four categories (1-red/brindle, 2-blond, 3-dark blond/light brown or 4-brown/black), as described in ref. 15. Individuals with red hair were excluded prior to the analyses, as it is a rare in our sample (frequency of 0.6%), and this phenotype is known to stem from rare variants in MC1R. A quantitative measure of constitutive skin pigmentation (the MI) was obtained using the Dermaspectrometer DSMEII reflectometer (Cortex Technology, Hadsund, Denmark). The MI was recorded from both inner arms and the mean of the two readings was used in the analyses. The MI was adjusted for variable color casts or illumination levels across images. For visually inspecting the skin color distribution corresponding to variation in MI (Fig. 1a), MI values were converted to approximate RGB (red, green, blue) values (Supplementary Figure 18).

In addition to a direct assessment of eye color into four categories, we obtained quantitative variables related to digital photographs of the study subjects (taken following a standardized protocol as described in ref. 39). One of the two eyes was selected based on image quality. Photographs were landmarked manually via a graphical interface designed in MATLAB (Supplementary Figure 1). Ten landmarks were used to delimit and extract the visible part of the iris. Additional landmarks were placed to select the whitest part of the sclera. This white reference and the darkest part of the pupil were used to normalize the image, adjusting for variable color casts or illumination levels across images. An adaptive threshold was then used to remove highlights such as reflections on the iris. The resulting images were individually checked for the presence of errors during the manual adjustments leading to their exclusion. In total, 5513 iris images were retained for extracting RGB pixel color values.

A set of 195 photos were landmarked independently by two raters to assess inter-rater variability in extracted iris color. The median absolute difference between the RGB color values of the two raters across the whole set was 3.3 units (Fig. 2d, scale of 0–255).

The multivariate median of the RGB values across all pixels was calculated in order to obtain average RGB values for an iris (Fig. 2d, Supplementary Figure 2). Such RGB values, or their principal components (Supplementary Figure 3C), have been used in certain genetic association studies. However, although the RGB color space is convenient for digital imaging, it is not necessarily appropriate in terms of human perception or biological relevance. Several other color spaces have therefore been considered in genetic studies of pigmentation. In particular, the HCL and CIE Lab color spaces have the advantage over RGB of being perception based. Furthermore, it has been shown that melanosome color is correlated with skin color; differences in the HCL and CIE Lab color spaces is that HCL, being directly derived from RGB, represents the three primary colors (red, green, blue) in opposing corners, while the CIE Lab represents four colors in different corners (red against green and blue against yellow). Since the HCL values in the CANDELA dataset occupy mainly the opposite red-orange and cyan-blue color hues (Fig. 2d), for this study we considered the HCL color space more informative than the nearly equivalent CIE Lab color space.

H is a circular variable representing color hue (tone) ranging from 0° to 360°, with red at 0°, green at 120° and blue at 240°. C (chroma or saturation) ranges from 0 to 1 (fully saturated color). L (lightness) ranges from 0 (black) to 1 (white). It was observed from the bicone color model (Fig. 2d) that the HCL values lie approximately on a two-dimensional plane passing through the vertical central axis at an angle of −20° (obtained from the circular median of H). H values were therefore standardized by subtracting 20°. Furthermore, since H is a circular variable, it was converted to cos(H) prior to its use for the analyses performed here. Cos(H) ranged from −1 (blue/grey eyes) to +1 (olive/brown/dark brown eyes). As the distribution of HCL values was nearly planar, sin(H) showed...
and used them to perform a conditioned GWAS. Searching online GWAS catalogs and published studies, we identified 161 SNPs that have been reported in previous association studies of pigmentation traits (Supplementary Table 12). Of these SNPs, 139 SNPs were present in the CANDELA imputed dataset (the rest being lost during QC). We obtained P values and proportions of trait variance explained for each of these 139 SNPs. We selected SNP variance was both genome-wide significant \((P < 5 \times 10^{-8})\) and explained a relatively large proportion of trait variance \((\text{proportion of } R^2 > 0.5\%)\, \text{Supplementary Table } 12\) to define a list of established pigmentation SNPs with strong effects in the CANDELA sample. If several of these SNPs were located in the same gene region (usually a region with strong LD), and in order to avoid collinearity, we retained only the most significant SNP. The following six SNPs met these criteria and were used to perform a conditioned GWAS: rs168191982 (SLC45A2), rs1220359 (Iryf3), rs108098826 (TPRY1), rs1800404 (OCA2), rs12913832 (HERC2) and rs1426654 (SLC24A5).

The polygenicity of the pigmentation traits examined in the CANDELA sample was evaluated using the tail strength \((T)\) statistic57, which measures the overall strength of polygenicity across the various traits examined in the dataset. The \(T\) statistic is related to other multiple-testing methods calculated on a set of \(P\) values, like the false discovery rate and the area under the curve. In a GWAS with \(n\) SNPs, if the ordered \(P\) values follow a uniform distribution, then \(T=0\), but as the distribution becomes more extreme, \(T\) increases, indicating greater polygenicity.

Under the null hypothesis of no association between the trait and all SNPs, \(T\) should equal 0. A positive value of \(T\) indicates that the overall effect of all SNPs is significant, with higher values of \(T\) indicating increasing greater polygenicity. We can approximate \(T\) by the GEDR (equivalent to taking a projection onto the plane) and those who failed the X-chromosome sex concordance check \((\text{sex estimated using } Y\text{-chromosome DNA data})\) for common pigmentation variation is an ideal setting in this study sample \(\text{(Supplementary Figure } 5\)\). There is in Hardy–Weinberg equilibrium, but is more direct since it is based on the genotype frequency, which unlike the \(P\) value does not depend on sample size. Only SNPs that satisfy these criteria across all genotyping platforms were retained55. The imputation ‘concordance’ score, which is a measure of genotyping quality, was also used to select single nucleotide polymorphisms (SNPs) \(\text{(see below)}\). Finally, subsequent to the GWAS analyses \(\text{(see below)}\), the genotyping cluster plots for the index SNP identified were checked manually to verify genotyping quality.

Statistical genetic analyses. Narrow-sense heritability \((\text{defined as the additive polygenic variance explained by a genetic relatedness matrix (GRM) computed from the SNP data})\) was estimated using the software GCTA by fitting an additive linear model with a random effect term whose variance is given by the GRM (with age and sex as covariates). The GRM was obtained using the LDcorrect algorithm, which accounts for LD between SNPs. An LD-pruned set of 160,858 autosomal SNPs was used to estimate ancestral allele states from information present in the 1000 Genomes data VCF files \(\text{(ensuring that all genome-wide and suggestive SNPs from the primary analysis are included)}\) (Supplementary Table 6). A meta-analysis was carried out for the novel index SNP identified in the primary analyses \(\text{(Table 1)}\) by testing for association separately in each country sample. Forest plots were produced with MATLAB 3.2.5 combining all regression coefficients and standard errors. Histograms of the traits within each country were compared to the Forest plots to examine how trait variability across countries relates to the association signals.

Selection analyses. We computed three selection statistics: the PBS99, iHS70 and Tajima’s \(D72\). Since we were mainly interested in the convergent evolution of pigmentation in West and East Eurasia, we restricted this analysis to CEU and CHB data from the 1000 Genomes Project. PBS scores for CEU were computed using CHB and YRI as reference and for CHB using CEU and YRI as reference. Pairwise \(FST\) were estimated using Reynolds equation76 using only SNPs that were polymorphic in at least two populations. The total number of SNPs with PBS scores \(\text{and CHB and CHB was } <8,000,000. \text{We calculated } \text{iHS using the software selassoc73. Ancestral allele states were retrieved from information present in the 1000 Genomes data VCF files (AA (ancestral allele) field) and SNPs with no ancestral allele state were discarded. Unstandardized iHS scores were only estimated for SNPs \(\text{and Phen2Sel77 scores. We also queried transcription levels for candidate genes in newly associated regions across all 53 human tissues included in the GTEx database46.}\)

Comparison of SNP imputation quality. We evaluated which imputation algorithm \(\text{impute2 provides a ‘concordance’ metric for chip genotypes, obtained by masking the SNP genotypes and imputing it using nearby chip SNPs. Genotyped SNPs having a low concordance value <0.7 or a large gap between info and concordance values (info_type0 = concord_type0 = 0), two suggested indicators of poor genotyping quality, were also removed. Median concordance values of the remaining chip SNPs was 0.994. After quality control (QC), the final imputed dataset contained genotypes for 9,143,600 SNPs.\)
frequencies and subtracting the mean and dividing by the standard deviation to obtain a final standardized statistic with a mean of 0 and variance of 1. The HapMap-2R037 genetic map was used to obtain genetic distances between SNPs. The final total number of SNPs in CEU and CHB was ~3,000,000. We calculated Tajima’s D using VCFTools18 on non-overlapping windows of 10 kb and discarded windows that contained less than 5 SNPs. The final total number of windows for CEU and CHB was ~266,000. We computed empirical P values using an outlier approach that ranks the genome-wide score for the number of values in the distribution, taking the upper tail for PBS and IHS and the lower tail for Tajima’s D selection scores. Throughout the text we considered SNPs with significant selection scores as those with empirical P values lower than 0.01.

To test an enrichment signal in genomic regions associated to pigmentation traits we first estimated haplotype blocks in the CANDELA sample using the definition of haplotype blocks implemented in PLINK 1.92. When constructing haplotype blocks, only pair of SNPs within 500 kb of each other were considered. For each haplotype block we then estimated the maximum PBS and IHS scores computed in the CEU and CHB populations, and retained only haplotype blocks with at least 5 SNPs. We then contrasted the distribution of maximum PBS and IHS scores at the haplotype blocks containing associated SNPs (i.e., those including SNPs with P values < 10\(^{-5}\)) with the distribution of maximum PBS and IHS scores at haplotype blocks in the rest of the genome. We tested the significance of the difference between distributions using a one-sided Mann–Whitney U-test. We did not use Tajima’s D selection scores to perform this enrichment analysis, as this selection statistic is computed in sliding windows (see above) and the windows would sometimes overlap two consecutive haplotype blocks.

To evaluate the possible correlation of allele frequencies at pigmentation genes with solar radiation levels we examined publicly available data for 64 native populations without evidence of recent admixture (Supplementary Table 10). All samples included a minimum of 10 individuals. Surface solar radiation data were obtained from the NASA Surface meteorology and Solar Energy (SSE) Web site (https://eosweb.larc.nasa.gov/sse/) in kWh/m\(^2\)/day units. These data included annual solar radiation averages from July 1983 to June 2005 on a 1-degree resolution grid over the globe. Annual solar radiation values were obtained for each population based on published coordinates for sampling locations. In cases of unpublished sampling location, we obtained this information directly from the authors or used approximate coordinates such as the middle of the town/or the sampling location. We used Bayenv\(^{2,5}\) to estimate Bayes Factors (BFs) relating solar radiation to allele frequencies at index SNPs. These BFs provide a measure of the increase in the fit of allele frequencies to a linear regression model including solar radiation levels over a null model including only population structure as predictor. The null model was constructed using a covariance matrix of allele frequencies between populations estimated from 10,000 random SNPs (not in LD) after 100,000 Markov chain Monte Carlo iterations. In addition to BFs we estimated Spearman’s rank correlation coefficient (ρ). We ranked the SNPs based on their BFs, and absolute ρ, to obtain empirical P values. The allele frequency at a SNP was only considered to be significantly associated to solar radiation if both BF and ρ estimates showed significance as recommended in Bayenv\(^2\). As the effect of pigmentation genes could differ between geographic regions, we also conducted separate analyses for Africans, Western Eurasians (including North Africans) and Eastern Eurasians (Supplementary Table 10 lists the populations included in each region).

To estimate the selection coefficient and the time since the start of selection at SNP (\(ρ_{2240751}\)), we used an ABC approach. We used msms\(^{76}\) to perform coalescent simulations modeling the demographic history of African, European and East Asian populations (for details of the parameters of the demographic model used, see ref.\(^{77}\) and Supplementary Note 1). We assumed that the minor allele frequency at the time of selection was 1% in Europeans and East Asians and 0.1% in Africans. We simulated 10,000 simulations (prior to PLS analysis, summary statistics were Box-Cox transformed) to identify the most informative statistics based on a subset of the derived allele frequency of the selected variant. We used partial least squares (PLS) to identify the most informative statistics based on a subset of 10,000 simulations (prior to PLS analysis, summary statistics were Box-Cox transformed so that their minimum values were between 1 and 2). For parameter inference we used the PLS-component that they carried the most information for each parameter (estimated using the root mean squared error) (Supplementary Figure 14). Estimation of parameters was performed using the abc R package\(^{28}\). We selected the top 0.5% simulations based on the smallest Euclidean distance between the observed and simulated summary statistics. From these quantities, we obtained the posterior probability distributions for the selection coefficient and the time since selection, and ranked the posterior median and the 95% credible intervals. We examined the accuracy of the ABC parameter estimates using the predicted error (i.e., the mean square error divided by the prior variance of the parameter) based on a leave-one-out cross-validation of 100 observations (Supplementary Figure 15).

Plots for the selection analyses were made in R.

**Immunohistochemistry of MFSD12.** Unshaven, full-thickness normal human adult scalp with terminal hair growth was used snap frozen in liquid nitrogen in cubes of 2 cm\(^3\). Cryosections of 6–8 µm were cut using a cryostat onto adhesive glass slides and stained with primary antibody against human C19Orf28/MFSD12 gp100. Quality testing of the antibody’s specificity was assessed using commercially obtained sections of human kidney tissue as a positive control. IgG isotype controls were used at the same concentration as the lowest primary antibody dilution. Co-distribution and co-localization of both antigens in the skin and the growing hair follicle were determined if there was merging of the MFSD12 (green-) and gp100 (red)-positive channels to give yellow/orange color. Human skin tissue used in this study was obtained with informed consent and with ethics committee approval.

**Data availability**

Raw genotype or phenotype data cannot be made available due to restrictions imposed by the ethics approval. Summary statistics from the GWAS analyses is deposited at GWAS central with the link http://www.gwascentral.org/study/HGVST3308 (to be available upon next release in Spring 2019).

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Author contributions


Additional information

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