

Genetic analysis of quantitative traits in medaka fish and humans

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Chapter 1

About

Code to render PDF:

```
bookdown::render_book("book", bookdown::pdf_book())
```

Code to render PDF with different fonts:

First make the bookdown::pdf_book: entry in _output.yml first.

Then...

```
bookdown::render_book("book")
```

To clean up the references:

```
citr::tidy_bib_file(rmd_file = c("book/index.Rmd",
                                 "book/01-Introduction.Rmd",
                                 "book/02-MIKK_genome.Rmd",
                                 "book/03-Pilot.Rmd",
                                 "book/04-MIKK_F2.Rmd",
                                 "book/06-Fst.Rmd",
                                 "book/07-references.Rmd"),
messy_bibliography = "book/book.bib",
file = "book/tidy_references.bib")
```

Test to understand which commands are creating errors:

```
bookdown::render_book("book",
                      bookdown::pdf_book(pandoc_args = "--listings",
                                         latex_engine = "xelatex",
                                         biblio_style = "apalike",
                                         csl = "chicago-fullnote-bibliography.csl",
                                         includes = rmarkdown::includes(in_header =
                                         documentclass = "book",
```

```
sansfont = "Georgia",
monofont = "Andale Mono",
highlight = "pygments",
fontsize = "9pt"))
```

citation_package = "natbib" throws an ugly error, and ends up removing all references in the document.

Weirdly, fonts only change if they go in index.Rmd.

1.1 bs4_book

```
bookdown::render_book("book",
  bookdown::bs4_book(css = "style.css",
    theme = list("primary" = "#52002E"),
    repo = list("base" = "https://github.com/rstudio/bookdown"),
    includes = rmarkdown::includes(in_header),
    footnotes_inline = T,
    bibliography = "book.bib"))
```

This is a *sample* book written in **Markdown**. You can use anything that Pandoc's Markdown supports; for example, a math equation $a^2 + b^2 = c^2$.

1.2 Usage

Each **bookdown** chapter is an .Rmd file, and each .Rmd file can contain one (and only one) chapter. A chapter *must* start with a first-level heading: # A good chapter, and can contain one (and only one) first-level heading.

Use second-level and higher headings within chapters like:
A short section or ### An even shorter section.

The index.Rmd file is required, and is also your first book chapter. It will be the homepage when you render the book.

1.3 Render book

You can render the HTML version of this example book without changing anything:

1. Find the **Build** pane in the RStudio IDE, and
2. Click on **Build Book**, then select your output format, or select “All formats” if you’d like to use multiple formats from the same book source files.

Or build the book from the R console:

```
bookdown::render_book()
```

To render this example to PDF as a `bookdown::pdf_book`, you’ll need to install XeLaTeX. You are recommended to install TinyTeX (which includes XeLaTeX): <https://yihui.org/tinytex/>.

1.4 Preview book

As you work, you may start a local server to live preview this HTML book. This preview will update as you edit the book when you save individual .Rmd files. You can start the server in a work session by using the RStudio add-in “Preview book”, or from the R console:

```
bookdown::serve_book()
```


Chapter 2

Introduction

2.1 A brief history of genetics

2.1.1 Ancient Greece

Humankind has long sought to understand the basis of biological variation. What gives rise to the wondrous variety of life forms on Earth? Why do individuals of a particular species differ from one another? How do children inherit traits that are similar to those of their parents, yet on the whole remain distinct from both their parents and their siblings? And are the traits we care about – our health, our intelligence, our ability to thrive in a changing world – pre-determined from birth, or continuously pliable throughout our lives?

Around 500 BC, the Ancient Grecian Pythagoras applied his understanding of triangles to this question, proposing the theory known as “spermism”. He posited that hereditary information was passed down from parent to child via male sperm, with the female only providing the nutrients that would allow it to grow, and, like the theorem that bears his name, that these two sides of the “triangle” the length of the third side: the characteristics of the child.¹

Over a century later, in 380 BC, Plato extended this metaphor in *The Republic* to argue that this principle could be applied to perfect humanity, by breeding perfect combinations of parents.

Aristotle joined the discussion with his treatise *Generation of Animals*, where he noted cases where human skin colour and other traits could

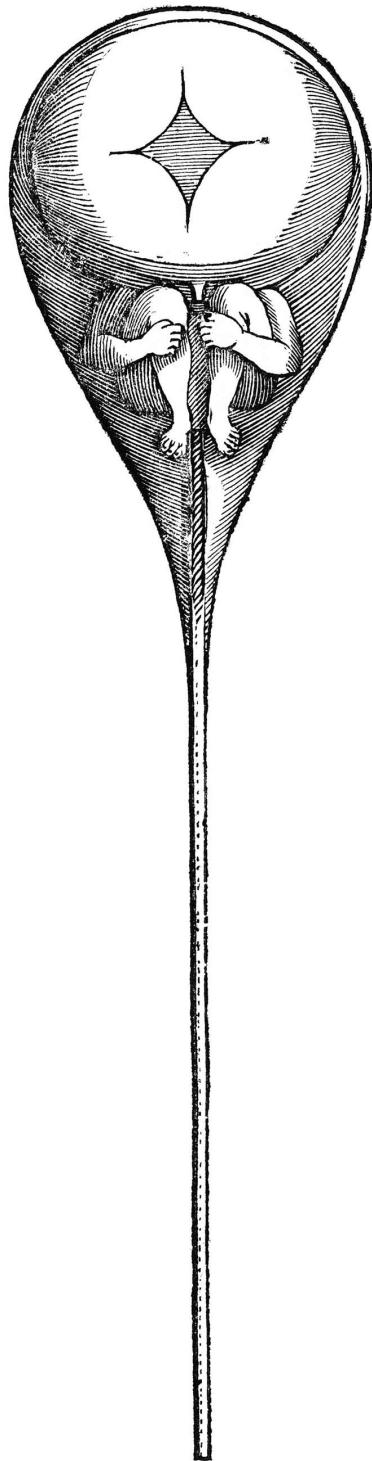
¹Siddhartha Mukherjee, *The Gene: An Intimate History* (Simon and Schuster, 2016), <https://books.google.com?id=XvAsDAAAQBAJ>.

skip generations, and thus hereditary information must not only be transmitted through sperm. He suggested an idea of “movement” – the transmission of information – from the father’s sperm, which sculpts the mother’s menstrual blood in the same way a carpenter carves a piece of wood.²

2.1.2 Medieval times

In medieval times, the prevailing theory was that a tiny human – a homunculus – sat within the sperm, waiting to be inflated upon its introduction to a woman’s uterus. However, this would require a homunculus to sit within another homunculus, *ad infinitum*, like Matryoshka dolls, all the way back to the Biblical first man, Adam. Even the inventor of the microscope, Nicolaas Hartsoeker, thought he saw one in a sperm he was studying.

²Mukherjee.



2.1.3 Charles Darwin and Gregor Mendel

In 1831, a young Charles Darwin boarded the HMS *Beagle* to embark on an expedition to collect specimens from South America. After collecting a huge number of fossils from the along the eastern coast and shipping them back to England, the *Beagle* spent 5 weeks touring through the 18 volcanic islands of the Galàpagos, where Darwin collected

Chapter 3

Genomic variations in the MIKK panel

This project was carried out in collaboration with Felix Loosli's group at the Karlsruhe Institute of Technology (KIT), and Joachim Wittbrodt's group in the Centre for Organismal Studies (COS) at the University of Heidelberg.

This chapter sets out my contributions to the the following pair of papers published in the journal *Genome Biology*, on both of which I am joint-first author:

- Tomas Fitzgerald et al.¹
- Adrien Leger et al.²

3.1 The Medaka Inbred Kiyosu-Karlsruhe (MIKK) panel

Biological traits are the product of an interaction between an organism's genes and its environment, often described as the relationship

¹"The Medaka Inbred Kiyosu-Karlsruhe (MIKK) Panel," *Genome Biology* 23, no. 1 (February 21, 2022): 59, <https://doi.org/10.1186/s13059-022-02623-z>.

²"Genomic Variations and Epigenomic Landscape of the Medaka Inbred Kiyosu-Karlsruhe (MIKK) Panel," *Genome Biology* 23, no. 1 (February 21, 2022): 58, <https://doi.org/10.1186/s13059-022-02602-4>.

between “nature and nurture”.³ This is especially true for complex traits such as behaviour, which I investigate in Chapters 4 and 5.

It is unfeasible to explore the relationship between genes and environment experimentally in humans due to the insufficient ability to manipulate either set of variables. Researchers accordingly resort to using model organisms, with which it is possible to control for both. The genetics of model organisms may be controlled to a degree by establishing inbred strains through the repeated mating of siblings over successive generations. Eventually, as the individuals within each line inherit the same same haplotype from their related parents, they become almost genetically identical to one another, with the added benefit that their genotypes can be replicated across time in subsequent generations. This utility has led to the establishment of “panels” of inbred strains for several model organisms including the thale cress (*Arabidopsis thaliana*),⁴ common bean (*Phaseolus vulgaris L.*),⁵ tomato (*Lycopersicon esculentum*),⁶ maize (*Zea mays*),⁷ nematode (*Caenorhabditis elegans*),⁸ fruit fly (*Drosophila melanogaster*),⁹ and mouse (*Mus musculus*).¹⁰

Although the mouse is an appropriate model for humans due to their orthologous mammalian organ systems and cell types, inbred strains of this organism descend from individuals that had already been

³ Robert Plomin and Kathryn Asbury, “Nature and Nurture: Genetic and Environmental Influences on Behavior,” *The ANNALS of the American Academy of Political and Social Science* 600, no. 1 (July 1, 2005): 86–98, <https://doi.org/10.1177/0002716205277184>.

⁴ Joy Bergelson and Fabrice Roux, “Towards Identifying Genes Underlying Ecologically Relevant Traits in *Arabidopsis Thaliana*,” *Nature Reviews Genetics* 11, no. 12, 12 (December 2010): 867–79, <https://doi.org/10.1038/nrg2896>.

⁵ William C. Johnson and Paul Gepts, “Segregation for Performance in Recombinant Inbred Populations Resulting from Inter-Gene Pool Crosses of Common Bean (*Phaseolus Vulgaris L.*)”, *Euphytica* 106, no. 1 (March 1, 1999): 45–56, <https://doi.org/10.1023/A:1003541201923>.

⁶ Vera Saliba-Colombani et al., “Efficiency of RFLP, RAPD, and AFLP Markers for the Construction of an Intraspecific Map of the Tomato Genome,” *Genome* 43, no. 1 (February 2000): 29–40, <https://doi.org/10.1139/g99-096>.

⁷ Anis M. Limami et al., “Genetic and Physiological Analysis of Germination Efficiency in Maize in Relation to Nitrogen Metabolism Reveals the Importance of Cytosolic Glutamine Synthetase,” *Plant Physiology* 130, no. 4 (December 1, 2002): 1860–70, <https://doi.org/10.1104/pp.009647>.

⁸ Kathryn S. Evans et al., “From QTL to Gene: *C. Elegans* Facilitates Discoveries of the Genetic Mechanisms Underlying Natural Variation,” *Trends in Genetics* 37, no. 10 (October 1, 2021): 933–47, <https://doi.org/10.1016/j.tig.2021.06.005>.

⁹ Trudy F. C. Mackay and Wen Huang, “Charting the Genotype–Phenotype Map: Lessons from the *Drosophila Melanogaster* Genetic Reference Panel,” *WIREs Developmental Biology* 7, no. 1 (2018): e289, <https://doi.org/10.1002/wdev.289>.

¹⁰ Michael C. Saul et al., “High-Diversity Mouse Populations for Complex Traits,” *Trends in Genetics* 35, no. 7 (July 1, 2019): 501–14, <https://doi.org/10.1016/j.tig.2019.04.003>.

3.1. THE MEDAKA INBRED KIYOSU-KARLSRUHE (MIKK) PANEL¹⁵

domesticated, and therefore do not represent the genetic variation present in wild populations. Furthermore, the large panels of inbred mice such as the Collaborative Cross (CC),¹¹ Diversity Outcross (DO)¹² and B6-by-D2 (BXD)¹³ are derived from only a small number of individuals. As gene-environment studies seek to ultimately understand their effects on traits “in the wild” (such as with humans), there is accordingly a need for a panel of inbred vertebrates that represents the genetic variation present in natural populations.

The medaka fish (*Oryzias latipes*) has been studied as a model organism in Japan for over a century,¹⁴ and is gaining recognition elsewhere as a powerful genetic model for vertebrates.¹⁵ In addition to possessing a number of desirable traits that are characteristic of model organisms (including their small-size, short reproduction time, and high fertility), medaka are also – uniquely among vertebrates – resilient to inbreeding from the wild.

Since 2010, the Birney Group at EMBL-EBI, in collaboration with the Wittbrodt Group at COS, University of Heidelberg and the Loosli Group at the Karlsruhe Institute of Technology (KIT), have been working to establish the world’s first panel of vertebrate inbred strains – now known as the Medaka Inbred Kiyosu-Karlsruhe Panel (**MIKK panel**). The MIKK Panel was bred from a wild population caught near Kiyosu in Southern Japan, and now comprises 80 inbred, near-isogenic “lines”.¹⁶

The MIKK Panel was created to map genetic variants associated with quantitative traits at a high resolution, and to explore the interactions between those variants and any environmental variables of interest. The purpose of the companion papers Fitzgerald et al.¹⁷ and Leger

¹¹David W. Threadgill et al., “The Collaborative Cross: A Recombinant Inbred Mouse Population for the Systems Genetic Era,” *ILAR Journal* 52, no. 1 (January 1, 2011): 24–31, <https://doi.org/10.1093/ilar.52.1.24>.

¹²Karen L Svenson et al., “High-Resolution Genetic Mapping Using the Mouse Diversity Outbred Population,” *Genetics* 190, no. 2 (February 1, 2012): 487–47, <https://doi.org/10.1534/genetics.111.132597>.

¹³Jeremy L. Peirce et al., “A New Set of BXD Recombinant Inbred Lines from Advanced Intercross Populations in Mice,” *BMC Genetics* 5, no. 1 (April 29, 2004): 7, <https://doi.org/10.1186/1471-2156-5-7>.

¹⁴Joachim Wittbrodt, Akihiro Shima, and Manfred Schartl, “Medaka — a Model Organism from the Far East,” *Nature Reviews Genetics* 3, no. 1, 1 (January 2002): 53–64, <https://doi.org/10.1038/nrg704>.

¹⁵Mikhail Spivakov et al., “Genomic and Phenotypic Characterization of a Wild Medaka Population: Towards the Establishment of an Isogenic Population Genetic Resource in Fish,” *G3 Genes|Genomes|Genetics* 4, no. 3 (March 1, 2014): 433–45, <https://doi.org/10.1534/g3.113.008722>.

¹⁶Fitzgerald et al., “The Medaka Inbred Kiyosu-Karlsruhe (MIKK) Panel.”

¹⁷

et al.¹⁸ was to introduce the MIKK panel to the scientific community, and describe the genetic characteristics of the MIKK panel that would make it a useful resource for other researchers who wish to explore the genetics of quantitative traits in vertebrates. My contributions to these papers involved visualising the inbreeding trajectory of the panel (Chapter 3.2.2), exploring the evolutionary history of the MIKK panel’s founding population (Chapter 3.2.3), measuring the levels of homozygosity across the panel (Chapter 3.2.4), assessing its allele-frequency distribution and rate of linkage disequilibrium (LD) decay (Chapter 3.2.5), and characterising the structural variants present in a smaller sample of lines using Oxford Nanopore long-read sequencing data (Chapter 3.3).

3.2 Genomic characterisation of the MIKK panel

3.2.1 MIKK panel DNA sequence dataset

For the preparation of Fitzgerald et al.¹⁹, 79 of the 80 extant MIKK panel lines – together with several wild Kiyosu samples and individuals from the established *iCab* medaka strain – had their DNA sequenced from brain samples using Illumina short-read sequencing technology. Tomas Fitzgerald from the Birney Group at EMBL-EBI then aligned these sequences to the *HdrR* medaka reference and called variants to produce the **MIKK Illumina call set** in the form of a .vcf file containing single nucleotide polymorphism (SNP) and small insertion-deletion (INDEL) calls for each line. To avoid allele frequency biases introduced by the 16 pairs/triplets of “sibling lines” (see 3.2.2), I removed each pair’s arbitrarily-labelled second sibling line from the variant call set, leaving 63 MIKK panel lines (**MIKK non-sibling call set**), and used only those calls for the analyses in Chapters 3.2.4 and 3.2.5.

For the preparation of Leger et al.²⁰, 12 MIKK panel lines had their DNA sequenced from brain samples using Oxford Nanopore Technologies (ONT) long-read sequencing technology. Adrien Leger from the Birney Group at EMBL-EBI then aligned these sequences to the *HdrR* medaka reference, and called variants to produce the

¹⁸“Genomic Variations and Epigenomic Landscape of the Medaka Inbred Kiyosu-Karlsruhe (MIKK) Panel.”

¹⁹“The Medaka Inbred Kiyosu-Karlsruhe (MIKK) Panel.”

²⁰“Genomic Variations and Epigenomic Landscape of the Medaka Inbred Kiyosu-Karlsruhe (MIKK) Panel.”

MIKK ONT call set in the form of a .vcf file containing structural variants calls for each line with tags for insertions (INS), deletions (DEL), duplications (SUP), inversions (INV) and translocations (TRA). The work described below used these variant call sets as the primary datasets.

3.2.2 Assessing the inbreeding trajectory of the MIKK panel

The MIKK panel was bred from a wild population of medaka found in the Kiyosu area near Toyohashi, Aichi Prefecture, in southern Japan.²¹ From this wild population, the Loosli Group at KIT set up random crosses of single mating pairs to create 115 ‘founder families’. For each founder family, they then set up between two and five single full-sibling-pair inbreeding crosses, which resulted in 253 F1 lines. Lines derived from the same founder family are referred to as ‘sibling lines’. Over the course of the next eight generations of inbreeding, they used only one mating pair per line. I generated Fig. 3.1A and B from the inbreeding data provided by the Loosli Group. Fig. 3.1A shows the number of lines that survived over the course of the first 14 generations of the inbreeding program, and the various causes for the termination of other lines. Fig. 3.1B shows the average fecundity levels of the surviving lines at generation F16. In addition, the Birney Group at EMBL-EBI generated morphometric data for the MIKK panel lines to demonstrate the distribution of physical phenotypes across the MIKK panel. I used this data on relative eye diameters to generate Fig. 3.1C.

3.2.3 Introgression with northern Japanese and Korean medaka populations

To explore the evolutionary history of the MIKK panel’s founding population, we sought to determine whether there was evidence of introgression between that southern Japanese population, and northern Japanese and Korean medaka populations. To this end, I used the 50-fish multiple alignment from Ensembl release 102 to obtain the aligned genome sequences for the established medaka inbred lines *HdrR* (southern Japan), *HNI* (northern Japan), and *HSOK* (Korea), as well as the most recent common ancestor of all three

²¹Spivakov et al., “Genomic and Phenotypic Characterization of a Wild Medaka Population.”

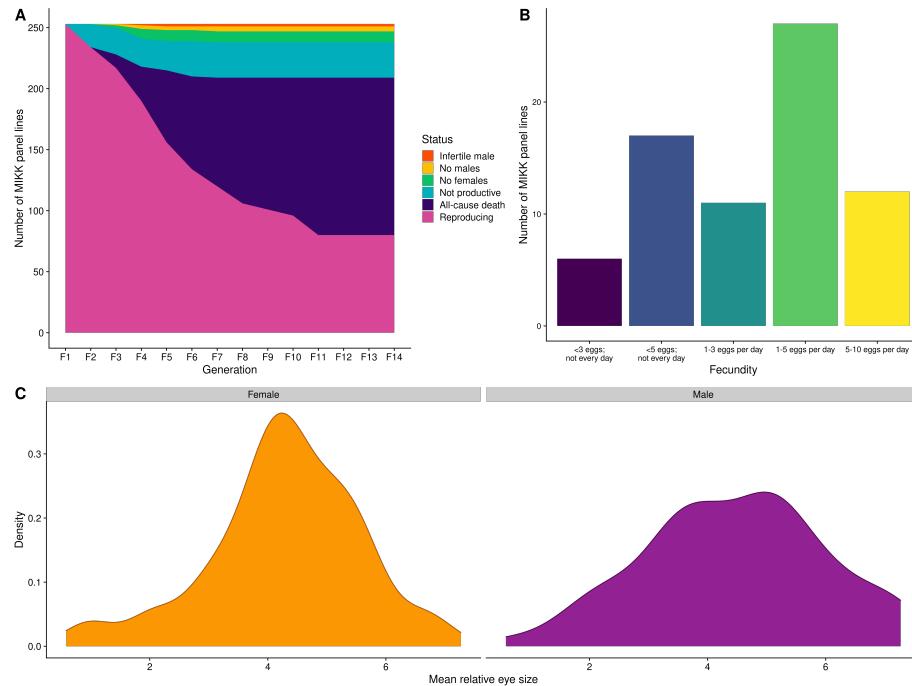


Figure 3.1: Inbreeding, fecundity and eye size in the MIKK panel lines. **A:** Status of all MIKK panel lines during the first 14 generations of inbreeding, showing cause of death for non-extant lines. **B:** Average fecundity of MIKK panel lines in generation F16, as measured during peak egg production in July 2020. **C:** Distribution of mean relative eye size for female and male medaka across all MIKK panel lines.

strains.²² Using the phylogenetic tree provided with the dataset, and the *ape* R package,²³ I identified the most recent common ancestor of those three strains. For each locus with a non-missing base for *HdrR*, I assigned the allele in that ancestral sequence as the ‘ancestral’ allele, and the alternative allele as the ‘derived’ allele, and then combined that dataset with the MIKK Illumina call set and variant calls for the southern Japanese *iCab* strain (see 3.2.1).

I then carried out an ABBA BABA analysis to calculate a modified ‘ad-mixture proportion’ statistic \hat{f}_d ²⁴ as a measure of the proportion of shared genome in 500-kb sliding windows between the MIKK panel and either *iCab*, *HNI*, or *HSOK* (Fig. 3.2), using the scripts provided by the first author of Martin, Davey, and Jiggins²⁵ on their GitHub page.²⁶

Based on the genome-wide mean \hat{f}_d , the MIKK panel shares approximately 25% of its genome with *iCab*, 9% with *HNI*, and 12% with *HSOK*. These results provide evidence that the MIKK panel’s originating population has more recently introgressed with medaka from Korea than with medaka from northern Japan. This supports the findings in Spivakov et al.²⁷, where the authors found little evidence of significant interbreeding between southern and northern Japanese medaka since the populations diverged. Although the proportional difference between *HNI* and *HSOK* is small, this further supports the general finding that northern and southern Japanese medaka strains show low levels of interbreeding that may be a result of geographical isolation or genome divergence.²⁸

²²“Index of /Pub/Release-102/Emf/Ensembl-Compara/Multiple_alignments/50_fish.epo/,” accessed January 25, 2022, https://ftp.ensembl.org/pub/release-102/emf/ensembl-compara/multiple_alignments/50_fish.epo/.

²³Emmanuel Paradis and Klaus Schliep, “Ape 5.0: An Environment for Modern Phylogenetics and Evolutionary Analyses in R,” *Bioinformatics* 35, no. 3 (February 1, 2019): 526–28, <https://doi.org/10.1093/bioinformatics/bty633>.

²⁴Simon H. Martin, John W. Davey, and Chris D. Jiggins, “Evaluating the Use of ABBA–BABA Statistics to Locate Introgressed Loci,” *Molecular Biology and Evolution* 32, no. 1 (January 1, 2015): 244–57, <https://doi.org/10.1093/molbev/msu269>.

²⁵

²⁶Simon martin, *Simonmartin/Genomics_general*, 2022, https://github.com/simonhmartin/genomics_general.

²⁷“Genomic and Phenotypic Characterization of a Wild Medaka Population.”

²⁸Takafumi Katsumura et al., “Medaka Population Genome Structure and Demographic History Described via Genotyping-by-Sequencing,” *G3 Genes|Genomes|Genetics* 9, no. 1 (January 1, 2019): 217–28, <https://doi.org/10.1534/g3.118.200779>.

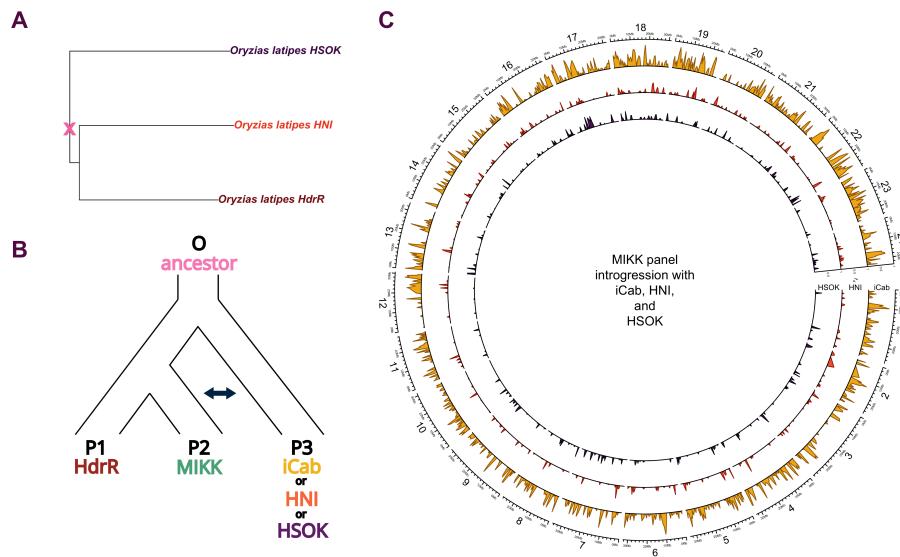


Figure 3.2: **Figure 2:** ABBA-BABA analysis. A. Phylogenetic tree generated from the Ensembl release 102 50-fish multiple alignment, showing only the medaka lines used in the ABBA-BABA analysis. B. Schema of the comparisons carried out in the ABBA-BABA analysis. C. Circos plot comparing introgression (\hat{f}_d) between the MIKK panel and either *iCab* (yellow), *HNI* (orange), or *HSOK* (purple), calculated within 500-kb sliding windows using a minimum of 250 SNPs per window.

3.2.4 Nucleotide diversity

As a means of assessing genetic diversity in the MIKK panel, I calculated nucleotide diversity ($\hat{\pi}$) within 500-kb non-overlapping windows across the genome of the 63 lines in the MIKK non-sibling call set (see 3.2.1), and compared this to the nucleotide diversity in 7 wild medaka from the same Kiyosu population from which the MIKK panel was derived. Mean and median nucleotide diversity in both the MIKK panel and wild Kiyosu medaka were close to 0, and slightly higher in the MIKK panel (mean: MIKK = 0.0038, wild = 0.0037; median: MIKK = 0.0033, wild = 0.0031). The patterns of varying nucleotide diversity across the genome are shared between the MIKK panel and wild Kiyosu medaka, where regions with high levels of repeat content tend to have higher nucleotide diversity ($r = 0.386$, $p < 0.001$) (Fig. 3.3). I also calculated $\hat{\pi}$ for each line individually, and as expected, levels of $\hat{\pi}$ around the (XX/XY) sex determination region of 1:~16-17 Mb are elevated in all lines relative to the consistently low levels found in most other chromosomes.

The higher level of $\hat{\pi}$ observed within specific regions on several chromosomes – such as chromosomes 2, 11, and 18 – correspond closely to the regions we identified as containing large (>250 kb) inversions that appear to be shared across at least some of the MIKK panel (Fig. 3.4). These regions are also enriched for large deletions and duplications.²⁹ Inversions cause permanent heterozygosity,³⁰ and duplications and deletions may have increased the density of called SNPs in these regions,³¹ so the observed depressions in homozygosity at these loci may be the result of such large structural variants that are present in the MIKK panel’s genomes.

Overall, this analysis confirms that the MIKK panel shows similar levels of homozygosity compared to classical laboratory inbred medaka strains, and possesses a strong increase in isogenic genotypes compared to wild medaka from the original wild population.

²⁹Leger et al., “Genomic Variations and Epigenomic Landscape of the Medaka Inbred Kiyosu-Karlsruhe (MIKK) Panel.”

³⁰Ary A. Hoffmann, Carla M. Sgr‘o, and Andrew R. Weeks, “Chromosomal Inversion Polymorphisms and Adaptation,” *Trends in Ecology & Evolution* 19, no. 9 (September 1, 2004): 482–88, <https://doi.org/10.1016/j.tree.2004.06.013>.

³¹David Fredman et al., “Complex SNP-related Sequence Variation in Segmental Genome Duplications,” *Nature Genetics* 36, no. 8, 8 (August 2004): 861–66, <https://doi.org/10.1038/ng1401>.

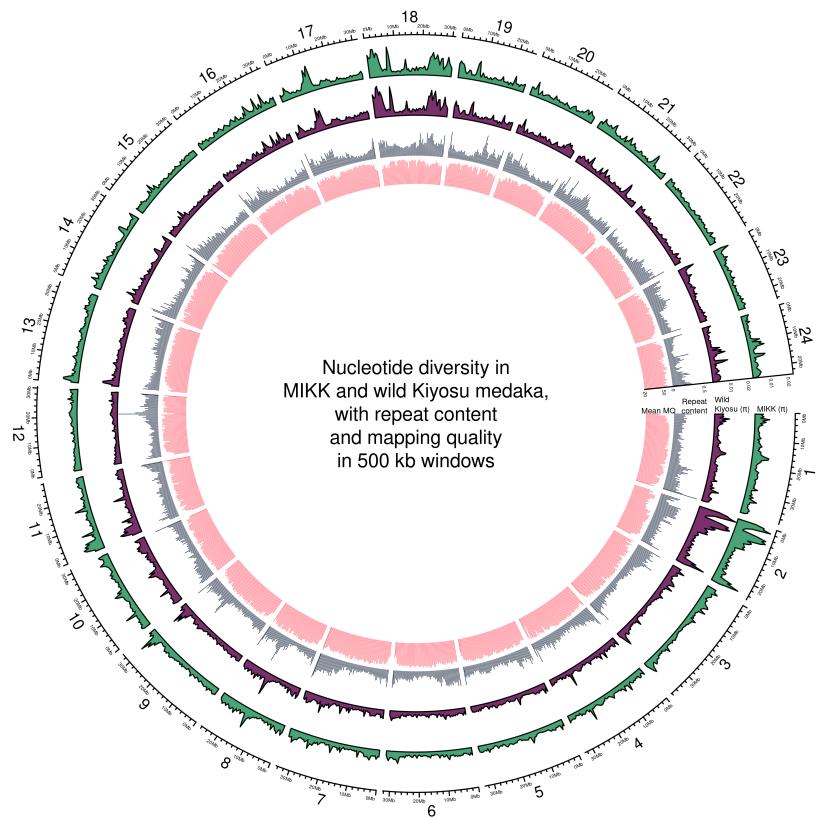


Figure 3.3: Circos plot with nucleotide diversity ($\hat{\pi}$) calculated within 500-kb non-overlapping windows for 63 non-sibling lines from the MIKK panel (green) and 7 wild Kiyosu medaka samples from the same originating population (purple); proportion of sequence classified as repeats by RepeatMasker (blue); and mean mapping quality (pink).

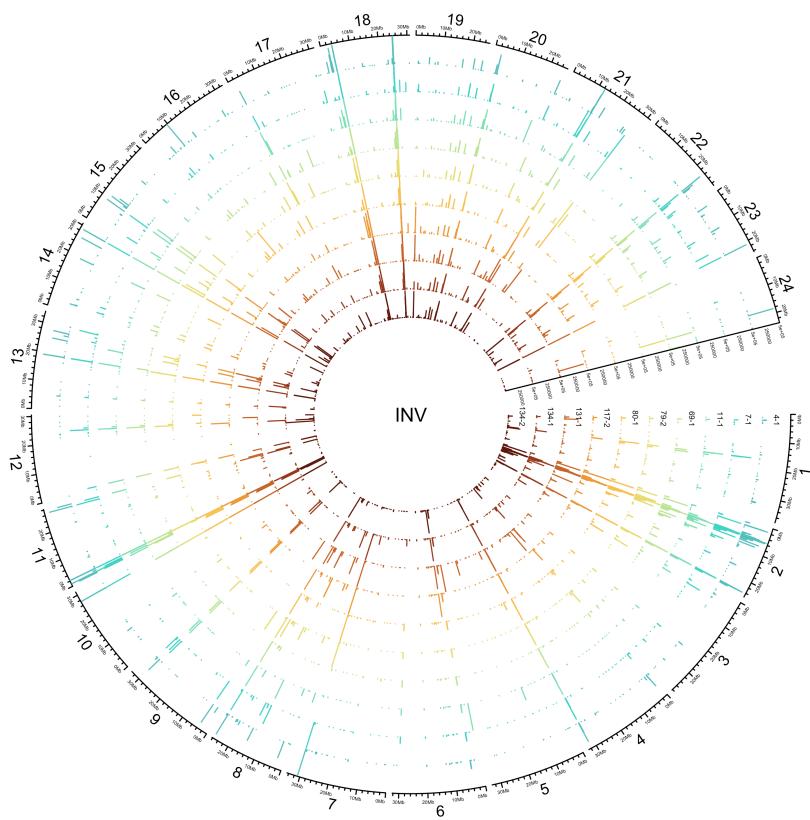


Figure 3.4: Inversions identified in 9 MIKK panel lines using a combination of Oxford Nanopore Technologies long-read and Illumina short-read sequences (see Chapter 3.3 below).

3.2.5 LD decay

I analysed the MIKK panel's allele frequency distribution and linkage disequilibrium (LD) structure to assess their likely effects on genetic mapping. To remove allele-frequency biases introduced by the presence of sibling lines in the MIKK panel, I used only the MIKK non-sibling call set (see Chapter 3.2.1).

To assess how accurately one may be able to map genetic variants using the MIKK panel relative to a human dataset, I compared the MIKK panel's minor allele frequency (MAF) distribution and LD structure against that of the 2,504 humans in the 1KG Phase 3 release.³² To prepare the “1KG call set”, I first downloaded the .vcf files for each autosome from the project's FTP site (<ftp://ftp.1000genomes.ebi.ac.uk/voll/ftp/release/20130502/>), then merged them into a single VCF using GATK.³³ I then used PLINK³⁴ to calculate the minor allele frequencies for all non-missing, biallelic SNPs in both the MIKK non-sibling and 1KG call sets (N SNPs = 16,395,558 and 81,042,381 respectively) (Fig. 3.5A). As expected, the 1KG and MIKK panel calls are similarly enriched for low-frequency variants, albeit to a lesser extent in the MIKK panel, which is likely due to its smaller sample size.

To determine the rate of LD decay in the MIKK panel and compare it to that in the 1KG sample, for both the MIKK non-sibling and 1KG call sets, I used PLINK to compute r^2 on each autosome for all pairs of non-missing, biallelic SNPs with MAF > 0.10 within 10 kb of one another (for 1KG and the MIKK panel respectively ~ 5.5M and ~ 3M SNPs, with a total number of pairwise r^2 observations of 204,152,922 and 146,785,673). I then grouped the r^2 observations for each pair of SNPs based on their distance from one another into non-overlapping bins of 100 bp in length, and calculated the mean r^2 in each of those bins to generate Fig. 3.5B using the mean r^2 and left boundary of each bin.

Based on the 1KG calls under these parameters, LD decays in humans to a mean r^2 of around 0.2-0.35 at a distance of 10 kb, whereas the MIKK panel reaches this level within 1 kb, with a mean r^2 of 0.8-0.4

³²“A Global Reference for Human Genetic Variation,” *Nature* 526, no. 7571 (2015): 68–74, <https://doi.org/10.1038/nature15393>.

³³Aaron McKenna et al., “The Genome Analysis Toolkit: A MapReduce Framework for Analyzing Next-Generation DNA Sequencing Data,” *Genome Research* 20, no. 9 (January 9, 2010): 1297–1303, <https://doi.org/10.1101/gr.107524.110>.

³⁴Christopher C Chang et al., “Second-Generation PLINK: Rising to the Challenge of Larger and Richer Datasets,” *GigaScience* 4, no. 1 (December 2015): 7, <https://doi.org/10.1186/s13742-015-0047-8>; Shaun M Purcell and Christopher C Chang, *PLINK* 1.9, n.d., www.cog-genomics.org/plink/1.9/.

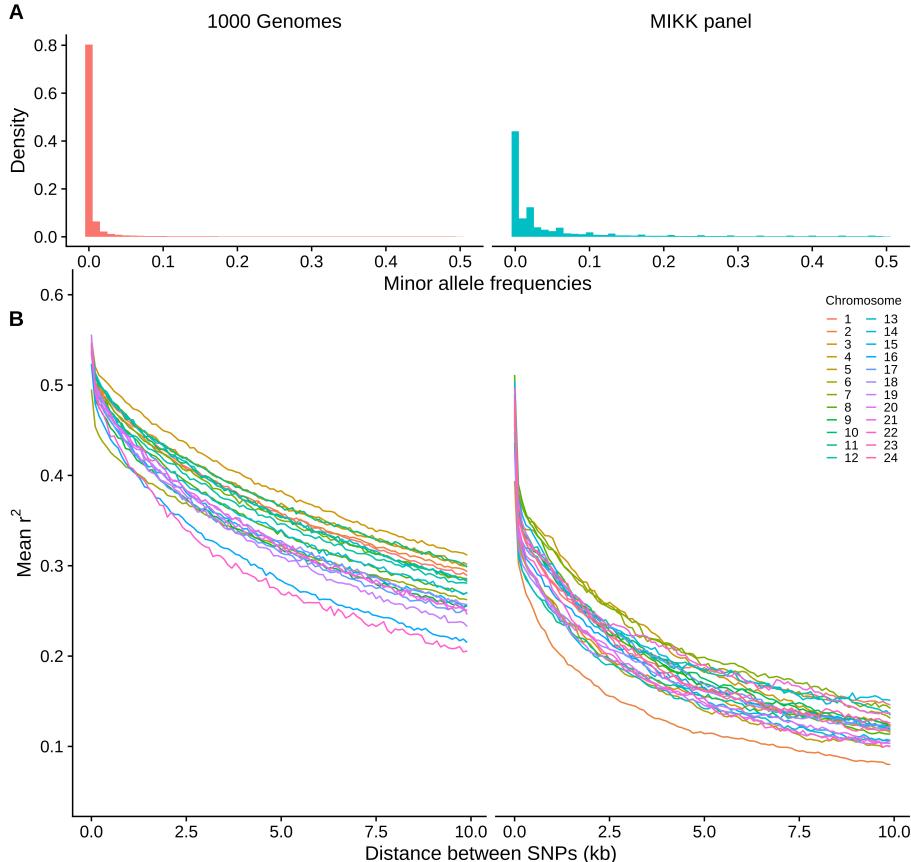


Figure 3.5: Minor allele frequency distributions and LD decay for biallelic, non-missing SNPs in the 1000 Genomes Phase 3 variant calls ($N = 2,504$) (1KG), and the MIKK panel Illumina-based calls excluding one of each pair of sibling lines ($N = 63$), across all autosomes (1KG: chrs 1-22; MIKK: chrs 1-24). **A:** Histogram of allele frequencies in the 1KG and MIKK panel calls. **B:** LD decay for each autosome, calculated by taking the mean r^2 of pairs of SNPs with MAF > 0.1 within non-overlapping 100 bp windows of distance from one another, up to a maximum of 10 kb. LD decays faster on chromosome 2 for the MIKK panel due to its higher recombination rate.

at a distance of ~100 bp. This implies that when a causal variant is present in at least two lines in the MIKK panel, one may be able to map causal variants at a higher resolution than in humans. We note that LD decays faster in chromosome 2 of the MIKK panel relative to the other chromosomes. This suggests that it has a much higher recombination rate, which is consistent with the linkage map described in Kiyoshi Naruse et al.³⁵, showing a higher genetic distance per Mb for this chromosome. This higher recombination rate in chromosome 2 may in turn be caused by its relatively high proportion of repeat content (Fig. 3.6).

3.3 Structural variation in the MIKK panel

As an alternative to the variation pangenome approach described in Leger et al.³⁶, I explored the structural variants (SVs) present in 9 of the MIKK panel lines in a reference-anchored manner, similar to many human studies. Differences in SVs between panel lines is another important class of genetic variation that could cause or contribute to significant phenotypic differences. Here we used ONT data obtained for 9 of the 12 selected lines allowing us to characterise larger SVs in the MIKK panel and to create a more extensive picture of genomic rearrangements compared to available medaka reference genomes. Adrien Leger from the Birney Group at EMBL-EBI first called structural variants using only the ONT long reads, producing a set of structural variants classified into five types: deletions (DEL), insertions (INS), translocations (TRA), duplications (DUP) and inversions (INV). I then “polished” the called DEL and INS variants with Illumina short reads to improve their accuracy. The polishing process filtered out 7.4% of DEL and 12.8% of INS variants, and adjusted the breakpoints (i.e. start and end positions) for 75-77% of DEL and INS variants in each sample by a mean of 23 bp for the start position, and 33 bp for the end position. This process produced a total of 143,826 filtered SVs.

The 9 “polished” samples contained a mean per-sample count of approximately 37K DEL variants (12% singletons), 29.5K INS variants (14%), 3.5K TRA variants (9%), 2.5K DUP (7%) and 600 INV (7%) (Fig. 3.7D). DEL variants were up to 494 kb in length, with 90% of unique DEL variants shorter than 3.8 kb. INS variants were only up to 13.8

³⁵“A Detailed Linkage Map of Medaka, *Oryzias Latipes*: Comparative Genomics and Genome Evolution,” *Genetics* 154, no. 4 (April 1, 2000): 1773–84, <https://www.genetics.org/content/154/4/1773>.

³⁶“Genomic Variations and Epigenomic Landscape of the Medaka Inbred Kiyosu-Karlsruhe (MIKK) Panel.”

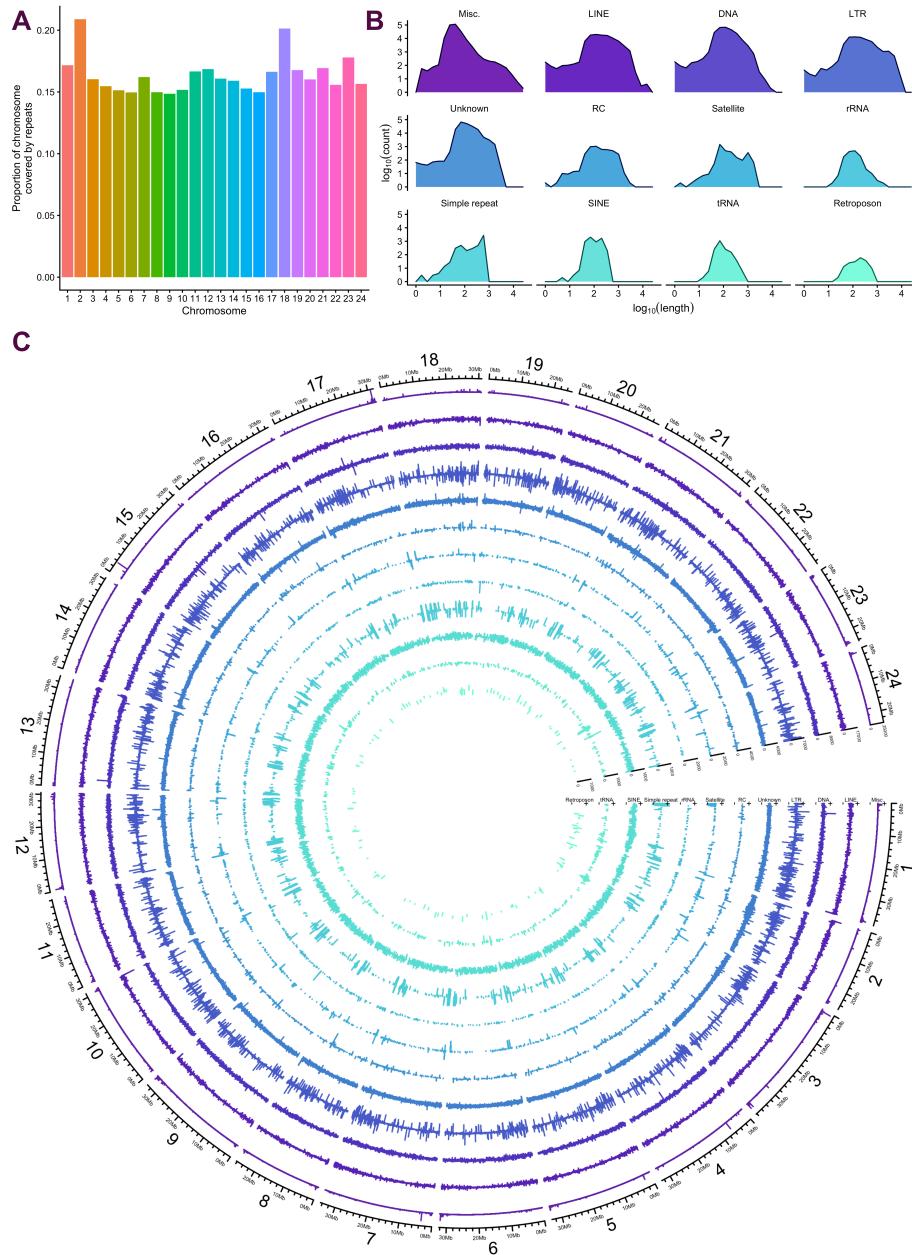


Figure 3.6: Repeat content in the *HdrR* genome based on Repeat-Masker results obtained by Jack Monahan. A. Proportion of repeat content per-chromosome. B. log₁₀ of repeat lengths and counts per repeat class. “Misc” includes all repeats assigned to their own specific class, for example “(GAG)_n” or “(GATCCA)_n”. C. Circos plot showing repeat length (radial axes) by locus (angular axis) and repeat class (track).

kb in length, with 90% of unique INS variants shorter than 2 kb. DUP and INV variants tended to be longer, with a mean length of 19 and 70.5 kb respectively (Fig. 3.7A). Fig. 3.7E shows the per-sample distribution of DEL variants across the genome. Most large DEL variants over 250 kb in length were common among the MIKK panel lines. A number of large DEL variants appear to have accumulated within the 0-10 Mb region of chromosome 2, which is enriched for repeats in the *HdrR* reference genome (Fig. 3.6).

SVs were generally enriched in regions covered by repeats. While only 16% of bases in the *HdrR* reference were classified as repeats (irrespective of strand), those bases overlapped with 72% of DEL, 63% of DUP, 81% of INV and 35% of TRA variant regions. However, repeat bases only overlapped with 21% of INS variants. We also assessed each SV's probability of being loss-of-function (pLI)³⁷ by calculating the logarithm of odds (LOD) for the pLI scores of all genes overlapping the variant (Fig. 3.7B,C). 30,357 out of 134,088 DEL, INS, DUP and INV variants overlapped at least one gene, and 9% of those had a score greater than 10, indicating a high probability that the SV would cause a loss of function. Two INS variants on chr2 had an outlying LOD score of 57 as a result of overlapping medaka gene ENSORLG00000003411, which has a pLI score of 1 – the highest intolerance to variants causing a loss of function. This gene is homologous with human genes *SCN1A*, *SCN2A* and *SCN3A*, which encode sodium channels and have been associated with neuronal and sleep disorders. We did not find evidence that longer SVs tended to have a higher probability of causing a loss of function (Fig. 3.7B).

We compared these polished INS and DEL calls with the high-quality graph-based alternative paths and large-scale deletions, respectively (see section titled *Novel genetic sequences and large-scale insertions and deletions in the MIKK panel* in Leger et al.³⁸). We found that 2 of the 19 regions covered by graph-based alternative paths, and 4 of the 16 regions covered by graph-based deletions, had no SVs that overlapped those regions at all, which suggests they would have been missed entirely when using a reference-anchored approach alone.

With the exception of one alternative path on chromosome 20, the alternative paths were not captured by INS variants, which only covered up to 63% of the bases in each region, and in many cases substantially less. On the other hand, for 8 of the 16 graph-based deletions, the DEL variants covered at least 85% of the bases in those

³⁷Monkol Lek et al., “Analysis of Protein-Coding Genetic Variation in 60,706 Humans,” *Nature* 536, no. 7616, 7616 (August 2016): 285–91, <https://doi.org/10.1038/nature19057>.

³⁸“Genomic Variations and Epigenomic Landscape of the Medaka Inbred Kiyosu-Karlsruhe (MIKK) Panel.”

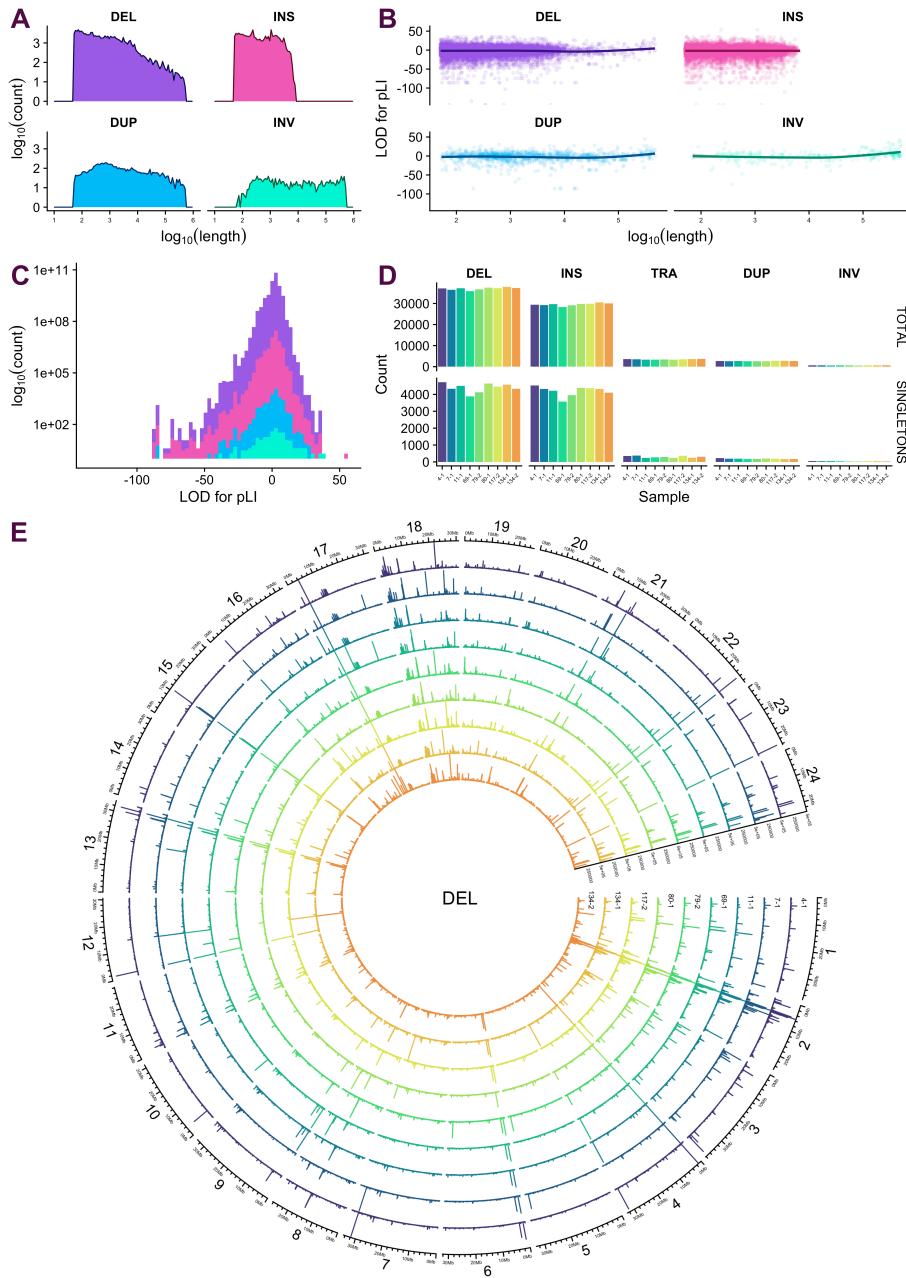


Figure 3.7: Polished SVs in 9 MIKK panel lines sequenced with ONT. DEL: deletion; INS: insertion; TRA: translocation; DUP: duplication; INV: inversion. A. Aggregate \log_{10} counts and lengths of distinct SVs by type, excluding TRA. B. pLI LOD scores in distinct SVs by SV type. C. Histogram of LOD scores by SV type. D. Total and singleton counts of SV types per sample. E. Circos plot showing per-sample distribution and lengths of DEL variants across the genome.

regions. The other 8 graph-based deletions were either not at all covered by DEL variants, or only slightly. This indicates that the reference-based approach is better at detecting large-scale deletions than alternative paths (“insertions”), but still misses around half of such variants relative to the graph-based approach.

3.4 Conclusions

Taken together, these analyses show that the MIKK panel is highly homozygous, with LD characteristics that will favour high-resolution genetic mapping relative to humans. In the future, the SV analysis performed on a subset of the MIKK panel will be expanded across the entire panel, which will permit the inclusion of both large- and small-scale variants in genetic linkage studies. I proceeded to use the MIKK panel to analyse bold/shy behaviours, as I describe in Chapter 5, with a view to carrying out an F2-cross linkage study to identify genetic variants associated with differences in the behaviours of an individual, and the extent to which they transmit those behaviours to their social companions. However, before carrying out this study, we first ran a “pilot” study on 5 previously-established inbred lines to validate our behavioural assay. This is the subject of the following chapter.

Chapter 4

Classification of bold/shy behaviours in 5 inbred medaka lines

Chapter 5

Bold/shy behaviours in the MIKK panel

Chapter 6

Variation in the frequency of trait-associated alleles across global human populations

In this chapter I illustrate the distribution of F_{ST} scores for loci associated with 587 traits, a subset of the GWAS Catalog which passed our criteria for suitable polygenic traits (Methods). Our analysis is empirical, in that we do not explicitly formulate a statistical test for drift or selection, differential or otherwise. Using high-coverage sequence data for 2,504 individuals from the 1000 Genomes Project phase 3 release, for each trait in the GWAS Catalog we calculated the distribution of F_{ST} across all approximately-unlinked SNPs associated with it (trait SNPs), and compared these F_{ST} distributions with the F_{ST} distributions of random-selected SNPs that were matched to the trait SNPs by their allele frequencies in European populations (control SNPs). Our results show that traits related to the physical correlates of “race” (such as skin-pigmentation, eye colour, and hair shape) tend to have relatively high F_{ST} values – signifying relatively high variance in allele frequencies between populations – whereas traits related to intelligence (such as self-reported EA, mathematical ability, and cognitive function measurement) tend to have lower F_{ST} values that are similar to those of most polygenic traits such as height and body mass index.

6.1 Background

6.1.1 Polygenic Risk Scores (PRS) and Genome-Wide Association Studies (GWAS)

As seen in previous chapters, an individual's phenotypic value at a given point in time is the product of complex interactions between their genome and their environment, accumulating during their initial development and continuing throughout their lifetimes.

A richer understanding of the cumulative effect of genetic variants on any trait allows for the prediction of the value that an individual is most likely to have for that trait. Of all human traits, diseases are particularly salient – in 2018, the global healthcare industry was valued at US\$8 trillion, and predicted to increase to US\$12 trillion by 2022.¹ This strong financial imperative complements the moral imperative to reduce suffering, together driving many to determine how to use genetic information to improve human health.

Once it became possible to sequence human genomes at scale, researchers have sought to use genetic information to predict an individual's likely value for a given trait.² It is thought that by combining genetic information with other environmental and phenotypic information, clinicians could work towards applying “precision medicine”, where their patients' medications, diet, and other lifestyle factors could be tailored to their unique needs. The genetic component of this pursuit is now commonly known as polygenic risk scores (PRS), also known as genetic risk profiling, which seeks to predict the likelihood of a given trait based on an individual's genomic variants. To date, PRS studies have shown reliable yet modest improvement above clinical models to predictions for a variety of health-related traits including blood pressure, breast cancer,³ prostate cancer,⁴ type I diabetes.⁵

¹“The \$11.9 Trillion Global Healthcare Market: Key Opportunities & Strategies (2014-2022) - ResearchAndMarkets.com,” June 25, 2019, <https://www.businesswire.com/news/home/20190625005862/en/The-11.9-Trillion-Global-Healthcare-Market-Key-Opportunities-Strategies-2014-2022---ResearchAndMarkets.com>.

²Naomi R. Wray, Michael E. Goddard, and Peter M. Visscher, “Prediction of Individual Genetic Risk to Disease from Genome-Wide Association Studies,” *Genome Research* 17, no. 10 (January 10, 2007): 1520–28, <https://doi.org/10.1101/gr.6665407>.

³Paige Maas et al., “Breast Cancer Risk From Modifiable and Nonmodifiable Risk Factors Among White Women in the United States,” *JAMA Oncology* 2, no. 10 (October 1, 2016): 1295–1302, <https://doi.org/10.1001/jamaoncol.2016.1025>.

⁴Fredrick R. Schumacher et al., “Association Analyses of More Than 140,000 Men Identify 63 New Prostate Cancer Susceptibility Loci,” *Nature Genetics* 50, no. 7, 7 (July 2018): 928–36, <https://doi.org/10.1038/s41588-018-0142-8>.

⁵Seth A. Sharp et al., “Development and Standardization of an Improved Type 1

PRS scores can further be combined with lifestyle and clinical factors to more accurately predict the risk of cardiovascular disease.⁶

The scores are calculated by summing the trait-associated alleles identified through genome-wide association studies (GWAS), weighted by the alleles' effect sizes.⁷ However, most GWAS have been performed with individuals of European ancestry. Although the proportion of participants in GWAS from a non-European background is increasing (from 4% in 20019 to 16 % in 2016),⁸ as of 2019, 79% of all GWAS participants recorded in the GWAS Catalog were of European ancestry.⁹ The consequence of this is that PRS scores are far better at predicting disease risk in individuals of European ancestry.¹⁰ For example, Martin, Gignoux, et al.¹¹ found that height was predicted to decrease with genetic distance from Europeans, despite robust evidence that West Africans are as tall as Europeans on average. Indeed, the predictive accuracy of PRS scores decays with genetic divergence of the GWAS "independent" or "test" sample from the "discovery" - or "training" - sample, as

Diabetes Genetic Risk Score for Use in Newborn Screening and Incident Diagnosis," *Diabetes Care* 42, no. 2 (January 11, 2019): 200–207, <https://doi.org/10.2337/dcl18-1785>.

⁶Amit V. Khera et al., "Genome-Wide Polygenic Scores for Common Diseases Identify Individuals with Risk Equivalent to Monogenic Mutations," *Nature Genetics* 50, no. 9, 9 (September 2018): 1219–24, <https://doi.org/10.1038/s41588-018-0188-z>; Iftikhar J. Kullo et al., "Incorporating a Genetic Risk Score Into Coronary Heart Disease Risk Estimates," *Circulation* 133, no. 12 (March 22, 2016): 1181–88, <https://doi.org/10.1161/CIRCULATIONAHA.115.020109>; Pradeep Natarajan et al., "Polygenic Risk Score Identifies Subgroup With Higher Burden of Atherosclerosis and Greater Relative Benefit From Statin Therapy in the Primary Prevention Setting," *Circulation* 135, no. 22 (May 30, 2017): 2091–101, <https://doi.org/10.1161/CIRCULATIONAHA.116.024436>; Martine Paquette et al., "Polygenic Risk Score Predicts Prevalence of Cardiovascular Disease in Patients with Familial Hypercholesterolemia," *Journal of Clinical Lipidology* 11, no. 3 (May 1, 2017): 725–732.e5, <https://doi.org/10.1016/j.jacl.2017.03.019>; Emmi Tikkannen et al., "Genetic Risk Prediction and a 2-Stage Risk Screening Strategy for Coronary Heart Disease," *Arteriosclerosis, Thrombosis, and Vascular Biology* 33, no. 9 (September 2013): 2261–66, <https://doi.org/10.1161/ATVBAHA.112.301120>.

⁷L. Duncan et al., "Analysis of Polygenic Risk Score Usage and Performance in Diverse Human Populations," *Nature Communications* 10, no. 1, 1 (July 25, 2019): 3328, <https://doi.org/10.1038/s41467-019-11112-0>.

⁸Alice B. Popejoy and Stephanie M. Fullerton, "Genomics Is Failing on Diversity," *Nature* 538, no. 7624, 7624 (October 2016): 161–64, <https://doi.org/10.1038/538161a>.

⁹Alicia R. Martin, Masahiro Kanai, et al., "Clinical Use of Current Polygenic Risk Scores May Exacerbate Health Disparities," *Nature Genetics* 51, no. 4, 4 (April 2019): 584–91, <https://doi.org/10.1038/s41588-019-0379-x>.

¹⁰Alicia R. Martin, Christopher R. Gignoux, et al., "Human Demographic History Impacts Genetic Risk Prediction Across Diverse Populations," *The American Journal of Human Genetics* 100, no. 4 (April 6, 2017): 635–49, <https://doi.org/10.1016/j.ajhg.2017.03.004>; Martin, Kanai, et al., "Clinical Use of Current Polygenic Risk Scores May Exacerbate Health Disparities."

¹¹"Human Demographic History Impacts Genetic Risk Prediction Across Diverse Populations."

established in both humans,¹² and livestock.¹³

These differences in representation cause PRS scores to have a lower accuracy for individuals of non-European ancestry. For example, compared to PRS scores for those of European ancestry, PRS scores across multiple traits for individuals of African ancestry are ~64-78% less accurate,¹⁴ and for individuals of South-Asian ancestry ~37% less accurate, and ~50% less accurate for individuals of East-Asian ancestry.¹⁵

What explains this disparity in predictive value? A number of factors may be responsible including:

1. GWAS neglect causal variants that do not exist within the “discovery” sample.¹⁶
2. The sample populations may differ in linkage disequilibrium (LD) – the correlation structure of the genome – which would change the estimated effect sizes of the causal variants, even when the causal variants themselves are the same.¹⁷ To illustrate, if a SNP has an LD r^2 with a causal variant of 0.8 in the discovery population and 0.6 in the target population, it would explain 25% = (1 - 0.6/0.8) less trait variation in the target population and therefore would be less predictive.¹⁸ Differences in effect-size estimates may typically be small for most regions of the genome, but PRS sum across these effects,

¹²Martin, Gignoux, et al.; Martin, Kanai, et al., “Clinical Use of Current Polygenic Risk Scores May Exacerbate Health Disparities.”

¹³Samuel A. Clark et al., “The Importance of Information on Relatives for the Prediction of Genomic Breeding Values and the Implications for the Makeup of Reference Data Sets in Livestock Breeding Schemes,” *Genetics Selection Evolution* 44, no. 1 (February 9, 2012): 4, <https://doi.org/10.1186/1297-9686-44-4>; David Habier et al., “The Impact of Genetic Relationship Information on Genomic Breeding Values in German Holstein Cattle,” *Genetics Selection Evolution* 42, no. 1 (February 19, 2010): 5, <https://doi.org/10.1186/1297-9686-42-5>; M. Pszczola et al., “Reliability of Direct Genomic Values for Animals with Different Relationships Within and to the Reference Population,” *Journal of Dairy Science* 95, no. 1 (January 1, 2012): 389–400, <https://doi.org/10.3168/jds.2011-4338>.

¹⁴Duncan et al., “Analysis of Polygenic Risk Score Usage and Performance in Diverse Human Populations”; Martin, Kanai, et al., “Clinical Use of Current Polygenic Risk Scores May Exacerbate Health Disparities.”

¹⁵Martin, Kanai, et al., “Clinical Use of Current Polygenic Risk Scores May Exacerbate Health Disparities.”

¹⁶Martin, Kanai, et al.

¹⁷Martin, Kanai, et al.

¹⁸Ying Wang et al., “Theoretical and Empirical Quantification of the Accuracy of Polygenic Scores in Ancestry Divergent Populations,” *Nature Communications* 11, no. 1, 1 (July 31, 2020): 3865, <https://doi.org/10.1038/s41467-020-17719-y>.

therefore aggregating these population differences.¹⁹ Previous empirical and simulation studies have shown that accuracy of PRS scores decay with increased genetic differentiation (F_{ST}) and LD differences between populations.²⁰

3. Allele frequencies of the causal variants, and the distribution of the effect sizes of the causal variants, may differ between populations.²¹
4. The environments and demographies may differ between populations. These differences are often correlated with genetic divergence due to geography, making it difficult to determine whether the associations are driven by the differences between population in their genetics, or their environments.²²

The first three factors can degrade predictive performance even in the absence of biological and environmental differences, whereas environmental and demographic differences can drive forces of natural selection can in turn drive differences in causal genetic architecture.²³

Differences in LD and allele frequencies between populations can explain 70-80% of the loss of PRS relative accuracy for traits like body mass index and type 2 diabetes.²⁴

¹⁹Martin, Kanai, et al., “Clinical Use of Current Polygenic Risk Scores May Exacerbate Health Disparities.”

²⁰Habier et al., “The Impact of Genetic Relationship Information on Genomic Breeding Values in German Holstein Cattle”; Pszczola et al., “Reliability of Direct Genomic Values for Animals with Different Relationships Within and to the Reference Population”; Marco Scutari, Ian Mackay, and David Balding, “Using Genetic Distance to Infer the Accuracy of Genomic Prediction,” *PLOS Genetics* 12, no. 9 (September 2, 2016): e1006288, <https://doi.org/10.1371/journal.pgen.1006288>; Wang et al., “Theoretical and Empirical Quantification of the Accuracy of Polygenic Scores in Ancestry Divergent Populations.”

²¹Martin, Gignoux, et al., “Human Demographic History Impacts Genetic Risk Prediction Across Diverse Populations”; Scutari, Mackay, and Balding, “Using Genetic Distance to Infer the Accuracy of Genomic Prediction.”

²²Martin, Kanai, et al., “Clinical Use of Current Polygenic Risk Scores May Exacerbate Health Disparities”; Sini Kermiinen et al., “Geographic Variation and Bias in the Polygenic Scores of Complex Diseases and Traits in Finland,” *The American Journal of Human Genetics* 104, no. 6 (June 6, 2019): 1169–81, <https://doi.org/10.1016/j.ajhg.2019.05.001>.

²³Martin, Kanai, et al., “Clinical Use of Current Polygenic Risk Scores May Exacerbate Health Disparities.”

²⁴Wang et al., “Theoretical and Empirical Quantification of the Accuracy of Polygenic Scores in Ancestry Divergent Populations.”

6.1.2 Effect of the environment on

6.1.3 Discovery of causal variants

The power to discover a causal variant through GWAS depends on the variant's effect size and frequency in the study population.²⁵ That is to say, the greater the effect of the variant, or the more common it is, the more likely it is to be discovered.

Many SNP arrays used for GWAS do not sequence the whole genome, but rather a selection (from several hundred thousand to millions) of genetic markers intended to present common genomic variation.²⁶ To increase the density of genotypes, which would increase the likelihood of refining the association signal and identifying causal variants, researchers often “impute” variants that aren't sequenced directly.²⁷ The imputation process involves “phasing” the study genotypes onto the genotypes of a “reference panel.”²⁸ However, if the reference panel does not sufficiently represent the populations in the study sample, they are likely to miss or incorrectly impute genotypes from those under-represented populations.²⁹

Genetic divergence between populations can be measured by F_{ST} , and the correlation between true and predicted phenotypic values decays approximately linearly with respect to F_{ST} .³⁰

It was demonstrated in simulations that using LD information from an external reference panel as a prior to infer the posterior mean effect size of a genetic variant can improve PRS predictive accuracy.³¹

²⁵ Martin, Kanai, et al., “Clinical Use of Current Polygenic Risk Scores May Exacerbate Health Disparities”; P. C. Sham et al., “Power of Linkage Versus Association Analysis of Quantitative Traits, by Use of Variance-Components Models, for Sibship Data,” *The American Journal of Human Genetics* 66, no. 5 (May 1, 2000): 1616–30, <https://doi.org/10.1086/302891>.

²⁶ Eleonora Porcu et al., “Genotype Imputation in Genome-Wide Association Studies,” *Current Protocols in Human Genetics* 78, no. 1 (2013): 1.25.1–14, <https://doi.org/10.1002/0471142905.hg0125s78>.

²⁷ Porcu et al.

²⁸ Shane McCarthy et al., “A Reference Panel of 64,976 Haplotypes for Genotype Imputation,” *Nature Genetics* 48, no. 10, 10 (October 2016): 1279–83, <https://doi.org/10.1038/ng.3643>.

²⁹ Martin, Kanai, et al., “Clinical Use of Current Polygenic Risk Scores May Exacerbate Health Disparities.”

³⁰ Scutari, Mackay, and Balding, “Using Genetic Distance to Infer the Accuracy of Genomic Prediction.”

³¹ Bjarni J Vilhjálmsson et al., “Modeling Linkage Disequilibrium Increases Accuracy of Polygenic Risk Scores,” *The American Journal of Human Genetics* 97, no. 4 (2015): 576–92.

Causal variants can differ in both frequency and effect size between different ancestry groups (e.g. for lactase persistence)

As noted in the 2019 review of PRS scores by Duncan et al.³², 67% of PRS studies included only participants of European ancestry, with another 19% including only East Asian ancestry participants, and only 3.8% with cohorts of African, Hispanic, or Indigenous ancestry.

As F_{ST} does not take into account the effect size or direction of the effect of the trait-associated allele, for highly-polygenic traits like the ones shown here, F_{ST} is almost entirely decoupled from the mean additive genetic value (or polygenic risk score) between populations,³³

6.2 Datasets

6.2.1 1000 Genomes

As the reference for human genomic variation across diverse populations, we used the New York Genome Center high-coverage, phased .vcf files³⁴ for the 2,504 individuals described in the 1000 Genomes phase 3 release.³⁵ We then annotated those .vcf files with human SNP IDs from dbSNP release 9606.³⁶

³²“Analysis of Polygenic Risk Score Usage and Performance in Diverse Human Populations.”

³³Jeremy J. Berg and Graham Coop, “A Population Genetic Signal of Polygenic Adaptation,” *PLOS Genetics* 10, no. 8 (August 7, 2014): e1004412, <https://doi.org/10.1371/journal.pgen.1004412>.

³⁴“Index of /Voll/Ftp/Data_collections/1000g_2504_high_coverage/Working/20201028_3202_phased/,” accessed March 24, 2022, http://ftp.1000genomes.ebi.ac.uk/voll/ftp/data_collections/1000G_2504_high_coverage/working/20201028_3202_phased/.

³⁵1000 Genomes Project Consortium et al., “A Global Reference for Human Genetic Variation,” *Nature* 526, no. 7571 (2015): 68.

³⁶Elizabeth M. Smigielski et al., “dbSNP: A Database of Single Nucleotide Polymorphisms,” *Nucleic Acids Research* 28, no. 1 (January 1, 2000): 352–55, <https://doi.org/10.1093/nar/28.1.352>.

6.2.2 GWAS Catalog

We used the R package *gwasrapidd*³⁷ to query all traits in the GWAS Catalog³⁸ as of 9 August 2021 ($N_{TRAITS} = 3,459$). For 541 of these traits, no matching variant IDs could be pulled out from the 1000 Genomes VCFs, leaving $N_{TRAITS} = 3,008$.

6.2.3 Linkage disequilibrium

To obtain the “trait SNP” dataset, for each trait, we sought to isolate the SNP closest to each of its true causal variants, and exclude the SNPs in linkage disequilibrium (LD) with them. To this end, we used PLINK 1.9³⁹ to “clump” the SNPs associated with each of the remaining 3,008 traits, using an index variant p-value threshold of 10^{-8} ,⁴⁰ r^2 threshold of 0.1,⁴¹ and base window size of 1 Mb. This process left us with 2,045 traits with at least one index SNP that met the p-value threshold. The index SNPs for each trait formed our set of trait SNPs. In order to target relatively polygenic traits, we further filtered out traits with fewer than 10 trait SNPs, leaving $N_{TRAITS} = 587$. Supplementary Fig. 4 shows the counts of unique SNP IDs associated with each trait before and after clumping, and an interactive version is available in the notebook cited above.

6.2.4 Control SNPs

To obtain our “control SNP” dataset, we assigned each trait SNP to one of 20 bins based on its minor allele frequency in European populations (as provided in the original 1000 Genomes .vcf files under the column header ‘INFO/AC_EUR’). For example, if a trait SNP had a minor allele frequency of 0.08 in European populations, it was

³⁷Ramiro Magno and Ana-Teresa Maia, “Gwasrapidd: An R Package to Query, Download and Wrangle GWAS Catalog Data,” *Bioinformatics* 36, no. 2 (January 15, 2020): 649–50, <https://doi.org/10.1093/bioinformatics/btz605>.

³⁸Jacqueline MacArthur et al., “The New NHGRI-EBI Catalog of Published Genome-Wide Association Studies (GWAS Catalog),” *Nucleic Acids Research* 45, no. D1 (January 4, 2017): D896–901, <https://doi.org/10.1093/nar/gkwl133>.

³⁹Chang et al., “Second-Generation PLINK”; Purcell and Chang, *PLINK 1.9*.

⁴⁰Orestis A. Panagiotou, John P. A. Ioannidis, and Genome-Wide Significance Project, “What Should the Genome-Wide Significance Threshold Be? Empirical Replication of Borderline Genetic Associations,” *International Journal of Epidemiology* 41, no. 1 (February 2012): 273–86, <https://doi.org/10.1093/ije/dyr178>.

⁴¹W. G. Hill and Alan Robertson, “Linkage Disequilibrium in Finite Populations,” *Theoretical and Applied Genetics* 38, no. 6 (June 1, 1968): 226–31, <https://doi.org/10.1007/BF01245622>.

assigned to the $(0.05, 0.1]$ bin. We did the same for all (unassociated) SNPs in the .vcf files, then paired each trait SNP with a random SNP from the .vcf file in the equivalent bin. These allele-frequency-paired random SNPs formed our set of “control SNPs”, which we used to infer the F_{ST} distribution of a random set of SNPs with the same allele frequencies as the trait SNPs, and against which we could compare the F_{ST} distribution of the trait SNPs.

6.2.5 F_{ST} and ranking traits by signed Kolmogorov-Smirnov D statistic

We then calculated F_{ST} for each of the trait SNPs and their matched control SNPs using the Weir and Cockerham method,⁴² as implemented in the R package *pegas*.⁴³ To rank all traits based on the directional difference in F_{ST} distributions between trait and control SNPs, we ran three Kolmogorov-Smirnov (KS) tests for each trait t with $x_t = F_{ST,traitSNPs}$ and $y_t = F_{ST,controlSNPs}$:

1. two-sided (D_t) ;
2. one-sided “greater” (D_t^+) ; and
3. one-sided “less” (D_t^-).

I note that $D_t = \max(D_t^+, D_t^-)$, where D_t^+ is the greatest vertical distance attained by the eCDF of x_t over the eCDF of y_t , and D_t^- is the greatest vertical distance attained by the eCDF of y_t over the eCDF of x_t .⁴⁴ Accordingly, we used a comparison of D_t^+ and D_t^- to created a signed D statistic (D), based on the logic that trait SNPs with a lower overall F_{ST} than control SNPs tend to have a higher D under the “greater” test than the “less” test, and vice versa.

Therefore, D_t^S :

⁴²B. S. Weir and C. Clark Cockerham, “Estimating F-Statistics for the Analysis of Population Structure,” *Evolution* 38, no. 6 (1984): 1358–70, <https://doi.org/10.2307/2408641>.

⁴³Emmanuel Paradis, “Pegas: An R Package for Population Genetics with an Integrated–Modular Approach,” *Bioinformatics* 26, no. 3 (February 1, 2010): 419–20, <https://doi.org/10.1093/bioinformatics/btp696>.

⁴⁴W. J. Conover, *Practical Nonparametric Statistics* (John Wiley & Sons, 1999), https://books.google.com?id=n_39DwAAQBAJ; J. Durbin, *Distribution Theory for Tests Based on Sample Distribution Function* (SIAM, 1973), <https://books.google.com?id=zAryCrT1IUYC>.

$$\begin{aligned}
 D_t^- > D_t^+ : & -D_t \\
 D_t^- = D_t^+ : & 0 \\
 D_t^- < D_t^+ : & D_t
 \end{aligned}$$

In **Figure 6.1** we present the F_{ST} distributions of trait SNPs for an illustrative subset of 28 human traits, ranked by D_t^S when compared with their matched control SNPs. **Figure 6.1A** shows the densities of SNPs as a function of F_{ST} , and **Figure 6.1B and C** show their empirical Cumulative Distribution Functions (eCDFs). **Figure 6.1B** includes the eCDFs of control SNPs in grey. eCDF figures for all 587 traits that passed our filters (Methods) are provided in Supplementary Fig. 1.

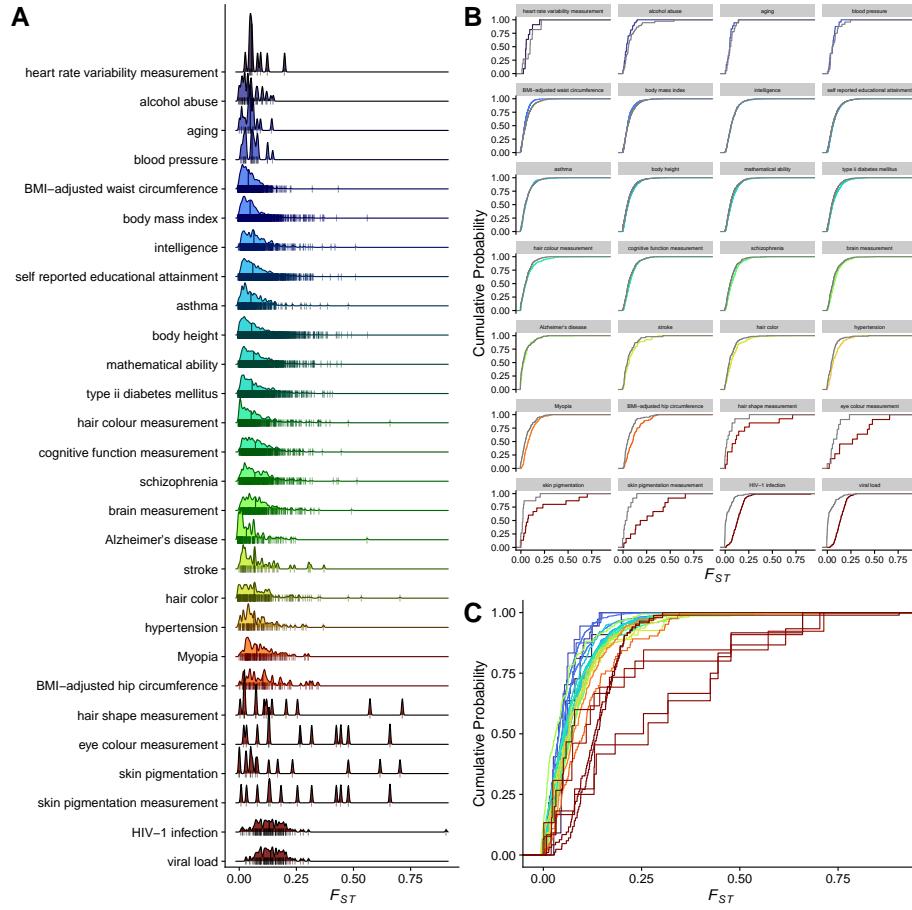


Figure 6.1: Distributions of F_{ST} across 28 illustrative human traits, ranked by signed-D (Kolmogorov-Smirnov test) comparing trait and control SNPs. A. F_{ST} density ridge plots with SNP markers. B. Empirical Cumulative Distribution Functions (eCDFs) of F_{ST} for trait-associated (colour) and random control (grey) SNPs, faceted by trait. C. Consolidated eCDFs of trait-associated SNPs from (B). eCDFs for all traits are included in Supplementary Figure 1.

References

- “A Global Reference for Human Genetic Variation.” *Nature* 526, no. 7571 (2015): 68–74. <https://doi.org/10.1038/nature15393>.
- Berg, Jeremy J., and Graham Coop. “A Population Genetic Signal of Polygenic Adaptation.” *PLOS Genetics* 10, no. 8 (August 7, 2014): e1004412. <https://doi.org/10.1371/journal.pgen.1004412>.
- Bergelson, Joy, and Fabrice Roux. “Towards Identifying Genes Underlying Ecologically Relevant Traits in *Arabidopsis Thaliana*.” *Nature Reviews Genetics* 11, no. 12, 12 (December 2010): 867–79. <https://doi.org/10.1038/nrg2896>.
- Chang, Christopher C, Carson C Chow, Laurent CAM Tellier, Shashaank Vattikuti, Shaun M Purcell, and James J Lee. “Second-Generation PLINK: Rising to the Challenge of Larger and Richer Datasets.” *GigaScience* 4, no. 1 (December 2015): 7. <https://doi.org/10.1186/s13742-015-0047-8>.
- Clark, Samuel A., John M. Hickey, Hans D. Daetwyler, and Julius HJ van der Werf. “The Importance of Information on Relatives for the Prediction of Genomic Breeding Values and the Implications for the Makeup of Reference Data Sets in Livestock Breeding Schemes.” *Genetics Selection Evolution* 44, no. 1 (February 9, 2012): 4. <https://doi.org/10.1186/1297-9686-44-4>.
- Conover, W. J. *Practical Nonparametric Statistics*. John Wiley & Sons, 1999. https://books.google.com?id=n_39DwAAQBAJ.
- Consortium, 1000 Genomes Project et al. “A Global Reference for Human Genetic Variation.” *Nature* 526, no. 7571 (2015): 68.
- Duncan, L., H. Shen, B. Gelaye, J. Meijsen, K. Ressler, M. Feldman, R. Peterson, and B. Domingue. “Analysis of Polygenic Risk Score Usage and Performance in Diverse Human Populations.” *Nature Communications* 10, no. 1, 1 (July 25, 2019): 3328. <https://doi.org/10.1038/s41467-019-11112-0>.
- Durbin, J. *Distribution Theory for Tests Based on Sample Distribution Function*. SIAM, 1973. <https://books.google.com?id=zAryCrTIIUYC>.
- Evans, Kathryn S., Marijke H. van Wijk, Patrick T. McGrath, Erik C. Andersen, and Mark G. Sterken. “From QTL to Gene: C. Ele-

- gans Facilitates Discoveries of the Genetic Mechanisms Underlying Natural Variation.” *Trends in Genetics* 37, no. 10 (October 1, 2021): 933–47. <https://doi.org/10.1016/j.tig.2021.06.005>.
- Fitzgerald, Tomas, Ian Brettell, Adrien Leger, Nadeshda Wolf, Natalja Kusminski, Jack Monahan, Carl Barton, et al. “The Medaka Inbred Kiyosu-Karlsruhe (MIKK) Panel.” *Genome Biology* 23, no. 1 (February 21, 2022): 59. <https://doi.org/10.1186/s13059-022-02623-z>.
- Fredman, David, Stefan J. White, Susanna Potter, Evan E. Eichler, Johan T. Den Dunnen, and Anthony J. Brookes. “Complex SNP-related Sequence Variation in Segmental Genome Duplications.” *Nature Genetics* 36, no. 8, 8 (August 2004): 861–66. <https://doi.org/10.1038/ng1401>.
- Habier, David, Jens Tetens, Franz-Reinhold Seefried, Peter Lichtner, and Georg Thaller. “The Impact of Genetic Relationship Information on Genomic Breeding Values in German Holstein Cattle.” *Genetics Selection Evolution* 42, no. 1 (February 19, 2010): 5. <https://doi.org/10.1186/1297-9686-42-5>.
- Hill, W. G., and Alan Robertson. “Linkage Disequilibrium in Finite Populations.” *Theoretical and Applied Genetics* 38, no. 6 (June 1, 1968): 226–31. <https://doi.org/10.1007/BF01245622>.
- Hoffmann, Ary A., Carla M. Sgrò, and Andrew R. Weeks. “Chromosomal Inversion Polymorphisms and Adaptation.” *Trends in Ecology & Evolution* 19, no. 9 (September 1, 2004): 482–88. <https://doi.org/10.1016/j.tree.2004.06.013>.
- “Index of /Pub/Release-102/Emf/Ensembl-Compara/Multiple_alignments/50_fish.epo/.” Accessed January 25, 2022. https://ftp.ensembl.org/pub/release-102/emf/ensembl-compara/multiple_alignments/50_fish.epo/.
- “Index of /Voll/Ftp/Data_collections/1000g_2504_high_coverage/Working/20201028_3202_phased/.” Accessed March 24, 2022. http://ftp.1000genomes.ebi.ac.uk/voll/ftp/data_collections/1000G_2504_high_coverage/working/20201028_3202_phased/.
- Johnson, William C., and Paul Gepts. “Segregation for Performance in Recombinant Inbred Populations Resulting from Inter-Gene Pool Crosses of Common Bean (*Phaseolus Vulgaris L.*).” *Euphytica* 106, no. 1 (March 1, 1999): 45–56. <https://doi.org/10.1023/A:1003541201923>.
- Katsumura, Takafumi, Shoji Oda, Hiroshi Mitani, and Hiroki Oota. “Medaka Population Genome Structure and Demographic History Described via Genotyping-by-Sequencing.” *G3 Genes|Genomes|Genetics* 9, no. 1 (January 1, 2019): 217–28. <https://doi.org/10.1534/g3.118.200779>.
- Kerminen, Sini, Alicia R. Martin, Jukka Koskela, Sanni E. Ruotsalainen, Aki S. Havulinna, Ida Surakka, Aarno Palotie, et al. “Geographic Variation and Bias in the Polygenic Scores of Complex Diseases and Traits in Finland.” *The American Journal of Human Genetics* 104, no. 1 (January 1, 2019): 10–21. <https://doi.org/10.1016/j.ajhg.2018.11.010>.

- Journal of Human Genetics* 104, no. 6 (June 6, 2019): 1169–81.
<https://doi.org/10.1016/j.ajhg.2019.05.001>.
- Khera, Amit V., Mark Chaffin, Krishna G. Aragam, Mary E. Haas, Carolina Roselli, Seung Hoan Choi, Pradeep Natarajan, et al. “Genome-Wide Polygenic Scores for Common Diseases Identify Individuals with Risk Equivalent to Monogenic Mutations.” *Nature Genetics* 50, no. 9, 9 (September 2018): 1219–24.
<https://doi.org/10.1038/s41588-018-0183-z>.
- Kullo, Iftikhar J., Hayan Jouni, Erin E. Austin, Sherry-Ann Brown, Teresa M. Kruisselbrink, Iyad N. Isseh, Raad A. Haddad, et al. “Incorporating a Genetic Risk Score Into Coronary Heart Disease Risk Estimates.” *Circulation* 133, no. 12 (March 22, 2016): 1181–88.
<https://doi.org/10.1161/CIRCULATIONAHA.115.020109>.
- Leger, Adrien, Ian Brettell, Jack Monahan, Carl Barton, Nadeshda Wolf, Natalja Kusminski, Cathrin Herder, et al. “Genomic Variations and Epigenomic Landscape of the Medaka Inbred Kiyosu-Karlsruhe (MIKK) Panel.” *Genome Biology* 23, no. 1 (February 21, 2022): 58.
<https://doi.org/10.1186/s13059-022-02602-4>.
- Lek, Monkol, Konrad J. Karczewski, Eric V. Minikel, Kaitlin E. Samocha, Eric Banks, Timothy Fennell, Anne H. O’NADonnell-Luria, et al. “Analysis of Protein-Coding Genetic Variation in 60,706 Humans.” *Nature* 536, no. 7616, 7616 (August 2016): 285–91.
<https://doi.org/10.1038/nature19057>.
- Limami, Anis M., Clothilde Rouillon, Gaëlle Glevarec, Andr’e Gal-lais, and Bertrand Hirel. “Genetic and Physiological Analysis of Germination Efficiency in Maize in Relation to Nitrogen Metabolism Reveals the Importance of Cytosolic Glutamine Synthetase.” *Plant Physiology* 130, no. 4 (December 1, 2002): 1860–70.
<https://doi.org/10.1104/pp.009647>.
- Maas, Paige, Myrto Barrdahl, Amit D. Joshi, Paul L. Auer, Mia M. Gaudet, Roger L. Milne, Fredrick R. Schumacher, et al. “Breast Cancer Risk From Modifiable and Nonmodifiable Risk Factors Among White Women in the United States.” *JAMA Oncology* 2, no. 10 (October 1, 2016): 1295–1302.
<https://doi.org/10.1001/jamaoncol.2016.1025>.
- MacArthur, Jacqueline, Emily Bowler, Maria Cerezo, Laurent Gil, Peggy Hall, Emma Hastings, Heather Junkins, et al. “The New NHGRI-EBI Catalog of Published Genome-Wide Association Studies (GWAS Catalog).” *Nucleic Acids Research* 45, no. D1 (January 4, 2017): D896–901.
<https://doi.org/10.1093/nar/gkw1133>.
- Mackay, Trudy F. C., and Wen Huang. “Charting the Genotype–Phenotype Map: Lessons from the *Drosophila Melanogaster* Genetic Reference Panel.” *WIREs Developmental Biology* 7, no. 1 (2018): e289.
<https://doi.org/10.1002/wdev.289>.
- Magno, Ramiro, and Ana-Teresa Maia. “Gwasrapidd: An R Package to Query, Download and Wrangle GWAS Catalog Data.” *Bioinfor-*

- matics* 36, no. 2 (January 15, 2020): 649–50. <https://doi.org/10.1093/bioinformatics/btz605>.
- Martin, Alicia R., Christopher R. Gignoux, Raymond K. Walters, Genevieve L. Wojcik, Benjamin M. Neale, Simon Gravel, Mark J. Daly, Carlos D. Bustamante, and Eimear E. Kenny. “Human Demographic History Impacts Genetic Risk Prediction Across Diverse Populations.” *The American Journal of Human Genetics* 100, no. 4 (April 6, 2017): 635–49. <https://doi.org/10.1016/j.ajhg.2017.03.004>.
- Martin, Alicia R., Masahiro Kanai, Yoichiro Kamatani, Yukinori Okada, Benjamin M. Neale, and Mark J. Daly. “Clinical Use of Current Polygenic Risk Scores May Exacerbate Health Disparities.” *Nature Genetics* 51, no. 4, 4 (April 2019): 584–91. <https://doi.org/10.1038/s41588-019-0379-x>.
- martin, Simon. *Simonhmartin/Genomics_general*, 2022. https://github.com/simonhmartin/genomics_general.
- Martin, Simon H., John W. Davey, and Chris D. Jiggins. “Evaluating the Use of ABBA–BABA Statistics to Locate Introgressed Loci.” *Molecular Biology and Evolution* 32, no. 1 (January 1, 2015): 244–57. <https://doi.org/10.1093/molbev/msu269>.
- McCarthy, Shane, Sayantan Das, Warren Kretzschmar, Olivier De laneau, Andrew R Wood, Alexander Teumer, Hyun Min Kang, et al. “A Reference Panel of 64,976 Haplotypes for Genotype Imputation.” *Nature Genetics* 48, no. 10, 10 (October 2016): 1279–83. <https://doi.org/10.1038/ng.3643>.
- McKenna, Aaron, Matthew Hanna, Eric Banks, Andrey Sivachenko, Kristian Cibulskis, Andrew Kernytsky, Kiran Garimella, et al. “The Genome Analysis Toolkit: A MapReduce Framework for Analyzing Next-Generation DNA Sequencing Data.” *Genome Research* 20, no. 9 (January 9, 2010): 1297–1303. <https://doi.org/10.1101/gr.107524.110>.
- Mukherjee, Siddhartha. *The Gene: An Intimate History*. Simon and Schuster, 2016. <https://books.google.com?id=XvAsDAAAQBAJ>.
- Naruse, Kiyoshi, Shoji Fukamachi, Hiroshi Mitani, Mariko Kondo, Tomoko Matsuoka, Shu Kondo, Nana Hanamura, et al. “A Detailed Linkage Map of Medaka, Oryzias Latipes: Comparative Genomics and Genome Evolution.” *Genetics* 154, no. 4 (April 1, 2000): 1773–84. <https://www.genetics.org/content/154/4/1773>.
- Natarajan, Pradeep, Robin Young, Nathan O. Stitziel, Sandosh Padmanabhan, Usman Baber, Roxana Mehran, Samantha Sartori, et al. “Polygenic Risk Score Identifies Subgroup With Higher Burden of Atherosclerosis and Greater Relative Benefit From Statin Therapy in the Primary Prevention Setting.” *Circulation* 135, no. 22 (May 30, 2017): 2091–101. <https://doi.org/10.1161/CIRCULATIONAHA.116.024436>.
- Panagiotou, Orestis A., John P. A. Ioannidis, and Genome-Wide Sig-

- nificance Project. “What Should the Genome-Wide Significance Threshold Be? Empirical Replication of Borderline Genetic Associations.” *International Journal of Epidemiology* 41, no. 1 (February 2012): 273–86. <https://doi.org/10.1093/ije/dyr178>.
- Paquette, Martine, Michael Chong, S’ebastien Th’eriault, Robert Dufour, Guillaume Par’e, and Alexis Baass. “Polygenic Risk Score Predicts Prevalence of Cardiovascular Disease in Patients with Familial Hypercholesterolemia.” *Journal of Clinical Lipidology* 11, no. 3 (May 1, 2017): 725–732.e5. <https://doi.org/10.1016/j.jacl.2017.03.019>.
- Paradis, Emmanuel. “Pegas: An R Package for Population Genetics with an Integrated–Modular Approach.” *Bioinformatics* 26, no. 3 (February 1, 2010): 419–20. <https://doi.org/10.1093/bioinformatics/btp696>.
- Paradis, Emmanuel, and Klaus Schliep. “Ape 5.0: An Environment for Modern Phylogenetics and Evolutionary Analyses in R.” *Bioinformatics* 35, no. 3 (February 1, 2019): 526–28. <https://doi.org/10.1093/bioinformatics/bty633>.
- Peirce, Jeremy L., Lu Lu, Jing Gu, Lee M. Silver, and Robert W. Williams. “A New Set of BXD Recombinant Inbred Lines from Advanced Intercross Populations in Mice.” *BMC Genetics* 5, no. 1 (April 29, 2004): 7. <https://doi.org/10.1186/1471-2156-5-7>.
- Plomin, Robert, and Kathryn Asbury. “Nature and Nurture: Genetic and Environmental Influences on Behavior.” *The ANNALS of the American Academy of Political and Social Science* 600, no. 1 (July 1, 2005): 86–98. <https://doi.org/10.1177/0002716205277184>.
- Popejoy, Alice B., and Stephanie M. Fullerton. “Genomics Is Failing on Diversity.” *Nature* 538, no. 7624, 7624 (October 2016): 161–64. <https://doi.org/10.1038/538161a>.
- Porcu, Eleonora, Serena Sanna, Christian Fuchsberger, and Lars G. Fritzsche. “Genotype Imputation in Genome-Wide Association Studies.” *Current Protocols in Human Genetics* 78, no. 1 (2013): 1.25.1–14. <https://doi.org/10.1002/0471142905.hg0125s78>.
- Pszczola, M., T. Strabel, H. A. Mulder, and M. P. L. Calus. “Reliability of Direct Genomic Values for Animals with Different Relationships Within and to the Reference Population.” *Journal of Dairy Science* 95, no. 1 (January 1, 2012): 389–400. <https://doi.org/10.3168/jds.2011-4338>.
- Purcell, Shaun M., and Christopher C Chang. *PLINK 1.9*, n.d. www.cog-genomics.org/plink/1.9/.
- Saliba-Colombani, Vera, Mathilde Causse, Laurent Gervais, and Jacqueline Philouze. “Efficiency of RFLP, RAPD, and AFLP Markers for the Construction of an Intraspecific Map of the Tomato Genome.” *Genome* 43, no. 1 (February 2000): 29–40. <https://doi.org/10.1139/g99-096>.
- Saul, Michael C., Vivek M. Philip, Laura G. Reinholdt, and Elissa J.

- Chesler. "High-Diversity Mouse Populations for Complex Traits." *Trends in Genetics* 35, no. 7 (July 1, 2019): 501–14. <https://doi.org/10.1016/j.tig.2019.04.003>.
- Schumacher, Fredrick R., Ali Amin Al Olama, Sonja I. Berndt, Sara Benlloch, Mahbubl Ahmed, Edward J. Saunders, Tokhir Dadaev, et al. "Association Analyses of More Than 140,000 Men Identify 63 New Prostate Cancer Susceptibility Loci." *Nature Genetics* 50, no. 7, 7 (July 2018): 928–36. <https://doi.org/10.1038/s41588-018-0142-8>.
- Scutari, Marco, Ian Mackay, and David Balding. "Using Genetic Distance to Infer the Accuracy of Genomic Prediction." *PLOS Genetics* 12, no. 9 (September 2, 2016): e1006288. <https://doi.org/10.1371/journal.pgen.1006288>.
- Sham, P. C., S. S. Cherny, S. Purcell, and J. K. Hewitt. "Power of Linkage Versus Association Analysis of Quantitative Traits, by Use of Variance-Components Models, for Sibship Data." *The American Journal of Human Genetics* 66, no. 5 (May 1, 2000): 1616–30. <https://doi.org/10.1086/302891>.
- Sharp, Seth A., Stephen S. Rich, Andrew R. Wood, Samuel E. Jones, Robin N. Beaumont, James W. Harrison, Darius A. Schneider, et al. "Development and Standardization of an Improved Type 1 Diabetes Genetic Risk Score for Use in Newborn Screening and Incident Diagnosis." *Diabetes Care* 42, no. 2 (January 11, 2019): 200–207. <https://doi.org/10.2337/dc18-1785>.
- Smigielski, Elizabeth M., Karl Sirotnik, Minghong Ward, and Stephen T. Sherry. "dbSNP: A Database of Single Nucleotide Polymorphisms." *Nucleic Acids Research* 28, no. 1 (January 1, 2000): 352–55. <https://doi.org/10.1093/nar/28.1.352>.
- Spivakov, Mikhail, Thomas O Auer, Ravindra Perivali, Ian Dunham, Dirk Dolle, Asao Fujiyama, Atsushi Toyoda, et al. "Genomic and Phenotypic Characterization of a Wild Medaka Population: Towards the Establishment of an Isogenic Population Genetic Resource in Fish." *G3 Genes|Genomes|Genetics* 4, no. 3 (March 1, 2014): 433–45. <https://doi.org/10.1534/g3.113.008722>.
- Svenson, Karen L., Daniel M Gatti, William Valdar, Catherine E Welsh, Riyan Cheng, Elissa J Chesler, Abraham A Palmer, Leonard McMillan, and Gary A Churchill. "High-Resolution Genetic Mapping Using the Mouse Diversity Outbred Population." *Genetics* 190, no. 2 (February 1, 2012): 437–47. <https://doi.org/10.1534/genetics.111.132597>.
- "The \$11.9 Trillion Global Healthcare Market: Key Opportunities & Strategies (2014-2022) - ResearchAndMarkets.com," June 25, 2019. <https://www.businesswire.com/news/home/20190625005862/en/The-11.9-Trillion-Global-Healthcare-Market-Key-Opportunities-Strategies-2014-2022---ResearchAndMarkets.com>.

- Threadgill, David W., Darla R. Miller, Gary A. Churchill, and Fernando Pardo-Manuel de Villena. “The Collaborative Cross: A Recombinant Inbred Mouse Population for the Systems Genetic Era.” *ILAR Journal* 52, no. 1 (January 1, 2011): 24–31. <https://doi.org/10.1093/ilar.52.1.24>.
- Tikkanen, Emmi, Aki S. Havulinna, Aarno Palotie, Veikko Salomaa, and Samuli Ripatti. “Genetic Risk Prediction and a 2-Stage Risk Screening Strategy for Coronary Heart Disease.” *Arteriosclerosis, Thrombosis, and Vascular Biology* 33, no. 9 (September 2013): 2261–66. <https://doi.org/10.1161/ATVBAHA.112.301120>.
- Vilhjálmsdóttir, Bjarni J., Jian Yang, Hilary K. Finucane, Alexander Gusev, Sara Lindström, Stephan Ripke, Giulio Genovese, et al. “Modeling Linkage Disequilibrium Increases Accuracy of Polygenic Risk Scores.” *The American Journal of Human Genetics* 97, no. 4 (2015): 576–92.
- Wang, Ying, Jing Guo, Guiyan Ni, Jian Yang, Peter M. Visscher, and Loic Yengo. “Theoretical and Empirical Quantification of the Accuracy of Polygenic Scores in Ancestry Divergent Populations.” *Nature Communications* 11, no. 1, 1 (July 31, 2020): 3865. <https://doi.org/10.1038/s41467-020-17719-y>.
- Weir, B. S., and C. Clark Cockerham. “Estimating F-Statistics for the Analysis of Population Structure.” *Evolution* 38, no. 6 (1984): 1358–70. <https://doi.org/10.2307/2408641>.
- Wittbrodt, Joachim, Akihiro Shima, and Manfred Schartl. “Medaka — a Model Organism from the Far East.” *Nature Reviews Genetics* 3, no. 1, 1 (January 2002): 53–64. <https://doi.org/10.1038/nrg704>.
- Wray, Naomi R., Michael E. Goddard, and Peter M. Visscher. “Prediction of Individual Genetic Risk to Disease from Genome-Wide Association Studies.” *Genome Research* 17, no. 10 (January 10, 2007): 1520–28. <https://doi.org/10.1101/gr.6665407>.