Supplementary Materials for Global Geographic, Seasonal, Environmental and Demographic Drivers of Variations in Longitudinal Cardiac Physiology in 5 million Fitbit Users

Katarina Vukosavljević[1,3], Abram Schönfeldt[1,4], Justin Phillips[1], YongSuk Cho[1], Tingting Zhu[3], Shwetak Patel[1,7], Soren Brage[6], Robert Harle[1,5] and Daniel Roggen[1,2]

[1]Google, Mountain View, CA, USA, [2]School of Engineering & Informatics, University of Sussex, Falmer, UK, [3]Institute of Biomedical Engineering, University of Oxford, Oxford, UK, [4]Nuffield Department of Population Health, University of Oxford, Oxford, UK, [5]Department of Computer Science and Technology, University of Cambridge, Cambridge, UK, [6]IMS Epidemiology, University of Cambridge School of Clinical Medicine, Cambridge, UK, [7]Paul G. Allen School of Computer Science and Engineering, University of Washington, Seattle, WA, USA

A. Correcting False Demographic Reporting

Following the dataset preparation process described in Section Methodology, we identified an anomaly in the birth year self-reported by participants, with an abnormally large number of users reporting to be born in year 2000, compared to those reporting to be born in 1999 or 2001. Indeed users are presented with a default choice in the Fitbit application used to connect to their wearable device. The application presents by default a birth year of 2000, and users may choose to simply accept this setting rather than enter their true date of birth.

Besides a distinct spike in user count for that date of birth, the inflated cohort size at age 22 skews the mean RHR to higher values and creates a distribution that is significantly different from cohorts in adjacent ages. This is quantified by a more than three-fold increase in the pairwise Wasserstein distance between the age 22 distribution and its neighbours (overall 0.47 bpm vs. age 21 and 0.55 bpm vs. age 23, compared to a baseline distance of only 0.14 bpm between ages 21 and 23), creating a visible deviation from the otherwise smooth, age-related evolution of RHR, Figure A.3 (Left).

To maintain the integrity of our analysis, we deal with this artifact during the preprocessing stage rather than within the statistical models themselves. This ensures reproducibility and provides a method for future studies encountering similar demographic reporting biases. Rather than excluding the entire age group, the following section describes a density-based thinning method that preserves as much valid physiological data as possible.

A.1. Density-Based Thinning

We implement a local density-based histogram-matching thinning algorithm. This method relies on the biological expectation of continuity in resting heart rate across the lifespan, assuming the true RHR distribution of 22-year-olds should be bounded by the distributions of their adjacent age cohorts (ages 21 and 23). With this approach we prioritise preserving as much data as possible while correcting for the skewed mean introduced by the reporting artifact. We apply the correction algorithm as follows:

1. **Stratification:** We stratify the cohort by sex and geographic latitude band to ensure that the underlying regional and demographic characteristics are preserved during the correction

Corresponding author(s): roggen@google.com

process.

2. **PDF Estimation:** For each stratum, we compute the empirical probability density functions (PDFs) of RHR at the adjacent ages, $P_{21}(x)$ and $P_{23}(x)$, using a histogram-based estimator. We define the target physiological distribution for age 22 as the midpoint of these adjacent PDFs:

$$P_{\text{target}}(x) = \frac{P_{21}(x) + P_{23}(x)}{2}$$

3. **Retention Probability:** We compute the empirical PDF of the observed 22-year-old cohort, $P_{22}(x)$, within the same stratum. For each participant aged 22 with mean RHR value x, we calculate a retention probability $p(x)$ proportional to the ratio of the target density to the observed density:

$$p(x) = \min\left(1, \frac{P_{\text{target}}(x)}{P_{22}(x)}\right)$$

4. **Randomised Thinning:** We perform randomised thinning, retaining each 22-year-old participant with probability $p(x)$.

This approach is robust because it exclusively targets and removes excess density that deviates from expected biological progression. By design, the algorithm leaves the 22-year-old sub-cohort intact in regions where the observed density aligns with the expected distribution of adjacent ages. Applying this local thinning removed 24,693 participants (0.51% of the overall RHR cohort), resulting in a final sample size of $N = 4,833,797$. The updated global RHR cohort characteristics are illustrated in Figure A.1.

A.2. Method Verification

Figure A.2 illustrates the empirical RHR distributions for ages 21, 22, and 23 overall and in each latitude band, before and after density-based thinning. Before thinning, the age 22 curve (red) shows unnatural shoulders and tail shifts compared to the smooth curves of ages 21 (green) and 23 (blue). After thinning, the age 22 distribution successfully recovers the expected biological mean and variance, reducing pairwise Wasserstein distances below or near the baseline distance between ages 21 and 23 (Age 22 vs. 21: 0.11 bpm, down from 0.47 bpm; Age 22 vs. 23: 0.05 bpm, down from 0.55 bpm; baseline 21 vs. 23: 0.14 bpm). This confirms that density-based thinning effectively resolves the anomaly by aligning the age 22 distribution with its neighbours.

Figure A.3 shows the effect of the thinning on the evolution of RHR and sample sizes with age. The left column shows that the spike in RHR at age 22 (red dashed line) is corrected in the thinned dataset (blue solid line), and the right column the corresponding reduction in the user counts.

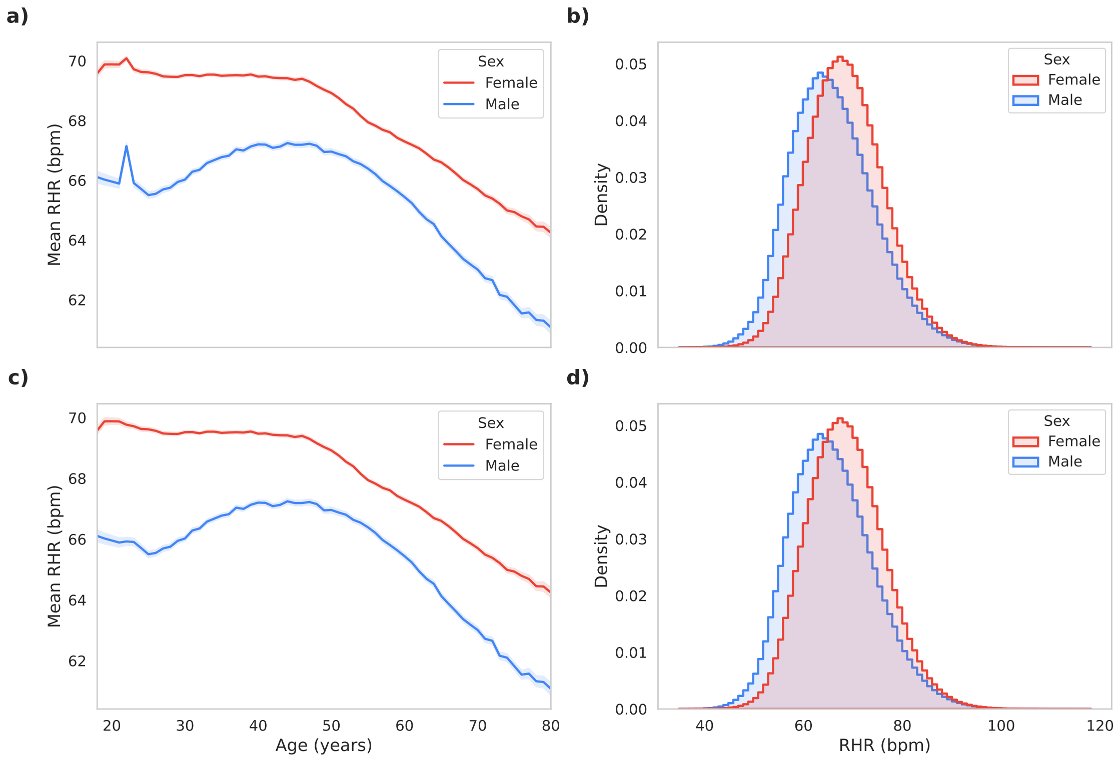


Figure A.1 | **Mean Resting heart rate (RHR) cohort age and sex distributions before (top row) and after (bottom row) density-based thinning.** The figure compares the cohort age trends and sex distributions in the raw dataset (top row, before thinning) and the thinned dataset (bottom row, after thinning). (Left column) Mean RHR per user age (95% CI shaded), demonstrating how the artificial spike at Age 22 is resolved in the thinned dataset. (Right column) Population density distribution of RHR by sex.

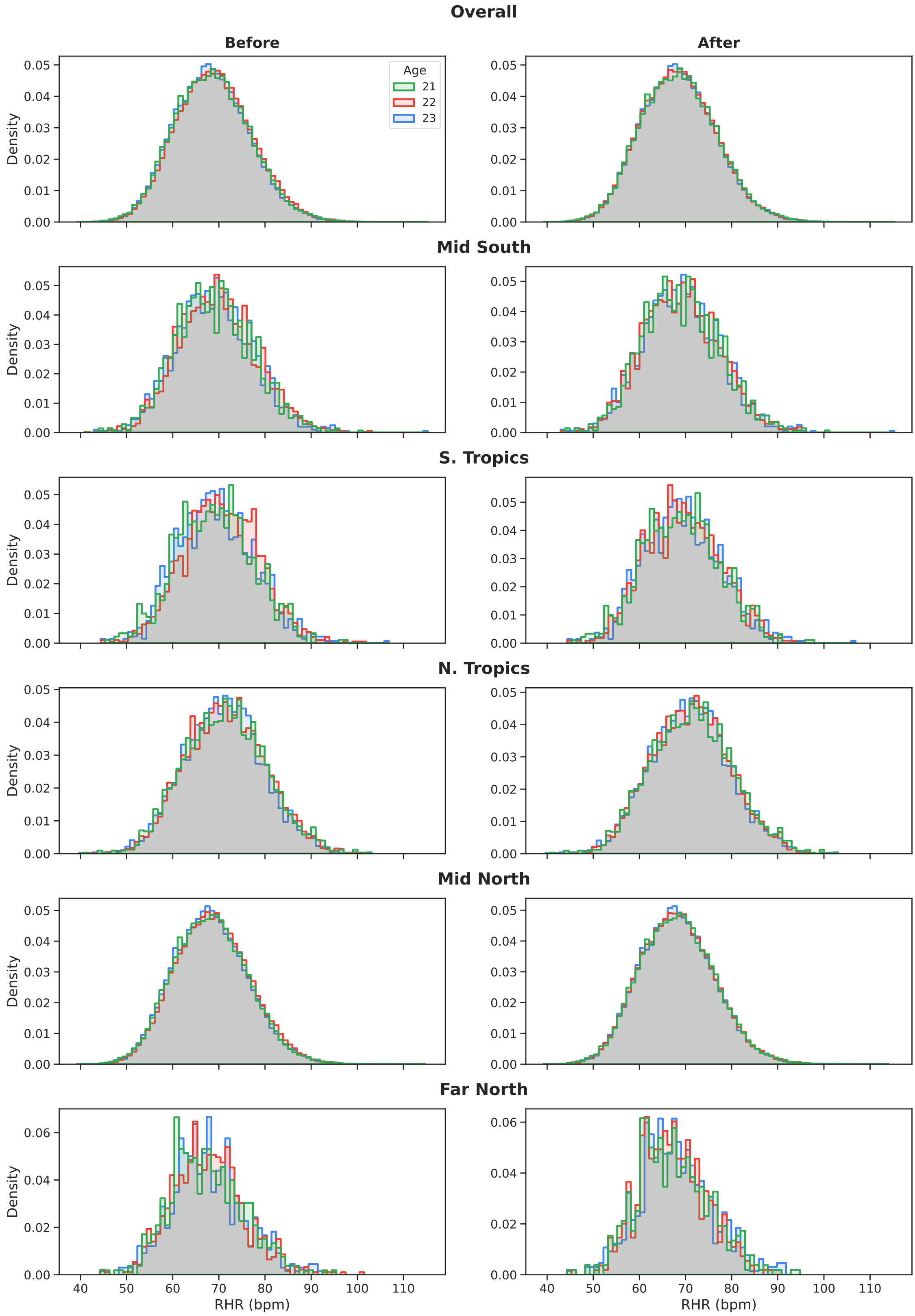


Figure A.2 | **RHR probability distributions for Ages 21, 22, and 23 before and after density-based thinning.** Curves are shown for the overall population and all five latitude bands (Mid South, Southern Tropics, Northern Tropics, Mid North, and Far North). The raw Age 22 distribution (red, left column) exhibits unnatural shape deviations. The thinned Age 22 distribution (red, right column) aligns with the biological bounds set by Ages 21 (green) and 23 (blue) across all cohorts.

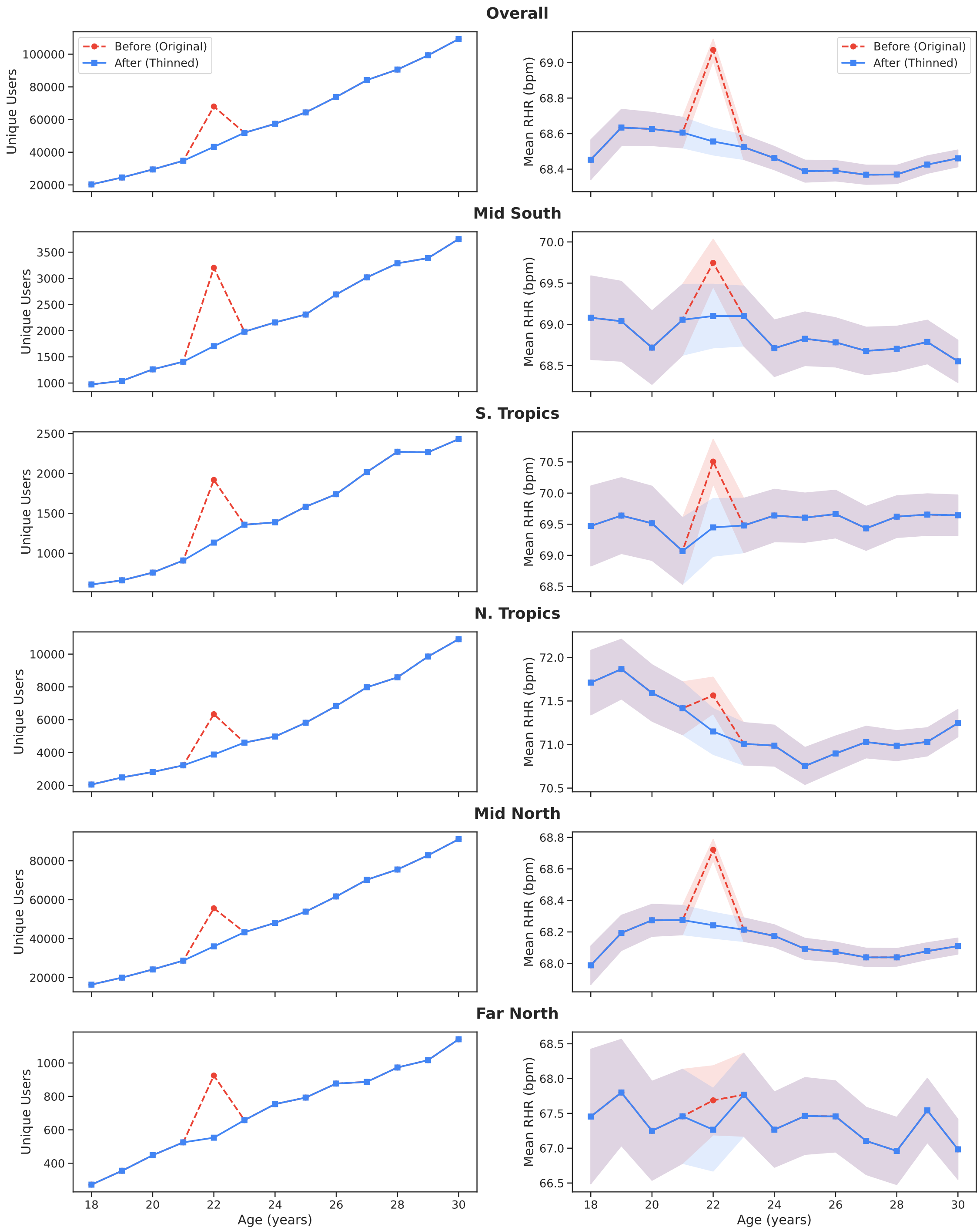


Figure A.3 | **Demographic trends and sample sizes before and after density-based thinning across latitude bands.** (Left column) Unique user count vs. age (18 to 30 years) for the overall population and all five latitude bands, showing the selective thinning of the default-reporting spike at age 22. (Right column) Mean RHR vs. age (95% CI shaded), demonstrating that the artificial spike at age 22 (red dashed line) is completely resolved in the thinned dataset (blue solid line) across all geographic cohorts.

B. Resting Heart Rate (RHR) Supplementary Materials

B.1. Baseline Temperature Residualisation Regressions

Here we provide the baseline temperature residualisation parameter estimates, as described in **??**. We summarise the resulting parameters and their 95% confidence intervals in Table A.1.

Table A.1 | **OLS temperature residualisation regression parameters for the RHR cohort.**

Parameter	T_{max} **[95% CI]**	T_{min} **[95% CI]**	T_{mean} **[95% CI]**
Intercept (α_0)	−0.0064 [−0.0065, −0.0063]	−0.0063 [−0.0064, −0.0062]	−0.0064 [−0.0065, −0.0063]
Abs Latitude Slope (α_1)	−0.4803 [−0.4805, −0.4801]	−0.3733 [−0.3736, −0.3730]	−0.4374 [−0.4377, −0.4372]
Signed Latitude Slope (α_2)	0.0035 [0.0033, 0.0037]	−0.0267 [−0.0270, −0.0265]	−0.0054 [−0.0057, −0.0052]
$m_{\sin_1}$ ($\alpha_{3,1}$)	−0.2800 [−0.2801, −0.2799]	−0.2919 [−0.2920, −0.2918]	−0.2860 [−0.2861, −0.2859]
$m_{\cos_1}$ ($\alpha_{4,1}$)	−0.4122 [−0.4123, −0.4121]	−0.3700 [−0.3702, −0.3699]	−0.3973 [−0.3974, −0.3972]
$m_{\sin_2}$ ($\alpha_{3,2}$)	0.0114 [0.0113, 0.0115]	0.0084 [0.0083, 0.0085]	0.0102 [0.0101, 0.0103]
$m_{\cos_2}$ ($\alpha_{4,2}$)	−0.0445 [−0.0446, −0.0443]	−0.0162 [−0.0164, −0.0161]	−0.0278 [−0.0279, −0.0277]
$m_{\sin_1} \cdot \phi_c$ ($\alpha_{5,1}$)	−0.2238 [−0.2240, −0.2236]	−0.2025 [−0.2028, −0.2023]	−0.2153 [−0.2155, −0.2151]
$m_{\cos_1} \cdot \phi_c$ ($\alpha_{6,1}$)	−0.2798 [−0.2800, −0.2796]	−0.2108 [−0.2110, −0.2105]	−0.2475 [−0.2477, −0.2472]
$m_{\sin_2} \cdot \phi_c$ ($\alpha_{5,2}$)	0.0119 [0.0117, 0.0121]	0.0074 [0.0072, 0.0077]	0.0127 [0.0125, 0.0130]
$m_{\cos_2} \cdot \phi_c$ ($\alpha_{6,2}$)	−0.0076 [−0.0078, −0.0074]	0.0048 [0.0045, 0.0050]	0.0006 [0.0004, 0.0009]
Model R^2	0.7853	0.6355	0.7222

B.2. Model Comparison and Progressive Fits

In this Section, we provide the results of the incremental LME modelling on the RHR cohort. Table A.2 details the complete model comparison grid and fit diagnostics across all tested candidate models. In Tables A.3 and A.4, we provide the complete parameter decomposition for the winning RHR models at each incremental stage. Table A.3 details the unstandardised estimates (Est., in bpm), while Table A.4 details the fully standardised trajectories (Std. β, in bpm per 2-SD predictor shift). Both tables report the 95% confidence intervals and random participant variance components (σ_α^2).

Table A.2 | **Model Comparison and Fit Diagnostics for all Resting Heart Rate (RHR) Candidate Models.**

Model	Fixed Effects Formula	Marg. R^2 [%]	Cond. R^2 [%]	ICC	RMSE [bpm]	Log-Likelihood	AIC	BIC
Stage 1 (Demo)								
1.1	$a \cdot s$	4.260	91.770	0.914	2.267	-103,821,879	207,643,770	207,643,863
1.2	$\boldsymbol{(a + a^2) \cdot s}$	**5.100**	**91.777**	**0.913**	**2.267**	**-103,801,367**	**207,602,749**	**207,602,873**
Stage 2 (Season)								
2.1	$(a + a^2) \cdot s + m_{\sin_1} + m_{\cos_1}$	5.156	91.835	0.914	2.259	-103,674,522	207,349,064	207,349,220
2.2	$\boldsymbol{(a + a^2) \cdot s + m_{\sin_1} + m_{\cos_1} + m_{\sin_2} + m_{\cos_2}}$	**5.178**	**91.857**	**0.914**	**2.257**	**-103,629,307**	**207,258,637**	**207,258,823**
Stage 3 (Spatial Geography)								
3.1	$(a + a^2) \cdot s + d$	5.148	91.824	0.914	2.261	-103,698,137	207,396,293	207,396,432
3.2	$(a + a^2) \cdot s + d + d^2$	5.155	91.849	0.914	2.259	-103,674,776	207,349,572	207,349,728
3.3	$(a + a^2) \cdot s + d \cdot (m_{\sin_1} + m_{\cos_1})$	5.178	91.872	0.914	2.256	-103,622,615	207,245,257	207,245,458
3.4	$(a + a^2) \cdot s + (d + d^2) \cdot (m_{\sin_1} + m_{\cos_1} + m_{\sin_2} + m_{\cos_2})$	5.203	91.868	0.914	2.254	-103,585,238	207,170,520	207,170,861
3.5	$(a + a^2) \cdot s + (m_{\sin_1} + m_{\cos_1} + m_{\sin_2} + m_{\cos_2}) + (\phi)$	5.221	91.838	0.914	2.257	-103,623,831	207,247,688	207,247,889
3.6	$(a+a^2) \cdot s+(m_{\sin_1}+m_{\cos_1}+m_{\sin_2}+m_{\cos_2})+(\phi)+\lambda_{\sin}+\lambda_{\cos}$	5.245	91.826	0.914	2.257	-103,622,368	207,244,766	207,244,999
3.7	$(a + a^2) \cdot s + (m_{\sin_1} + m_{\cos_1} + m_{\sin_2} + m_{\cos_2}) + (\phi + \phi^2)$	5.262	91.813	0.914	2.257	-103,616,448	207,232,924	207,233,141
3.8	$(a + a^2) \cdot s + (m_{\sin_1} + m_{\cos_1} + m_{\sin_2} + m_{\cos_2}) + (\phi + \phi^2) + \lambda_{\sin} + \lambda_{\cos}$	5.290	91.804	0.913	2.257	-103,615,478	207,230,988	207,231,236
3.9	$\boldsymbol{(a + a^2) \cdot s + (m_{\sin_1} + m_{\cos_1} + m_{\sin_2} + m_{\cos_2}) \cdot (\phi + \phi^2) + \lambda_{\sin} + \lambda_{\cos}}$	**5.312**	**91.831**	**0.914**	**2.254**	**-103,564,051**	**207,128,149**	**207,128,522**
Stage 4 (Temperature)								
4.1	$(a + a^2) \cdot s + (m_{\sin_1} + m_{\cos_1} + m_{\sin_2} + m_{\cos_2}) + (T_{\text{mean}})$	5.184	91.874	0.914	2.256	-103,618,651	207,237,328	207,237,529
4.2	$(a+a^2) \cdot s+(m_{\sin_1}+m_{\cos_1}+m_{\sin_2}+m_{\cos_2})+(T_{\max}+T_{\min})$	5.191	91.869	0.914	2.256	-103,616,084	207,232,196	207,232,414
4.3	$(a + a^2) \cdot s + (m_{\sin_1} + m_{\cos_1} + m_{\sin_2} + m_{\cos_2}) + (T_{\max} + T^2_{\max} + T_{\min} + T^2_{\min})$	5.191	91.882	0.914	2.255	-103,611,843	207,223,718	207,223,966
4.4	$\boldsymbol{(a + a^2) \cdot s + (m_{\sin_1} + m_{\cos_1} + m_{\sin_2} + m_{\cos_2}) \cdot (T_{\max} + T^2_{\max} + T_{\min} + T^2_{\min})}$	**5.208**	**91.878**	**0.914**	**2.254**	**-103,589,549**	**207,179,162**	**207,179,659**
Stage 5 (Joint)								
5.1	$(a + a^2) \cdot s + (m_{\sin_1} + m_{\cos_1} + m_{\sin_2} + m_{\cos_2}) \cdot (\phi + \phi^2) + \lambda_{\sin} + \lambda_{\cos} + T^{\text{res}}_{\max} + (T^{\text{res}}_{\max})^2 + T^{\text{res}}_{\min} + (T^{\text{res}}_{\min})^2$	5.323	91.834	0.914	2.253	-103,556,467	207,112,990	207,113,425
5.2	$(a + a^2) \cdot s + (m_{\sin_1} + m_{\cos_1} + m_{\sin_2} + m_{\cos_2}) \cdot (T^{\text{res}}_{\max} + (T^{\text{res}}_{\max})^2 + T^{\text{res}}_{\min} + (T^{\text{res}}_{\min})^2) + \phi + \phi^2 + \lambda_{\sin} + \lambda_{\cos}$	5.330	91.834	0.914	2.253	-103,556,927	207,113,925	207,114,484
5.3	$\boldsymbol{(a + a^2) \cdot s + (m_{\sin_1} + m_{\cos_1} + m_{\sin_2} + m_{\cos_2}) \cdot (\phi + \phi^2) + (m_{\sin_1} + m_{\cos_1} + m_{\sin_2} + m_{\cos_2}) \cdot (T^{\text{res}}_{\max} + (T^{\text{res}}_{\max})^2 + T^{\text{res}}_{\min} + (T^{\text{res}}_{\min})^2) + \lambda_{\sin} + \lambda_{\cos}}$	**5.327**	**91.838**	**0.914**	**2.252**	**-103,546,895**	**207,093,878**	**207,094,560**

Notes: Models are enumerated by hierarchical stage and candidate index matching the main text. Information criteria (AIC, BIC) and Log-Likelihood are estimated via Maximum Likelihood (ML). Marginal R^2 [%] represents variance explained by fixed effects; Conditional R^2 [%] represents total variance explained including random participant intercepts.

Table A.3 | **Full Unstandardised Fixed-Effects Parameter Estimates, Variance Components, and Model Fit Diagnostics for Longitudinal Resting Heart Rate (RHR) Models across Progressive Hierarchical Stages.**

	Stage 1 Winner		Stage 2 Winner		Stage 3 Winner		Stage 4 Winner		Stage 5 Winner	
Predictors	**Est. [bpm]**	**95% CI [bpm]**	**Est. [bpm]**	**95% CI [bpm]**	**Est. [bpm]**	**95% CI [bpm]**	**Est. [bpm]**	**95% CI [bpm]**	**Est. [bpm]**	**95% CI [bpm]**
Fixed Effects: Demographics										
(Intercept)	67.65	[67.64, 67.66]	67.64	[67.64, 67.65]	67.65	[67.65, 67.66]	67.71	[67.70, 67.72]	67.63	[67.63, 67.64]
a (Age)	0.21	[0.21, 0.21]	0.21	[0.21, 0.21]	0.21	[0.21, 0.21]	0.21	[0.21, 0.21]	0.21	[0.21, 0.21]
$a \cdot s$	0.23	[0.22, 0.23]	0.23	[0.22, 0.23]	0.23	[0.22, 0.23]	0.23	[0.22, 0.23]	0.23	[0.22, 0.23]
a^2	-0.00	[-0.00, -0.00]	-0.00	[-0.00, -0.00]	-0.00	[-0.00, -0.00]	-0.00	[-0.00, -0.00]	-0.00	[-0.00, -0.00]
$a^2 \cdot s$	-0.00	[-0.00, -0.00]	-0.00	[-0.00, -0.00]	-0.00	[-0.00, -0.00]	-0.00	[-0.00, -0.00]	-0.00	[-0.00, -0.00]
s (Sex)	-2.53	[-2.54, -2.51]	-2.53	[-2.55, -2.52]	-2.57	[-2.59, -2.56]	-2.52	[-2.53, -2.50]	-2.57	[-2.59, -2.56]
Fixed Effects: Seasonality										
$m_{\cos_1}$	–		0.23	[0.23, 0.23]	0.23	[0.23, 0.23]	0.02	[0.01, 0.02]	0.16	[0.16, 0.16]
$m_{\cos_2}$	–		0.15	[0.15, 0.15]	0.15	[0.15, 0.15]	0.17	[0.17, 0.18]	0.14	[0.14, 0.14]
$m_{\sin_1}$	–		0.15	[0.15, 0.15]	0.15	[0.15, 0.15]	0.04	[0.04, 0.04]	0.12	[0.12, 0.12]
$m_{\sin_2}$	–		-0.08	[-0.08, -0.07]	-0.07	[-0.08, -0.07]	-0.02	[-0.02, -0.02]	-0.09	[-0.09, -0.09]
Fixed Effects: Spatial Geography										
$\lambda_{\cos}$	–		–		-0.12	[-0.12, -0.11]	–		-0.02	[-0.03, -0.01]
ϕ (Latitude)	–		–		0.00	[0.00, 0.00]	–		0.00	[0.00, 0.00]
ϕ^2	–		–		-0.00	[-0.00, -0.00]	–		-0.00	[-0.00, -0.00]
$\phi \cdot m_{\cos_1}$	–		–		0.00	[0.00, 0.00]	–		0.00	[0.00, 0.00]
$\phi^2 \cdot m_{\cos_1}$	–		–		-0.00	[-0.00, -0.00]	–		-0.00	[-0.00, -0.00]
$\phi \cdot m_{\cos_2}$	–		–		-0.00	[-0.00, -0.00]	–		0.00	[0.00, 0.00]
$\phi^2 \cdot m_{\cos_2}$	–		–		0.00	[0.00, 0.00]	–		0.00	[0.00, 0.00]
$\phi \cdot m_{\sin_1}$	–		–		0.00	[0.00, 0.00]	–		0.00	[0.00, 0.00]
$\phi^2 \cdot m_{\sin_1}$	–		–		-0.00	[-0.00, -0.00]	–		-0.00	[-0.00, -0.00]
$\phi \cdot m_{\sin_2}$	–		–		-0.00	[-0.00, -0.00]	–		-0.00	[-0.00, -0.00]
$\phi^2 \cdot m_{\sin_2}$	–		–		-0.00	[-0.00, -0.00]	–		0.00	[0.00, 0.00]
$\lambda_{\sin}$ (Longitude)	–		–		-0.03	[-0.04, -0.03]	–		0.04	[0.03, 0.05]
Fixed Effects: Temperature										
$T_{\max}/T_{\max}^{\text{res}}$	–		–		–		0.01	[0.01, 0.01]	0.28	[0.27, 0.29]
$T_{\max}^2/(T_{\max}^{\text{res}})^2$	–		–		–		-0.00	[-0.00, -0.00]	-0.09	[-0.11, -0.08]
$T_{\min}/T_{\min}^{\text{res}}$	–		–		–		-0.04	[-0.04, -0.04]	-0.50	[-0.51, -0.49]
$T_{\min}^2/(T_{\min}^{\text{res}})^2$	–		–		–		0.00	[0.00, 0.00]	-0.06	[-0.07, -0.05]
$(T_{\max}/T_{\max}^{\text{res}}) \cdot m_{\cos_1}$	–		–		–		0.03	[0.03, 0.04]	-0.36	[-0.38, -0.35]
$((T_{\max}/T_{\max}^{\text{res}})^2) \cdot m_{\cos_1}$	–		–		–		-0.00	[-0.00, -0.00]	-0.07	[-0.08, -0.05]
$(T_{\min}/T_{\min}^{\text{res}}) \cdot m_{\cos_1}$	–		–		–		0.02	[0.02, 0.02]	0.20	[0.19, 0.21]
$((T_{\min}/T_{\min}^{\text{res}})^2) \cdot m_{\cos_1}$	–		–		–		-0.00	[-0.00, -0.00]	-0.04	[-0.05, -0.02]
$(T_{\max}/T_{\max}^{\text{res}}) \cdot m_{\cos_2}$	–		–		–		-0.06	[-0.06, -0.06]	-0.37	[-0.38, -0.36]
$((T_{\max}/T_{\max}^{\text{res}})^2) \cdot m_{\cos_2}$	–		–		–		0.00	[0.00, 0.00]	0.21	[0.20, 0.22]
$(T_{\min}/T_{\min}^{\text{res}}) \cdot m_{\cos_2}$	–		–		–		0.03	[0.03, 0.03]	0.20	[0.19, 0.21]
$((T_{\min}/T_{\min}^{\text{res}})^2) \cdot m_{\cos_2}$	–		–		–		-0.00	[-0.00, -0.00]	-0.24	[-0.25, -0.23]
$(T_{\max}/T_{\max}^{\text{res}}) \cdot m_{\sin_1}$	–		–		–		0.01	[0.01, 0.02]	-0.26	[-0.27, -0.24]
$((T_{\max}/T_{\max}^{\text{res}})^2) \cdot m_{\sin_1}$	–		–		–		-0.00	[-0.00, -0.00]	0.16	[0.14, 0.17]
$(T_{\min}/T_{\min}^{\text{res}}) \cdot m_{\sin_1}$	–		–		–		0.01	[0.01, 0.01]	0.13	[0.12, 0.14]
$((T_{\min}/T_{\min}^{\text{res}})^2) \cdot m_{\sin_1}$	–		–		–		-0.00	[-0.00, -0.00]	-0.05	[-0.07, -0.04]
$(T_{\max}/T_{\max}^{\text{res}}) \cdot m_{\sin_2}$	–		–		–		0.02	[0.02, 0.02]	0.15	[0.14, 0.16]
$((T_{\max}/T_{\max}^{\text{res}})^2) \cdot m_{\sin_2}$	–		–		–		-0.00	[-0.00, -0.00]	-0.17	[-0.18, -0.16]
$(T_{\min}/T_{\min}^{\text{res}}) \cdot m_{\sin_2}$	–		–		–		-0.01	[-0.01, -0.01]	-0.02	[-0.03, -0.01]
$((T_{\min}/T_{\min}^{\text{res}})^2) \cdot m_{\sin_2}$	–		–		–		0.00	[0.00, 0.00]	0.11	[0.10, 0.12]
Variance Components										
Residual Var (σ_ε^2)	5.83		5.77		5.76		5.76		5.75	
Intercept Var (σ_α^2 user)	61.45		61.46		60.98		61.46		60.97	

Notes: Unstandardised parameter estimates across all progressive hierarchical stages. Fixed-effects notation defined as: a, age; s, sex; h, seasonal harmonics; ϕ, latitude; λ, longitude; T, temperature. Interaction terms are denoted by $(\cdot)$. *Est.* denotes unstandardised coefficients. Estimates are presented in beats per minute [bpm] and represent absolute changes, except for the Intercept which represents the baseline mean in bpm. **Bold values indicate coefficients that are NOT statistically significant ($p \geq 0.05$, 95% CI includes zero).** Empty cells indicate variables not structurally introduced until later hierarchical stages. Indented items indicate explicit parameter metrics nested within their respective structural grouping.

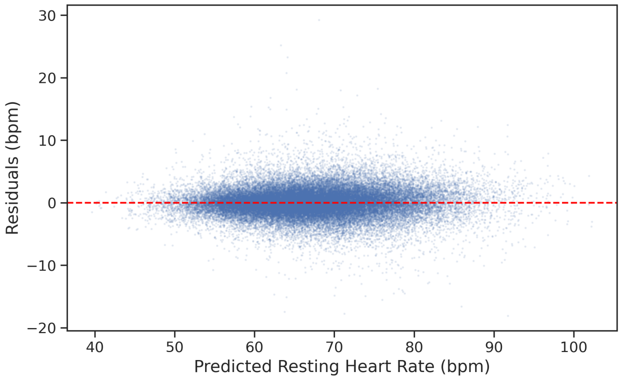
Table A.4 | **Full Standardised Fixed-Effects Trajectories, Variance Components, and Model Fit Diagnostics for Longitudinal Resting Heart Rate (RHR) Models across Progressive Hierarchical Stages.**

	Stage 1 Winner		Stage 2 Winner		Stage 3 Winner		Stage 4 Winner		Stage 5 Winner	
Predictors	**Std. β [bpm]**	**Std. CI [bpm]**	**Std. β [bpm]**	**Std. CI [bpm]**	**Std. β [bpm]**	**Std. CI [bpm]**	**Std. β [bpm]**	**Std. CI [bpm]**	**Std. β [bpm]**	**Std. CI [bpm]**
Fixed Effects: Demographics										
(Intercept)	67.65	[67.64, 67.66]	67.64	[67.64, 67.65]	67.65	[67.65, 67.66]	67.71	[67.70, 67.72]	67.63	[67.63, 67.64]
a (Age)	6.21	[6.12, 6.30]	6.21	[6.12, 6.30]	6.19	[6.10, 6.28]	6.23	[6.14, 6.32]	6.20	[6.11, 6.29]
$a \cdot s$	6.66	[6.47, 6.85]	6.67	[6.48, 6.86]	6.65	[6.47, 6.84]	6.68	[6.49, 6.87]	6.66	[6.48, 6.85]
a^2	-8.73	[-8.82, -8.64]	-8.73	[-8.82, -8.64]	-8.73	[-8.82, -8.64]	-8.77	[-8.86, -8.68]	-8.74	[-8.83, -8.65]
$a^2 \cdot s$	-6.06	[-6.25, -5.87]	-6.06	[-6.25, -5.87]	-6.02	[-6.21, -5.83]	-6.07	[-6.26, -5.88]	-6.03	[-6.22, -5.85]
s (Sex)	-2.53	[-2.54, -2.51]	-2.53	[-2.55, -2.52]	-2.57	[-2.59, -2.56]	-2.52	[-2.53, -2.50]	-2.57	[-2.59, -2.56]
Fixed Effects: Seasonality										
$m_{\cos_1}$	–		0.23	[0.23, 0.23]	0.23	[0.23, 0.23]	0.02	[0.01, 0.02]	0.16	[0.16, 0.16]
$m_{\cos_2}$	–		0.15	[0.15, 0.15]	0.15	[0.15, 0.15]	0.17	[0.17, 0.18]	0.14	[0.14, 0.14]
$m_{\sin_1}$	–		0.15	[0.15, 0.15]	0.15	[0.15, 0.15]	0.04	[0.04, 0.04]	0.12	[0.12, 0.12]
$m_{\sin_2}$	–		-0.08	[-0.08, -0.07]	-0.07	[-0.08, -0.07]	-0.02	[-0.02, -0.02]	-0.09	[-0.09, -0.09]
Fixed Effects: Spatial Geography										
$\lambda_{\cos}$	–		–		-0.12	[-0.12, -0.11]	–		-0.02	[-0.03, -0.01]
ϕ (Latitude)	–		–		0.12	[0.11, 0.13]	–		0.09	[0.08, 0.10]
ϕ^2	–		–		-0.46	[-0.47, -0.46]	–		-0.57	[-0.58, -0.56]
$\phi \cdot m_{\cos_1}$	–		–		0.33	[0.32, 0.33]	–		0.31	[0.30, 0.32]
$\phi^2 \cdot m_{\cos_1}$	–		–		-0.21	[-0.22, -0.21]	–		-0.22	[-0.23, -0.22]
$\phi \cdot m_{\cos_2}$	–		–		-0.05	[-0.05, -0.04]	–		0.04	[0.03, 0.04]
$\phi^2 \cdot m_{\cos_2}$	–		–		0.13	[0.13, 0.14]	–		0.02	[0.02, 0.03]
$\phi \cdot m_{\sin_1}$	–		–		0.36	[0.36, 0.36]	–		0.41	[0.41, 0.42]
$\phi^2 \cdot m_{\sin_1}$	–		–		-0.28	[-0.28, -0.27]	–		-0.31	[-0.32, -0.31]
$\phi \cdot m_{\sin_2}$	–		–		-0.04	[-0.04, -0.04]	–		-0.13	[-0.13, -0.12]
$\phi^2 \cdot m_{\sin_2}$	–		–		-0.03	[-0.04, -0.03]	–		0.03	[0.03, 0.03]
$\lambda_{\sin}$ (Longitude)	–		–		-0.03	[-0.04, -0.03]	–		0.04	[0.03, 0.05]
Fixed Effects: Temperature										
$T_{\max}/T^{\text{res}}_{\max}$	–		–		–		0.26	[0.23, 0.28]	0.28	[0.27, 0.29]
$T^2_{\max}/(T^{\text{res}}_{\max})^2$	–		–		–		-0.08	[-0.10, -0.06]	-0.09	[-0.11, -0.08]
$T_{\min}/T^{\text{res}}_{\min}$	–		–		–		-0.78	[-0.80, -0.76]	-0.50	[-0.51, -0.49]
$T^2_{\min}/(T^{\text{res}}_{\min})^2$	–		–		–		0.16	[0.15, 0.17]	-0.06	[-0.07, -0.05]
$(T_{\max}/T^{\text{res}}_{\max}) \cdot m_{\cos_1}$	–		–		–		0.64	[0.61, 0.68]	-0.36	[-0.38, -0.35]
$((T_{\max}/T^{\text{res}}_{\max})^2) \cdot m_{\cos_1}$	–		–		–		-0.70	[-0.73, -0.68]	-0.07	[-0.08, -0.05]
$(T_{\min}/T^{\text{res}}_{\min}) \cdot m_{\cos_1}$	–		–		–		0.32	[0.30, 0.34]	0.20	[0.19, 0.21]
$((T_{\min}/T^{\text{res}}_{\min})^2) \cdot m_{\cos_1}$	–		–		–		-0.04	[-0.05, -0.03]	-0.04	[-0.05, -0.02]
$(T_{\max}/T^{\text{res}}_{\max}) \cdot m_{\cos_2}$	–		–		–		-1.11	[-1.13, -1.08]	-0.37	[-0.38, -0.36]
$((T_{\max}/T^{\text{res}}_{\max})^2) \cdot m_{\cos_2}$	–		–		–		0.58	[0.56, 0.60]	0.21	[0.20, 0.22]
$(T_{\min}/T^{\text{res}}_{\min}) \cdot m_{\cos_2}$	–		–		–		0.51	[0.50, 0.52]	0.20	[0.19, 0.21]
$((T_{\min}/T^{\text{res}}_{\min})^2) \cdot m_{\cos_2}$	–		–		–		-0.25	[-0.25, -0.24]	-0.24	[-0.25, -0.23]
$(T_{\max}/T^{\text{res}}_{\max}) \cdot m_{\sin_1}$	–		–		–		0.27	[0.24, 0.31]	-0.26	[-0.27, -0.24]
$((T_{\max}/T^{\text{res}}_{\max})^2) \cdot m_{\sin_1}$	–		–		–		-0.20	[-0.23, -0.17]	0.16	[0.14, 0.17]
$(T_{\min}/T^{\text{res}}_{\min}) \cdot m_{\sin_1}$	–		–		–		0.12	[0.10, 0.14]	0.13	[0.12, 0.14]
$((T_{\min}/T^{\text{res}}_{\min})^2) \cdot m_{\sin_1}$	–		–		–		-0.08	[-0.09, -0.07]	-0.05	[-0.07, -0.04]
$(T_{\max}/T^{\text{res}}_{\max}) \cdot m_{\sin_2}$	–		–		–		0.39	[0.37, 0.41]	0.15	[0.14, 0.16]
$((T_{\max}/T^{\text{res}}_{\max})^2) \cdot m_{\sin_2}$	–		–		–		-0.38	[-0.40, -0.36]	-0.17	[-0.18, -0.16]
$(T_{\min}/T^{\text{res}}_{\min}) \cdot m_{\sin_2}$	–		–		–		-0.20	[-0.21, -0.19]	-0.02	[-0.03, -0.01]
$((T_{\min}/T^{\text{res}}_{\min})^2) \cdot m_{\sin_2}$	–		–		–		0.15	[0.14, 0.15]	0.11	[0.10, 0.12]
Variance Components										
Residual Var (σ^2_ε)	5.83		5.77		5.76		5.76		5.75	
Intercept Var (σ^2_α user)	61.45		61.46		60.98		61.46		60.97	

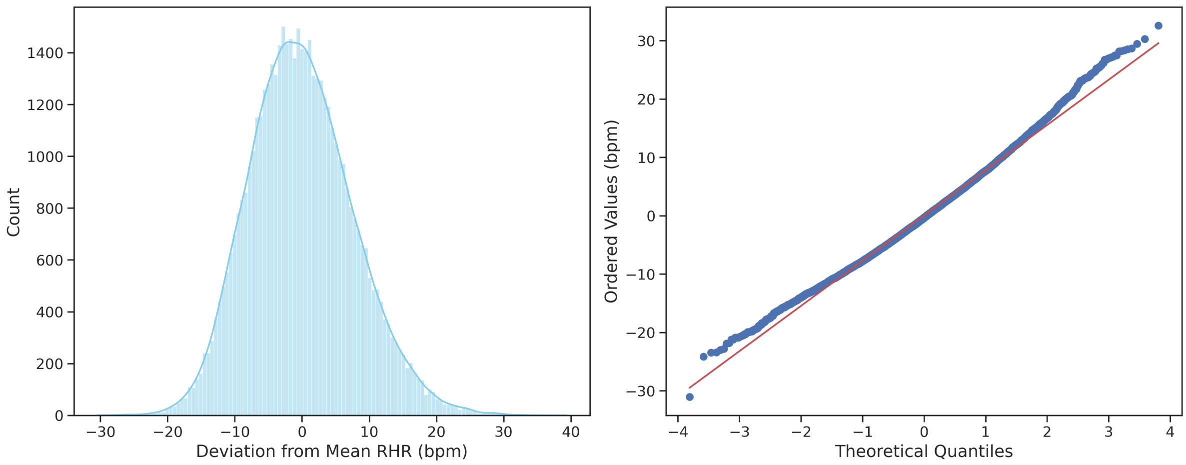
Notes: Standardised parameter estimates across all progressive hierarchical stages. Fixed-effects notation defined as: a, age; s, sex; h, seasonal harmonics; ϕ, latitude; λ, longitude; T, temperature. Interaction terms are denoted by $(\cdot)$. *Std.* β refers to standardised fixed-effects coefficients. Estimates are presented in beats per minute [bpm] and represent absolute changes, except for the Intercept which represents the baseline mean in bpm. **Bold values indicate coefficients that are NOT statistically significant ($p \geq 0.05$, 95% CI includes zero).** Empty cells indicate variables not structurally introduced until later hierarchical stages. Indented items indicate explicit parameter metrics nested within their respective structural grouping.

B.3. Model Diagnostics

Model diagnostics for the winning joint RHR model (Model 5.3) are presented in Figure A.4. The visual evaluation confirms that the statistical assumptions of the LMEs are satisfied. Specifically, the conditional residual plot (a) demonstrates homoscedasticity, with conditional residual errors (incorporating participant-specific random intercepts) forming a uniform, symmetric band clustered tightly around the zero line across the range of predicted RHR values (bpm). Furthermore, the user baseline RHR distribution (b, left) exhibits a smooth, symmetrical bell curve centred at the cohort baseline mean of approximately 67.5 bpm, while the corresponding Q-Q plot (b, right) shows that participant-specific baseline values ($\beta_0 + u \sim \mathcal{N}(\beta_0, \sigma_u^2)$) closely track the theoretical diagonal line. A minor tail-off is visible at the extreme outer quantiles, which is an expected biological heavy-tail artifact in massive real-world datasets and does not threaten model validity.



(a) Residuals vs. Fitted Values



(b) Random Effects Distribution and Q-Q Plot

Figure A.4 | **Model Diagnostics for the RHR Winning Model (Model 5.3). (a)** Residuals versus fitted values, indicating homoscedasticity through a uniform error spread across predicted values. **(b)** Distribution of participant random intercepts displaying a normal bell curve (Left) alongside a Normal Q-Q plot confirming the normality assumption of the random effects is met across central quantiles (Right).

B.4. Comparison with External RHR Seasonality Baseline

To validate our findings against published literature, we compared the monthly seasonality profiles of our thinned 2022 cohort (Fitbit devices) against the 2019 baseline monthly means reported in the external multi-country study by Ong et al. which utilised Oura ring devices [1].

Figure A.5 overlays the raw monthly mean heart rate (bpm) for the 20 countries common to both datasets. The results demonstrate a high degree of seasonal phase and shape matching between the two cohorts. In particular, both cohorts display inverted winter-peak and summer-trough patterns in the Southern Hemisphere (Australia and New Zealand) compared to the Northern Hemisphere. Singapore, located near the equator, displays virtually flat seasonal profiles in both cohorts.

The absolute difference in resting heart rate of approximately 5–7 bpm is observed between the cohorts, with Oura RHR being lower than our Fitbit RHR. This is expected due to differences in wearable hardware, but is primarily due the differences in the cohort compositions. Authors note their cohort consists of majority men, with the mean age between 35 and 45 years old, whereas ours consists of majority women with an average age of 45.9 ± 14.8. Importantly, the annual trends between the two cohorts show good tracking between the countries, which is significant as our cohort is orders of magnitude larger than the Oura cohort across most countries, as detailed in the panel legends (e.g. $N = 2,257,373$ vs. $N =$ 10,000+ in the United States, and $N = 252,993$ vs. $N = 4,000$ in Germany), which provides further evidence that our observations and findings translate across different populations.

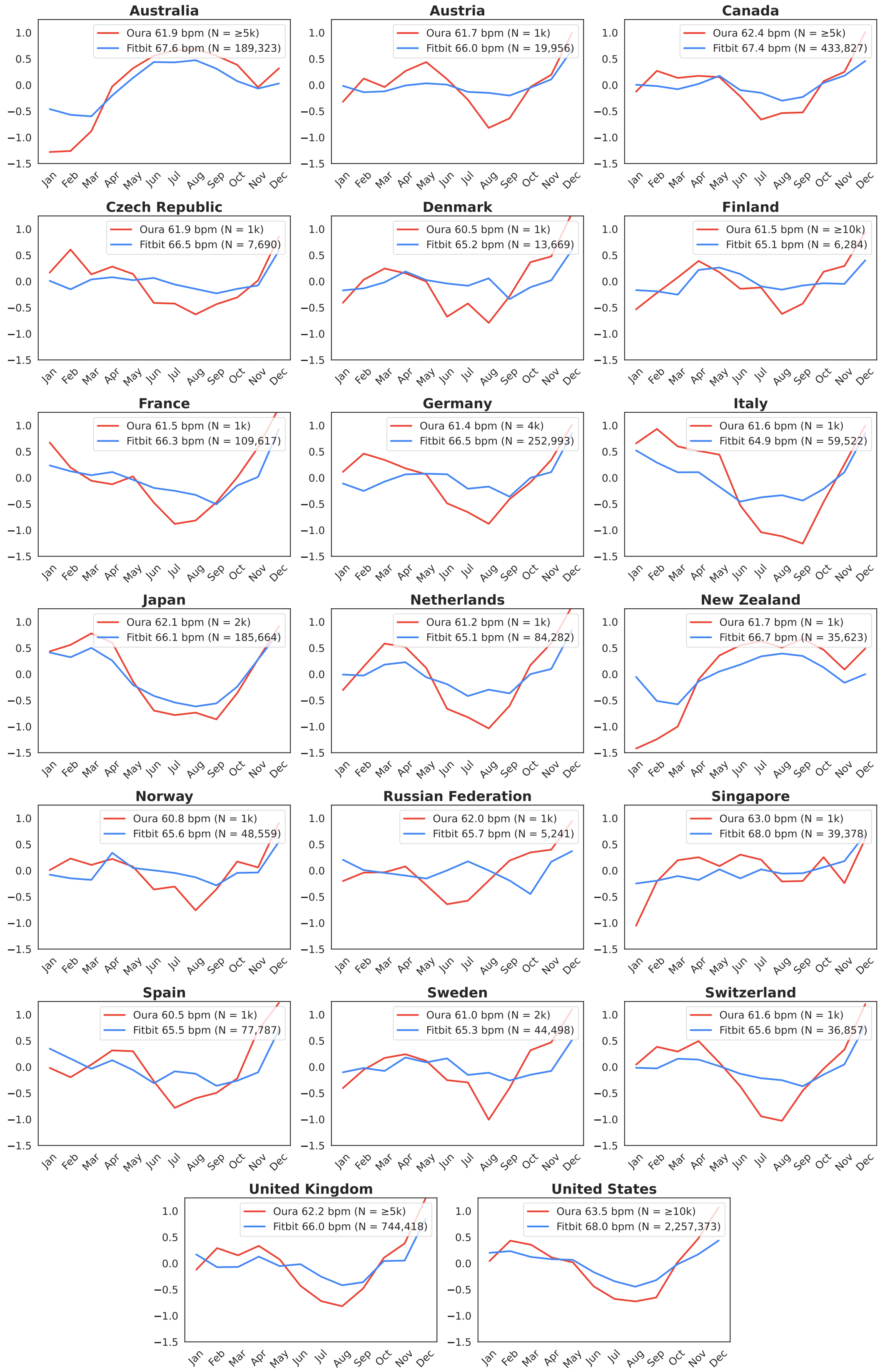


Figure A.5 | **RHR monthly seasonality comparison between the published 2019 baseline (Oura) and our 2022 cohort (Fitbit).** Subplots overlay the raw monthly resting heart rate (bpm) across the 20 common countries. Grid lines have been omitted for clarity. In each panel, the legend reports the respective number of unique users (N) in the Oura paper and in our cohort.

C. Heart Rate Variability (HRV) Supplementary Materials

C.1. Baseline Temperature Residualisation Regressions

Here we provide the baseline temperature residualisation parameter estimates, as described in **??**. These regressions yield the baseline parameters summarised in Table A.5.

Table A.5 | **OLS temperature residualisation regression parameters for the HRV cohort.**

Parameter	$T_{\max}$ **[95% CI]**	$T_{\min}$ **[95% CI]**	T_{mean} **[95% CI]**
Intercept (α_0)	−0.0143 [−0.0145, −0.0142]	−0.0152 [−0.0153, −0.0150]	−0.0148 [−0.0149, −0.0147]
Abs Latitude Slope (α_1)	−0.4680 [−0.4683, −0.4677]	−0.3521 [−0.3525, −0.3517]	−0.4206 [−0.4210, −0.4203]
Signed Latitude Slope (α_2)	0.0066 [0.0062, 0.0069]	−0.0239 [−0.0243, −0.0235]	−0.0027 [−0.0031, −0.0024]
$m_{\sin_1}$ ($\alpha_{3,1}$)	−0.2917 [−0.2918, −0.2915]	−0.3065 [−0.3067, −0.3063]	−0.2995 [−0.2997, −0.2994]
$m_{\cos_1}$ ($\alpha_{4,1}$)	−0.4259 [−0.4261, −0.4258]	−0.3831 [−0.3833, −0.3829]	−0.4111 [−0.4112, −0.4109]
$m_{\sin_2}$ ($\alpha_{3,2}$)	0.0117 [0.0115, 0.0118]	0.0096 [0.0094, 0.0098]	0.0110 [0.0108, 0.0111]
$m_{\cos_2}$ ($\alpha_{4,2}$)	−0.0453 [−0.0454, −0.0451]	−0.0157 [−0.0159, −0.0155]	−0.0279 [−0.0281, −0.0277]
$m_{\sin_1} \cdot \phi_c$ ($\alpha_{5,1}$)	−0.2130 [−0.2133, −0.2127]	−0.1951 [−0.1956, −0.1947]	−0.2066 [−0.2069, −0.2062]
$m_{\cos_1} \cdot \phi_c$ ($\alpha_{6,1}$)	−0.2662 [−0.2665, −0.2659]	−0.1966 [−0.1970, −0.1962]	−0.2339 [−0.2342, −0.2335]
$m_{\sin_2} \cdot \phi_c$ ($\alpha_{5,2}$)	0.0086 [0.0083, 0.0090]	0.0035 [0.0030, 0.0039]	0.0092 [0.0088, 0.0095]
$m_{\cos_2} \cdot \phi_c$ ($\alpha_{6,2}$)	−0.0057 [−0.0060, −0.0054]	0.0066 [0.0062, 0.0070]	0.0023 [0.0019, 0.0026]
Model R^2	0.7944	0.6417	0.7306

C.2. Model Comparison and Progressive Fits

This Section provides supplementary analyses for the LME models fitted on the HRV cohort. Because HRV exhibits a log-normal population distribution, all models were evaluated in log-transformed space ($\ln \text{HRV}$). Parameter estimates and trajectories are transformed back to physical units as percentage changes ($(e^{\beta} - 1) \times 100$) to help direct physiological interpretability. Table A.6 summarises the complete model selection process across all tested HRV candidate models. Tables A.7 and A.8 detail the full parameter breakdown for the winning HRV models across all 5 incremental stages. Table A.7 details unstandardised percentage changes (Est., $(e^{\beta} - 1) \times 100$), while Table A.8 details standardised coefficients (Std. β, $(e^{\beta} - 1) \times 100$ per 2-SD predictor shift) with exact 95% confidence intervals and random variance components.

Table A.6 | **Model Comparison and Fit Diagnostics for all Heart Rate Variability (HRV) Candidate Models.**

Model	Fixed Effects Formula	Marg. R^2 [%]	Cond. R^2 [%]	ICC	RMSE [%]	Log-Likelihood	AIC	BIC
Stage 1 (Demo)								
1.1	$a \cdot s$	18.379	90.983	0.890	12.022%	7,296,811	-14,593,610	-14,593,522
1.2	$\boldsymbol{(a + a^2) \cdot s}$	**20.595**	**90.927**	**0.886**	**12.022%**	**7,335,461**	**-14,670,906**	**-14,670,789**
Stage 2 (Season)								
2.1	$(a + a^2) \cdot s + m_{\sin_1} + m_{\cos_1}$	20.864	91.205	0.889	11.834%	7,550,724	-15,101,429	-15,101,283
2.2	$\boldsymbol{(a + a^2) \cdot s + m_{\sin_1} + m_{\cos_1} + m_{\sin_2} + m_{\cos_2}}$	**20.911**	**91.263**	**0.890**	**11.794%**	**7,597,309**	**-15,194,593**	**-15,194,418**
Stage 3 (Spatial Geography)								
3.1	$(a + a^2) \cdot s + d$	20.788	91.135	0.888	11.881%	7,496,594	-14,993,171	-14,993,039
3.2	$(a + a^2) \cdot s + d + d^2$	20.797	91.160	0.888	11.868%	7,511,488	-15,022,955	-15,022,809
3.3	$(a + a^2) \cdot s + d \cdot (m_{\sin_1} + m_{\cos_1})$	20.924	91.294	0.890	11.774%	7,619,778	-15,239,530	-15,239,340
3.4	$(a + a^2) \cdot s + (d + d^2) \cdot (m_{\sin_1} + m_{\cos_1} + m_{\sin_2} + m_{\cos_2})$	20.956	91.322	0.890	11.753%	7,644,803	-15,289,561	-15,289,239
3.5	$(a + a^2) \cdot s + (m_{\sin_1} + m_{\cos_1} + m_{\sin_2} + m_{\cos_2}) + (\phi)$	20.907	91.265	0.890	11.794%	7,597,495	-15,194,964	-15,194,774
3.6	$(a+a^2) \cdot s + (m_{\sin_1} + m_{\cos_1} + m_{\sin_2} + m_{\cos_2}) + (\phi) + \lambda_{\sin} + \lambda_{\cos}$	20.964	91.254	0.889	11.794%	7,599,250	-15,198,471	-15,198,251
3.7	$(a + a^2) \cdot s + (m_{\sin_1} + m_{\cos_1} + m_{\sin_2} + m_{\cos_2}) + (\phi + \phi^2)$	20.911	91.264	0.890	11.794%	7,597,505	-15,194,983	-15,194,778
3.8	$(a + a^2) \cdot s + (m_{\sin_1} + m_{\cos_1} + m_{\sin_2} + m_{\cos_2}) + (\phi + \phi^2) + \lambda_{\sin} + \lambda_{\cos}$	20.959	91.255	0.889	11.794%	7,599,254	-15,198,476	-15,198,241
3.9	$\boldsymbol{(a+a^2) \cdot s + (m_{\sin_1} + m_{\cos_1} + m_{\sin_2} + m_{\cos_2}) \cdot (\phi) + \lambda_{\sin} + \lambda_{\cos}}$	**21.017**	**91.319**	**0.890**	**11.749%**	**7,651,348**	**-15,302,658**	**-15,302,380**
Stage 4 (Temperature)								
4.1	$(a + a^2) \cdot s + (m_{\sin_1} + m_{\cos_1} + m_{\sin_2} + m_{\cos_2}) + (T_{\text{mean}})$	20.955	91.288	0.890	11.776%	7,619,154	-15,238,282	-15,238,092
4.2	$(a + a^2) \cdot s + (m_{\sin_1} + m_{\cos_1} + m_{\sin_2} + m_{\cos_2}) + (T_{\max} + T_{\min})$	20.950	91.296	0.890	11.773%	7,621,031	-15,242,034	-15,241,829
4.3	$(a + a^2) \cdot s + (m_{\sin_1} + m_{\cos_1} + m_{\sin_2} + m_{\cos_2}) + (T_{\max} + T_{\max}^2 + T_{\min} + T_{\min}^2)$	20.999	91.329	0.890	11.755%	7,640,995	-15,281,957	-15,281,723
4.4	$\boldsymbol{(a + a^2) \cdot s + (m_{\sin_1} + m_{\cos_1} + m_{\sin_2} + m_{\cos_2}) \cdot (T_{\max} + T_{\max}^2 + T_{\min} + T_{\min}^2)}$	**21.002**	**91.342**	**0.890**	**11.746%**	**7,652,730**	**-15,305,395**	**-15,304,927**
Stage 5 (Joint)								
5.1	$(a + a^2) \cdot s + (m_{\sin_1} + m_{\cos_1} + m_{\sin_2} + m_{\cos_2}) \cdot (\phi) + \lambda_{\sin} + \lambda_{\cos} + T_{\max}^{\text{res}} + (T_{\max}^{\text{res}})^2 + T_{\min}^{\text{res}} + (T_{\min}^{\text{res}})^2$	21.032	91.340	0.890	11.735%	7,667,297	-15,334,547	-15,334,211
5.2	$(a + a^2) \cdot s + (m_{\sin_1} + m_{\cos_1} + m_{\sin_2} + m_{\cos_2}) \cdot (T_{\max}^{\text{res}} + (T_{\max}^{\text{res}})^2 + T_{\min}^{\text{res}} + (T_{\min}^{\text{res}})^2) + \phi + \lambda_{\sin} + \lambda_{\cos}$	21.035	91.338	0.890	11.740%	7,660,702	-15,321,335	-15,320,823
5.3	$\boldsymbol{(a + a^2) \cdot s + (m_{\sin_1} + m_{\cos_1} + m_{\sin_2} + m_{\cos_2}) \cdot (\phi) + (m_{\sin_1} + m_{\cos_1} + m_{\sin_2} + m_{\cos_2}) \cdot (T_{\max}^{\text{res}} + (T_{\max}^{\text{res}})^2 + T_{\min}^{\text{res}} + (T_{\min}^{\text{res}})^2) + \lambda_{\sin} + \lambda_{\cos}}$	**21.032**	**91.356**	**0.891**	**11.727%**	**7,677,082**	**-15,354,085**	**-15,353,515**

Notes: Models are enumerated by hierarchical stage and candidate index matching the main text. Information criteria (AIC, BIC) and Log-Likelihood are estimated via Maximum Likelihood (ML). Marginal R^2 [%] represents variance explained by fixed effects; Conditional R^2 [%] represents total variance explained including random participant intercepts.

Table A.7 | **Full Unstandardised Fixed-Effects Parameter Estimates, Variance Components, and Model Fit Diagnostics for Longitudinal Heart Rate Variability (HRV) Models across Progressive Hierarchical Stages.**

	Stage 1 Winner		Stage 2 Winner		Stage 3 Winner		Stage 4 Winner		Stage 5 Winner	
Predictors	**Est. [%]**	**95% CI [%]**	**Est. [%]**	**95% CI [%]**	**Est. [%]**	**95% CI [%]**	**Est. [%]**	**95% CI [%]**	**Est. [%]**	**95% CI [%]**
Fixed Effects: Demographics										
(Intercept)	35.44	[35.43, 35.46]	35.45	[35.44, 35.47]	35.57	[35.55, 35.59]	35.40	[35.39, 35.42]	35.30	[35.28, 35.32]
a (Age)	-4.00	[-4.02, -3.98]	-4.01	[-4.03, -3.99]	-4.02	[-4.04, -4.00]	-4.01	[-4.03, -3.99]	-4.02	[-4.04, -4.00]
$a \cdot s$	-1.25	[-1.30, -1.21]	-1.26	[-1.30, -1.21]	-1.26	[-1.31, -1.22]	-1.26	[-1.30, -1.22]	-1.26	[-1.31, -1.22]
a^2	0.03	[0.03, 0.03]	0.03	[0.03, 0.03]	0.03	[0.03, 0.03]	0.03	[0.03, 0.03]	0.03	[0.03, 0.03]
$a^2 \cdot s$	0.01	[0.01, 0.01]	0.01	[0.01, 0.01]	0.01	[0.01, 0.01]	0.01	[0.01, 0.01]	0.01	[0.01, 0.01]
s (Sex)	5.15	[5.05, 5.25]	5.22	[5.12, 5.33]	5.10	[5.00, 5.20]	4.96	[4.86, 5.07]	5.02	[4.92, 5.12]
Fixed Effects: Seasonality										
$m_{\cos_1}$	–		-2.15	[-2.16, -2.15]	-2.15	[-2.16, -2.14]	-0.21	[-0.23, -0.19]	-1.25	[-1.27, -1.23]
$m_{\cos_2}$	–		-0.85	[-0.86, -0.84]	-0.85	[-0.86, -0.85]	-0.81	[-0.82, -0.80]	-0.82	[-0.84, -0.81]
$m_{\sin_1}$	–		-1.75	[-1.76, -1.74]	-1.74	[-1.75, -1.73]	-0.40	[-0.42, -0.38]	-1.24	[-1.26, -1.22]
$m_{\sin_2}$	–		0.99	[0.98, 1.00]	0.99	[0.98, 1.00]	0.45	[0.43, 0.46]	0.43	[0.42, 0.45]
Fixed Effects: Spatial Geography										
$\lambda_{\cos}$	–		–		0.43	[0.39, 0.48]	–		0.34	[0.29, 0.39]
ϕ (Latitude)	–		–		-0.00	[-0.00, -0.00]	–		**-0.00**	**[-0.00, 0.00]**
$\phi \cdot m_{\cos_1}$	–		–		-0.00	[-0.00, -0.00]	–		-0.00	[-0.00, -0.00]
$\phi \cdot m_{\cos_2}$	–		–		-0.00	[-0.00, -0.00]	–		-0.00	[-0.00, -0.00]
$\phi \cdot m_{\sin_1}$	–		–		-0.00	[-0.00, -0.00]	–		-0.00	[-0.00, -0.00]
$\phi \cdot m_{\sin_2}$	–		–		0.00	[0.00, 0.00]	–		0.00	[0.00, 0.00]
$\lambda_{\sin}$ (Longitude)	–		–		1.16	[1.11, 1.20]	–		0.96	[0.91, 1.00]
Fixed Effects: Temperature										
$T_{\max}/T_{\max}^{\mathrm{res}}$	–		–		–		0.25	[0.24, 0.26]	2.02	[1.93, 2.11]
$T_{\max}^2/(T_{\max}^{\mathrm{res}})^2$	–		–		–		-0.00	[-0.00, -0.00]	0.18	[0.09, 0.28]
$T_{\min}/T_{\min}^{\mathrm{res}}$	–		–		–		-0.05	[-0.05, -0.04]	**-0.08**	**[-0.16, 0.00]**
$T_{\min}^2/(T_{\min}^{\mathrm{res}})^2$	–		–		–		0.01	[0.00, 0.01]	2.10	[2.01, 2.19]
$(T_{\max}/T_{\max}^{\mathrm{res}}) \cdot m_{\cos_1}$	–		–		–		-0.21	[-0.22, -0.20]	-1.43	[-1.53, -1.34]
$((T_{\max}/T_{\max}^{\mathrm{res}})^2) \cdot m_{\cos_1}$	–		–		–		0.01	[0.01, 0.01]	0.61	[0.51, 0.72]
$(T_{\min}/T_{\min}^{\mathrm{res}}) \cdot m_{\cos_1}$	–		–		–		-0.05	[-0.06, -0.04]	0.49	[0.40, 0.58]
$((T_{\min}/T_{\min}^{\mathrm{res}})^2) \cdot m_{\cos_1}$	–		–		–		-0.00	[-0.00, -0.00]	-1.20	[-1.30, -1.10]
$(T_{\max}/T_{\max}^{\mathrm{res}}) \cdot m_{\cos_2}$	–		–		–		0.32	[0.31, 0.33]	1.87	[1.80, 1.94]
$((T_{\max}/T_{\max}^{\mathrm{res}})^2) \cdot m_{\cos_2}$	–		–		–		-0.01	[-0.01, -0.01]	-1.98	[-2.05, -1.90]
$(T_{\min}/T_{\min}^{\mathrm{res}}) \cdot m_{\cos_2}$	–		–		–		-0.18	[-0.18, -0.17]	-1.29	[-1.36, -1.23]
$((T_{\min}/T_{\min}^{\mathrm{res}})^2) \cdot m_{\cos_2}$	–		–		–		0.00	[0.00, 0.00]	1.61	[1.54, 1.68]
$(T_{\max}/T_{\max}^{\mathrm{res}}) \cdot m_{\sin_1}$	–		–		–		-0.13	[-0.15, -0.12]	-1.52	[-1.60, -1.45]
$((T_{\max}/T_{\max}^{\mathrm{res}})^2) \cdot m_{\sin_1}$	–		–		–		0.01	[0.00, 0.01]	0.59	[0.48, 0.70]
$(T_{\min}/T_{\min}^{\mathrm{res}}) \cdot m_{\sin_1}$	–		–		–		-0.09	[-0.10, -0.09]	0.38	[0.31, 0.46]
$((T_{\min}/T_{\min}^{\mathrm{res}})^2) \cdot m_{\sin_1}$	–		–		–		0.00	[0.00, 0.00]	-1.36	[-1.46, -1.26]
$(T_{\max}/T_{\max}^{\mathrm{res}}) \cdot m_{\sin_2}$	–		–		–		-0.09	[-0.10, -0.08]	-1.73	[-1.80, -1.66]
$((T_{\max}/T_{\max}^{\mathrm{res}})^2) \cdot m_{\sin_2}$	–		–		–		0.00	[0.00, 0.00]	-0.27	[-0.35, -0.19]
$(T_{\min}/T_{\min}^{\mathrm{res}}) \cdot m_{\sin_2}$	–		–		–		0.14	[0.13, 0.14]	0.77	[0.69, 0.84]
$((T_{\min}/T_{\min}^{\mathrm{res}})^2) \cdot m_{\sin_2}$	–		–		–		-0.00	[-0.00, -0.00]	-0.32	[-0.39, -0.25]
Variance Components										
Residual SD (proportional) [%]	12.884%		12.639%		12.591%		12.587%		12.567%	
Intercept SD (proportional) [%]	40.133%		40.175%		40.142%		40.204%		40.165%	

Notes: Unstandardised parameter estimates across all progressive hierarchical stages. Fixed-effects notation defined as: a, age; s, sex; h, seasonal harmonics; ϕ, latitude; λ, longitude; T, temperature. Interaction terms are denoted by $(\cdot)$. *Est.* denotes unstandardised coefficients. Estimates are transformed as $(e^{\beta} - 1) \times 100$ to represent percentage changes in HRV [%], except for the Intercept which is exponentiated to represent the geometric mean in ms. **Bold values indicate coefficients that are NOT statistically significant** ($p \geq 0.05$, **95% CI includes zero).** Empty cells indicate variables not structurally introduced until later hierarchical stages. Indented items indicate explicit parameter metrics nested within their respective structural grouping.

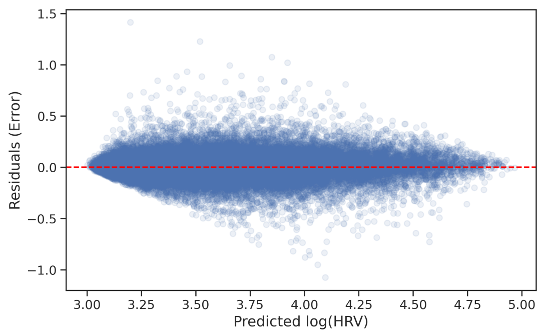
Table A.8 | **Full Standardised Fixed-Effects Trajectories, Variance Components, and Model Fit Diagnostics for Longitudinal Heart Rate Variability (HRV) Models across Progressive Hierarchical Stages.**

	Stage 1 Winner		Stage 2 Winner		Stage 3 Winner		Stage 4 Winner		Stage 5 Winner	
Predictors	**Std. β [%]**	**Std. CI [%]**	**Std. β [%]**	**Std. CI [%]**	**Std. β [%]**	**Std. CI [%]**	**Std. β [%]**	**Std. CI [%]**	**Std. β [%]**	**Std. CI [%]**
Fixed Effects: Demographics										
(Intercept)	35.44	[35.43, 35.46]	35.45	[35.44, 35.47]	35.57	[35.55, 35.59]	35.40	[35.39, 35.42]	35.30	[35.28, 35.32]
a (Age)	-68.11	[-68.29, -67.92]	-68.14	[-68.33, -67.96]	-68.22	[-68.40, -68.03]	-68.18	[-68.37, -68.00]	-68.26	[-68.45, -68.08]
$a \cdot s$	-29.71	[-30.55, -28.85]	-29.76	[-30.60, -28.90]	-29.90	[-30.75, -29.05]	-29.86	[-30.71, -29.00]	-29.92	[-30.77, -29.06]
a^2	124.71	[123.40, 126.03]	124.80	[123.49, 126.12]	125.60	[124.29, 126.92]	125.08	[123.77, 126.40]	125.83	[124.51, 127.15]
$a^2 \cdot s$	35.87	[34.23, 37.52]	35.87	[34.23, 37.52]	36.11	[34.48, 37.77]	36.14	[34.50, 37.80]	36.19	[34.55, 37.85]
s (Sex)	5.15	[5.05, 5.25]	5.22	[5.12, 5.33]	5.10	[5.00, 5.20]	4.96	[4.86, 5.07]	5.02	[4.92, 5.12]
Fixed Effects: Seasonality										
$m_{\cos_1}$	–		-2.15	[-2.16, -2.15]	-2.15	[-2.16, -2.14]	-0.21	[-0.23, -0.19]	-1.25	[-1.27, -1.23]
$m_{\cos_2}$	–		-0.85	[-0.86, -0.84]	-0.85	[-0.86, -0.85]	-0.81	[-0.82, -0.80]	-0.82	[-0.84, -0.81]
$m_{\sin_1}$	–		-1.75	[-1.76, -1.74]	-1.74	[-1.75, -1.73]	-0.40	[-0.42, -0.38]	-1.24	[-1.26, -1.22]
$m_{\sin_2}$	–		0.99	[0.98, 1.00]	0.99	[0.98, 1.00]	0.45	[0.43, 0.46]	0.43	[0.42, 0.45]
Fixed Effects: Spatial Geography										
$\lambda_{\cos}$	–		–		0.43	[0.39, 0.48]	–		0.34	[0.29, 0.39]
ϕ (Latitude)	–		–		-0.36	[-0.41, -0.31]	–		**-0.04**	**[-0.10, 0.01]**
$\phi \cdot m_{\cos_1}$	–		–		-1.64	[-1.66, -1.63]	–		-1.34	[-1.37, -1.32]
$\phi \cdot m_{\cos_2}$	–		–		-0.22	[-0.24, -0.20]	–		-0.26	[-0.28, -0.24]
$\phi \cdot m_{\sin_1}$	–		–		-2.13	[-2.15, -2.11]	–		-2.16	[-2.18, -2.13]
$\phi \cdot m_{\sin_2}$	–		–		0.67	[0.65, 0.69]	–		0.33	[0.31, 0.35]
$\lambda_{\sin}$ (Longitude)	–		–		1.16	[1.11, 1.20]	–		0.96	[0.91, 1.00]
Fixed Effects: Temperature										
$T_{\max}/T_{\max}^{\mathrm{res}}$	–		–		–		4.81	[4.59, 5.04]	2.02	[1.93, 2.11]
$T_{\max}^2/(T_{\max}^{\mathrm{res}})^2$	–		–		–		-0.42	[-0.59, -0.25]	0.18	[0.09, 0.28]
$T_{\min}/T_{\min}^{\mathrm{res}}$	–		–		–		-0.84	[-0.96, -0.72]	**-0.08**	**[-0.16, 0.00]**
$T_{\min}^2/(T_{\min}^{\mathrm{res}})^2$	–		–		–		1.63	[1.55, 1.71]	2.10	[2.01, 2.19]
$(T_{\max}/T_{\max}^{\mathrm{res}}) \cdot m_{\cos_1}$	–		–		–		-3.84	[-4.08, -3.60]	-1.43	[-1.53, -1.34]
$((T_{\max}/T_{\max}^{\mathrm{res}})^2) \cdot m_{\cos_1}$	–		–		–		4.60	[4.40, 4.80]	0.61	[0.51, 0.72]
$(T_{\min}/T_{\min}^{\mathrm{res}}) \cdot m_{\cos_1}$	–		–		–		-0.91	[-1.05, -0.77]	0.49	[0.40, 0.58]
$((T_{\min}/T_{\min}^{\mathrm{res}})^2) \cdot m_{\cos_1}$	–		–		–		-0.64	[-0.73, -0.55]	-1.20	[-1.30, -1.10]
$(T_{\max}/T_{\max}^{\mathrm{res}}) \cdot m_{\cos_2}$	–		–		–		6.18	[6.01, 6.36]	1.87	[1.80, 1.94]
$((T_{\max}/T_{\max}^{\mathrm{res}})^2) \cdot m_{\cos_2}$	–		–		–		-3.49	[-3.63, -3.36]	-1.98	[-2.05, -1.90]
$(T_{\min}/T_{\min}^{\mathrm{res}}) \cdot m_{\cos_2}$	–		–		–		-3.10	[-3.19, -3.01]	-1.29	[-1.36, -1.23]
$((T_{\min}/T_{\min}^{\mathrm{res}})^2) \cdot m_{\cos_2}$	–		–		–		1.40	[1.33, 1.46]	1.61	[1.54, 1.68]
$(T_{\max}/T_{\max}^{\mathrm{res}}) \cdot m_{\sin_1}$	–		–		–		-2.48	[-2.72, -2.24]	-1.52	[-1.60, -1.45]
$((T_{\max}/T_{\max}^{\mathrm{res}})^2) \cdot m_{\sin_1}$	–		–		–		3.36	[3.15, 3.56]	0.59	[0.48, 0.70]
$(T_{\min}/T_{\min}^{\mathrm{res}}) \cdot m_{\sin_1}$	–		–		–		-1.66	[-1.78, -1.53]	0.38	[0.31, 0.46]
$((T_{\min}/T_{\min}^{\mathrm{res}})^2) \cdot m_{\sin_1}$	–		–		–		0.53	[0.44, 0.61]	-1.36	[-1.46, -1.26]
$(T_{\max}/T_{\max}^{\mathrm{res}}) \cdot m_{\sin_2}$	–		–		–		-1.65	[-1.82, -1.48]	-1.73	[-1.80, -1.66]
$((T_{\max}/T_{\max}^{\mathrm{res}})^2) \cdot m_{\sin_2}$	–		–		–		0.96	[0.82, 1.10]	-0.27	[-0.35, -0.19]
$(T_{\min}/T_{\min}^{\mathrm{res}}) \cdot m_{\sin_2}$	–		–		–		2.45	[2.35, 2.56]	0.77	[0.69, 0.84]
$((T_{\min}/T_{\min}^{\mathrm{res}})^2) \cdot m_{\sin_2}$	–		–		–		-1.39	[-1.46, -1.33]	-0.32	[-0.39, -0.25]
Variance Components										
Residual SD (proportional) [%]	12.884%		12.639%		12.591%		12.587%		12.567%	
Intercept SD (proportional) [%]	40.133%		40.175%		40.142%		40.204%		40.165%	

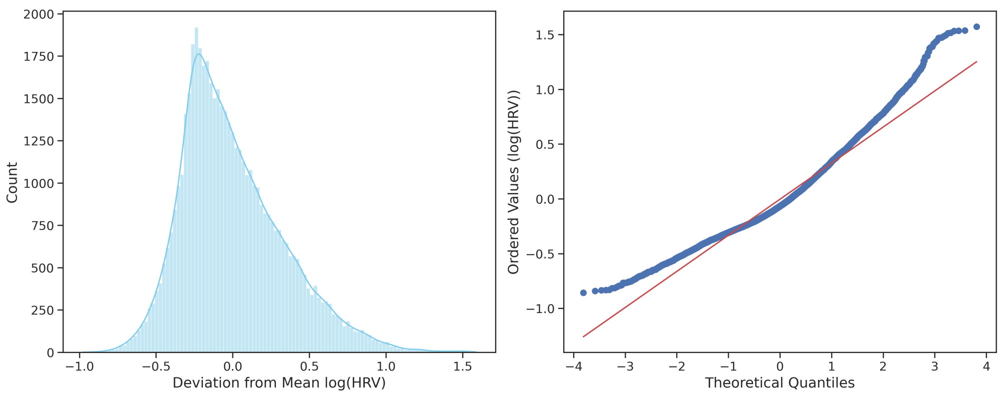
Notes: Standardised parameter estimates across all progressive hierarchical stages. Fixed-effects notation defined as: a, age; s, sex; h, seasonal harmonics; ϕ, latitude; λ, longitude; T, temperature. Interaction terms are denoted by $(\cdot)$. *Std. β* refer to standardised fixed-effect coefficients. Estimates are transformed as $(e^{\beta} - 1) \times 100$ to represent percentage changes in HRV [%], except for the Intercept which is exponentiated to represent the geometric mean in ms. **Bold values indicate coefficients that are NOT statistically significant ($p \geq 0.05$, 95% CI includes zero).** Empty cells indicate variables not structurally introduced until later hierarchical stages. Indented items indicate explicit parameter metrics nested within their respective structural grouping.

C.3. Model Diagnostics

Model diagnostics for the winning joint HRV model (Model 5.3) are presented in Figure A.6. The visual evaluation confirms that the statistical assumptions of the Linear Mixed-Effects framework are well-satisfied. Specifically, the conditional residual plot (a), back-transformed to the original units (milliseconds) via a smearing estimator, shows the expected mild heteroscedastic trumpet shape that is characterised by log-normal physiological data, while demonstrating that prediction errors remain symmetric and centred around zero across the range of predicted HRV values (ms). Furthermore, the user baseline HRV distribution (b, left) is plotted in milliseconds (ms), showing the expected right-skewed log-normal distribution centred at a geometric mean of approximately 35 ms. The corresponding Q-Q plot (b, right) is plotted on the model's log-scale for normality evaluation, but its ordered value axis is formatted in actual milliseconds (ms) for direct clinical interpretability. The user baseline values track the theoretical normal quantiles with high fidelity, confirming that the normality assumption of the participant-specific random intercepts ($u \sim \mathcal{N}(0, \sigma_u^2)$) holds robustly on the log-transformed scale. Minor deviations at the extreme ends are expected in large real-world cohorts and do not threaten the model's validity.



(a) Residuals vs. Fitted Values



(b) Random Effects Distribution and Q-Q Plot

Figure A.6 | **Model Diagnostics for the HRV Winning Model (Model 5.3).** **(a)** Residuals versus fitted values, indicating homoscedasticity through a uniform error spread across predicted values. **(b)** Distribution of participant random intercepts displaying a slightly skewed curve (Left) alongside a Normal Q-Q plot confirming the normality assumption of the random effects is met across central quantiles (Right).

References

[1] Ong, J. L., Lau, T., Karsikas, M., Kinnunen, H. & Chee, M. W. A longitudinal analysis of COVID-19 lockdown stringency on sleep and resting heart rate measures across 20 countries. *Scientific Reports* **11**, 14413 (2021).