**Supplementary Materials**

**Performance trade-offs and ageing**

**in the “world’s greatest athletes” [max 90 characters; current: 88]**

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**Running head:** constraints on human performance

**Table S1.** Effect of wind assistance (m·s-1; *z*-transformed), age (years; *z*-transformed), and experience (number of participations; *z*-transformed) on performance of elite athletes in each event of the (*a*) decathlon, and (*b*) heptathlon. Shown are the posterior modes and 95% credible intervals (CI) of the regression coefficients. Bold estimates have 95%CI that do not overlap with zero



**Table S2.** Among-individual variance, within-individual variance, and repeatability of performance in each event of the (*a*) decathlon, and (*b*) heptathlon. Shown are the posterior modes and 95% credible intervals (CI) of the variance and repeatability estimates from univariate mixed models fitted with the functions lmer(), sim(), and rpt() (R packages lme4, arm, and rptR). Also shown are the repeatability estimates obtained from the multivariate mixed models and their standard error (se) obtained using the pin() function (R package nadiv).



**Table S3.** Correlations at the (*a*) among-individual and (*b*) within-individual levels for all pairwise combinations of events of the decathlon. The 95% confidence intervals (CI) were calculated using profile likelihoods. Bold estimates have 95%CI that do not overlap with zero.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| event 1 | event 2 | (*a*) among-individual correlation |  | (*b*) within-individual correlation |
|  |  | estimate | 95% CI |  |  | estimate | 95% CI |  |
|  |  |  | lower | upper |  |  | lower | upper |
| shot put | discus | **0.66** | **0.62** | **0.70** |  | **0.24** | **0.22** | **0.27** |
| javelin | discus | **0.32** | **0.26** | **0.38** |  | **0.13** | **0.10** | **0.15** |
| javelin | shot put | **0.37** | **0.32** | **0.43** |  | **0.21** | **0.19** | **0.24** |
| pole vault | discus | **-0.10** | **-0.17** | **-0.03** |  | **0.13** | **0.10** | **0.15** |
| pole vault | shot put | **-0.13** | **-0.19** | **-0.06** |  | **0.15** | **0.12** | **0.18** |
| pole vault | javelin | **-0.12** | **-0.18** | **-0.05** |  | **0.04** | **0.01** | **0.07** |
| high jump | discus | **-0.11** | **-0.17** | **-0.04** |  | 0.01 | **-**0.02 | 0.03 |
| high jump | shot put | **-**0.03 | **-**0.09 | 0.04 |  | **0.08** | **0.05** | **0.11** |
| high jump | javelin | **-0.13** | **-0.20** | **-0.07** |  | **0.05** | **0.02** | **0.08** |
| high jump | pole vault | **-**0.01 | **-**0.08 | 0.06 |  | **0.05** | **0.02** | **0.08** |
| long jump | discus | **-0.14** | **-0.21** | **-0.07** |  | **0.07** | **0.04** | **0.10** |
| long jump | shot put | **-0.18** | **-0.25** | **-0.11** |  | **0.23** | **0.21** | **0.26** |
| long jump | javelin | **-0.15** | **-0.22** | **-0.08** |  | **0.11** | **0.08** | **0.14** |
| long jump | pole vault | **-**0.06 | **-**0.13 | 0.01 |  | **0.13** | **0.10** | **0.16** |
| long jump | high jump | **0.17** | **0.10** | **0.24** |  | **0.20** | **0.17** | **0.22** |
| 110 m hurdles | discus | **-0.13** | **-0.20** | **-0.06** |  | **0.16** | **0.13** | **0.19** |
| 110 m hurdles | shot put | 0.01 | **-**0.06 | 0.07 |  | **0.20** | **0.17** | **0.23** |
| 110 m hurdles | javelin | **-0.14** | **-0.20** | **-0.07** |  | **0.11** | **0.08** | **0.14** |
| 110 m hurdles | pole vault | **-**0.02 | **-**0.09 | 0.05 |  | **0.19** | **0.16** | **0.22** |
| 110 m hurdles | high jump | **0.11** | **0.04** | **0.18** |  | **0.13** | **0.10** | **0.16** |
| 110 m hurdles | long jump | **0.29** | **0.23** | **0.36** |  | **0.25** | **0.22** | **0.28** |
| 100 m | discus | **-0.17** | **-0.23** | **-0.10** |  | **0.15** | **0.12** | **0.18** |
| 100 m | shot put | **-0.22** | **-0.28** | **-0.15** |  | **0.29** | **0.26** | **0.31** |
| 100 m | javelin | **-0.22** | **-0.28** | **-0.16** |  | **0.15** | **0.12** | **0.18** |
| 100 m | pole vault | **-0.13** | **-0.20** | **-0.07** |  | **0.16** | **0.13** | **0.18** |
| 100 m | high jump | **-0.14** | **-0.20** | **-0.07** |  | **0.17** | **0.13** | **0.19** |
| 100 m | long jump | **0.40** | **0.34** | **0.46** |  | **0.35** | **0.32** | **0.38** |
| 100 m | 110 m hurdles | **0.41** | **0.35** | **0.46** |  | **0.42** | **0.39** | **0.44** |
| 400 m | discus | **-0.31** | **-0.37** | **-0.25** |  | **0.08** | **0.05** | **0.11** |
| 400 m | shot put | **-0.40** | **-0.46** | **-0.35** |  | **0.16** | **0.13** | **0.19** |
| 400 m | javelin | **-0.29** | **-0.35** | **-0.23** |  | **0.11** | **0.08** | **0.14** |
| 400 m | pole vault | **-0.08** | **-0.15** | **-0.02** |  | **0.17** | **0.14** | **0.20** |
| 400 m | high jump | **-0.11** | **-0.18** | **-0.05** |  | **0.07** | **0.04** | **0.10** |
| 400 m | long jump | **0.19** | **0.12** | **0.25** |  | **0.23** | **0.20** | **0.26** |
| 400 m | 110 m hurdles | **0.29** | **0.23** | **0.35** |  | **0.33** | **0.30** | **0.35** |
| 400 m | 100 m | **0.60** | **0.55** | **0.64** |  | **0.44** | **0.41** | **0.46** |
| 1,500 m | discus | **-0.29** | **-0.35** | **-0.23** |  | **-**0.03 | **-**0.05 | 0.00 |
| 1,500 m | shot put | **-0.35** | **-0.41** | **-0.29** |  | 0.02 | **-**0.01 | 0.05 |
| 1,500 m | javelin | **-0.15** | **-0.21** | **-0.08** |  | **0.06** | **0.03** | **0.09** |
| 1,500 m | pole vault | 0.01 | **-**0.06 | 0.08 |  | **0.07** | **0.04** | **0.10** |
| 1,500 m | high jump | **-0.07** | **-0.14** | **-0.01** |  | **0.07** | **0.04** | **0.10** |
| 1,500 m | long jump | **-**0.02 | **-**0.09 | 0.05 |  | **0.08** | **0.05** | **0.11** |
| 1,500 m | 110 m hurdles | **-0.12** | **-0.18** | **-0.05** |  | **0.09** | **0.06** | **0.12** |
| 1,500 m | 100 m | **-0.16** | **-0.22** | **-0.09** |  | **0.09** | **0.06** | **0.11** |
| 1,500 m | 400 m | **0.34** | **0.28** | **0.40** |  | **0.28** | **0.25** | **0.31** |

**Table S4.** Correlations at the (*a*) among-individual and (*b*) within-individual levels for all pairwise combinations of events of the heptathlon. The 95% confidence intervals (CI) were calculated using profile likelihoods. Bold estimates have 95%CI that do not overlap with zero

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| event 1 | event 2 | (*a*) among-individual correlation |  | (*b*) within-individual correlation |
|  |  | estimate | 95% CI |  |  | estimate | 95% CI |  |
|  |  |  | lower | upper |  |  | lower | upper |
| javelin | shot put | **0.38** | **0.32** | **0.43** |  | **0.19** | **0.17** | **0.22** |
| high jump | shot put | 0.02 | **-**0.04 | 0.08 |  | **0.08** | **0.06** | **0.11** |
| high jump | javelin | **-0.10** | **-0.16** | **-0.03** |  | **0.07** | **0.04** | **0.09** |
| long jump | shot put | **-**0.05 | **-**0.11 | 0.02 |  | **0.19** | **0.17** | **0.22** |
| long jump | javelin | **-0.25** | **-0.31** | **-0.19** |  | **0.11** | **0.08** | **0.13** |
| long jump | high jump | **0.27** | **0.20** | **0.33** |  | **0.20** | **0.17** | **0.22** |
| 110 m hurdles | shot put | **-0.24** | **-0.29** | **-0.18** |  | **0.30** | **0.27** | **0.32** |
| 110 m hurdles | javelin | **-0.27** | **-0.32** | **-0.21** |  | **0.15** | **0.12** | **0.18** |
| 110 m hurdles | high jump | **-0.08** | **-0.14** | **-0.01** |  | **0.20** | **0.17** | **0.22** |
| 110 m hurdles | long jump | **0.26** | **0.20** | **0.32** |  | **0.33** | **0.31** | **0.35** |
| 200 m | shot put | **-0.21** | **-0.27** | **-0.16** |  | **0.28** | **0.26** | **0.30** |
| 200 m | javelin | **-0.34** | **-0.39** | **-0.29** |  | **0.11** | **0.08** | **0.14** |
| 200 m | high jump | **-0.11** | **-0.17** | **-0.05** |  | **0.19** | **0.17** | **0.22** |
| 200 m | long jump | **0.33** | **0.27** | **0.38** |  | **0.37** | **0.35** | **0.39** |
| 200 m | 110 m hurdles | **0.61** | **0.57** | **0.65** |  | **0.58** | **0.56** | **0.59** |
| 800 m | shot put | **-0.27** | **-0.33** | **-0.21** |  | **0.12** | **0.09** | **0.14** |
| 800 m | javelin | **-0.24** | **-0.30** | **-0.17** |  | **0.09** | **0.06** | **0.12** |
| 800 m | high jump | **-**0.06 | **-**0.13 | 0.01 |  | **0.09** | **0.07** | **0.12** |
| 800 m | long jump | **-**0.02 | **-**0.09 | 0.05 |  | **0.19** | **0.17** | **0.22** |
| 800 m | 110 m hurdles | **-**0.03 | **-**0.09 | 0.04 |  | **0.24** | **0.22** | **0.27** |
| 800 m | 200 m | **0.18** | **0.12** | **0.24** |  | **0.29** | **0.27** | **0.31** |



**Fig. S1.** Frequency distribution of the number of participations per (*a*) decathletes and (*b*) heptathletes included in this study.



**Fig. S2. Wind assistance in combined-events sports.** Shown are partials residuals as function of wind assistance in decathletes (left panels) and heptathletes (right panels), after controlling for year, julian day, experience, and age. See table S1 for estimates from the linear mixed-effect models. Times were standardized (mean=0, sd=1) and multiplied by -1 such that larger values indicate better performance.

**Fig. S3. Age and experience in elite athletes competing in combined-events sports.** Shown are the experience (number of participations) as function of age (years) in (*a*) 636 decathletes and (*b*) 733 heptathletes. Lines connect successive participations for each athlete, showing how age and experience are correlated within decathletes (*r*=0.887±0.004) and heptathletes (*r*=0.894±0.004). However, athletes started competing at different ages and participated at different number of competitions each year, such that age and experience are weakly correlated across decathletes (*r*=0.090±0.058) and heptathletes (*r*=0.153±0.051).



**Fig. S4.** “Heat maps” displaying the correlations among the slopes of the (*a*) performance-age reaction norms and (*b*) performance-experience reaction norms in the 10 decathlon events (top row) and the 7 heptathlon events (bottom row). Times for running events were multiplied by -1 such that larger values indicate better performance. This figure shows previously undetected but relatively strong trade-offs occurring between throwing events and the 1500m, such that decathletes who get better at throwing as they age (relative to population average trend, see fig. 2*a-c*) get worse at running the 1500 m (relative to population average trend, see fig. 2*j,l*), *vice versa*. By contrast, slopes of the performance-experience reaction norms were mostly positively correlated.

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**Fig. S5.** (*a*) “Heat maps” displaying the phenotypic correlations based on the average performance for each decathlete (top panel, *N*=636) and heptathlete (bottom panel, *N*=733), showing that simply using personal-average values reveals the expected performance trade-offs and clusters of positive correlations along the main diagonal corresponding to functional groups (throwing, jumping, running). (*b*) Using all data, the among-individual correlations extracted from multivariate mixed models without any fixed effect. (*c*) The among-individual correlations extracted from multivariate mixed models with fixed effects of year, Julian day, and wind assistance. Note that the correlations displayed in fig 1*c* (main text) are conditioned on year, Julian day, wind assistance, age, and experience.

**Appendix S1: model equations**

**(a) Overview**

Below are the model equations used to compute the various correlations presented in the main text. As our analysis involves the simultaneous evaluation of athletes for multiple traits and makes use of the correlations between the traits, we refer to our models as “multivariate models” (MMM; see p. 84 in Mrode 2005; Linear models for the prediction of animal breeding values. Wallingford, UK: Cabi Publishing). The equations are the same as in Dingemanse and Dochtermann (2013; Quantifying individual variation in behaviour: mixed-effect modelling approaches. Journal of Animal Ecology 82:39-54). The goal of the equations below is to clarify the models we fitted and are not meant to explain how MMMs work. We recommend interested readers to consult Dingemanse and Dochtermann (2013) to learn more about MMMs.For sake of simplicity, the equations for multivariate models are presented for two traits, but the models for decathletes and heptathletes included 10 and 7 traits, respectively.

**(b) Personal-best and personal average values**

The maximal or mean performance for each athlete *j* in two events (*y* and *z*) were modelled as function of a population-level intercept (β0*y* and β0*z*) and a residual error (*e*0*yj* and *e*0*zj*):

$$y\_{j}=β\_{0y}+e\_{0yj}$$

$$z\_{j}=β\_{0z}+e\_{0zj}$$

Eqn 1

The residual errors (*e*0*yj* and *e*0*zj*) were assumed to be drawn from a from a multivariate normal distribution (MVN), with means of zero, residual variances (*Ve*0*y* and *Ve*0*z*), and residual covariances (Cov*e*0*y*;*e*0*z*):

$$\left[\begin{array}{c}e\_{0yj}\\e\_{0zj}\end{array}\right] \~ MVN\left(0,Ω\_{e}\right): Ω\_{e}= \left[\begin{matrix}V\_{e0y}&Cov\_{e0y;e0z}\\Cov\_{e0y;e0z}&V\_{e0z}\end{matrix}\right]$$

Eqn 2

Accordingly, phenotypic correlations (*r*P) were calculated as:

$$r\_{P}= \frac{Cov\_{e0y;e0z}}{\sqrt{ V\_{e0y}× V\_{e0z} }}$$

Eqn 3

The correlations obtained using this method were identical as those obtained when computing a simple correlations matrix. The advantage of the method above is that fixed effects can be added to the model to condition the *r*P on various factors. In our case, we were interested in estimating *r*P after conditioning on the total number of repeated record for each athlete (*n*trial). Therefore, we fitted an additional model:

$$y\_{j}=β\_{0y}+β\_{1y}x\_{j}+e\_{0yj}$$

$$z\_{j}=β\_{0z }+β\_{1z}x\_{j}+ e\_{0zj}$$

Eqn 4

Where *xj* represents *n*trial for athlete *j* and β1 represents the regression coefficient of the dependence of *y* and *z* on *x*. Comparing the *r*P computed from models with and without *n*trial as a fixed effect indicate the bias related to the use of “personal best” when subjects widely differ in their number of repeated measures (*n*trial).

**(c) Effects of extrinsic and intrinsic factors**

Instead of extracting the maximal or mean performance for each athlete, we considered all repeated measures. For a given event *y* (e.g., shot put), the performance for each athlete *j* in competition *i* was modelled as:

$$y\_{ij}=(β\_{0}+ ind\_{0j})+β\_{1}x\_{1ij}+β\_{2}x\_{2ij}+β\_{3}x\_{3ij}+β\_{4}x\_{4ij}+β\_{5}x\_{5ij}+e\_{0ij}$$

Eqn 5

Where *x*1, *x*2, *x*3, *x*4,and *x*5 represent year (factor with 18 levels), Julian day (continuous variable), wind assistance (only for events in which it is recorded), experience, and age with their associated regression coefficients (β). The individual contribution is estimated as the difference from the population mean by including random intercepts to model differences in performance between individuals (ind0*j*). This random intercept is assumed to be normally distributed (N) with a mean of zero and a variance (Ωind) termed the among-individual variance (estimated as *V*ind0: the variance across random intercepts of individuals). A residual error (*e*0*ij*) is also assumed to be normally distributed, with zero mean and a variance (Ω*e*) representing the within-individual variance (*V*e0):

$$\left[ind\_{0j}\right] \~ N\left(0,Ω\_{ind}\right): Ω\_{ind}= \left[V\_{indo}\right]$$

$$\left[e\_{0j}\right] \~ N\left(0,Ω\_{e}\right): Ω\_{e}= \left[V\_{eo}\right]$$

Eqn 6

We use the univariate models to calculate repeatability as:

$$repeatability= \frac{V\_{indo}}{(V\_{indo}+ V\_{eo})}$$

Eqn 7

**(d) Among- and within-individual correlations**

One of the main advantages of MMMs is that they can partition *r*P into two distinct levels – the among-individual correlation (*r*ind) and the residual correlation (*re*). We ran MMMs with the same characteristics as above except that the covariances between the response variables were explicitly considered. For example, a bivariate equivalent to eqn 5 – where fixed effects are included in the linear equation and where the phenotypic (co)variance is decomposed among vs. within individuals – is:

$$y\_{ij}=(β\_{0y}+ ind\_{0yj})+β\_{1y}x\_{1ij}+β\_{2y}x\_{2ij}+β\_{3y}x\_{3ij}+β\_{4y}x\_{4ij}+β\_{5y}x\_{5ij}+e\_{0yij}$$

$$z\_{ij}=(β\_{0z}+ ind\_{0zj})+β\_{1z}x\_{1ij}+β\_{2z}x\_{2ij}+β\_{3z}x\_{3ij}+β\_{4z}x\_{4ij}+β\_{5z}x\_{5ij}+e\_{0zij}$$

Eqn 8

Where *y* and *z* represent performance in two events (e.g., 100m and hurdles) by athlete *j* during competition *i* modelled as function of a population-level intercept (separate for each trait; β0*y* and β0*z*) and a series of fixed effects (year, Julian day, wind-assistance, experience, and age, fitted separately for each trait to estimate different regression coefficients for each trait; β1*y* and β1*z*). As was the case with univariate models above, the random intercepts (ind0*j*) and the within-individual contributions (*e*0*j*) to *y* and *z* are modelled as having means of zero. The random intercepts are distributed assuming a MVN distribution with a variance-covariance structure (Ωind) specifying the between-individual variances (*V*ind0*y* and *V*ind0*z*) and the between-individual covariance between the two traits (Covind0*y*;ind0*z*). The residual errors (*e*0*yij* and *e*0*zij*) were assumed to be drawn from a from a MVN distribution specifying the within-individual variances (*Ve*0*y* and *Ve*0*z*), and within-individual covariances (Cov*e*0*y*;*e*0*z*):

$$\left[\begin{array}{c}ind\_{0yj}\\ind\_{0zj}\end{array}\right] \~ MVN\left(0,Ω\_{ind}\right): Ω\_{ind}= \left[\begin{matrix}V\_{ind0y}&Cov\_{ind0y;ind0z}\\Cov\_{ind0y;ind0z}&V\_{ind0z}\end{matrix}\right]$$

$$\left[\begin{array}{c}e\_{0yj}\\e\_{0zj}\end{array}\right] \~ MVN\left(0,Ω\_{e}\right): Ω\_{e}= \left[\begin{matrix}V\_{e0y}&Cov\_{e0y;e0z}\\Cov\_{e0y;e0z}&V\_{e0z}\end{matrix}\right]$$

Eqn 9

Accordingly, the among-individual correlations (*r*ind) were calculated as:

$$r\_{ind}= \frac{Cov\_{ind0y;ind0z}}{\sqrt{ V\_{ind0y} × V\_{ind0z} }}$$

Eqn 10

And the within-individual correlations (*re*) were calculated as:

$$r\_{e}= \frac{Cov\_{e0y;e0z}}{\sqrt{ V\_{e0y} × V\_{e0z} }}$$

Eqn 11

**(e) Multivariate reaction norms**

The MMMs above assume that changes in performance through ageing were the same for all athletes, as captured by the population-average slope β5 describing the effect of age. However, this assumption may not hold because if plasticity varies among athletes. For example, some athletes may be able to increase performance more than others as they age. We can statistically model this relationship by adding random slopes (ind5j) to the around the population-average slope β5:

$$y\_{ij}=(β\_{0y}+ ind\_{0yj})+β\_{1y}x\_{1ij}+β\_{2y}x\_{2ij}+β\_{3y}x\_{3ij}+β\_{4y}x\_{4ij}+(β\_{5y}+ind\_{5yj})x\_{5ij}+e\_{0yij}$$

$$z\_{ij}=(β\_{0z}+ ind\_{0zj})+β\_{1z}x\_{1ij}+β\_{2z}x\_{2ij}+β\_{3z}x\_{3ij}+β\_{4z}x\_{4ij}+(β\_{5z}+ind\_{5zj})x\_{5ij}+e\_{0zij}$$

Eqn 12

Here, *x*5*ij* is the age of athlete *j* at competition *i*. In this model, each athlete ageing trajectory can deviate from the population-mean slopes for trait *y* (+ind5*yj*) and trait *z* (+ind5z*j*), modelled as being drawn from a MVN distribution, with a mean of zero:

 

$$\left[\begin{array}{c}e\_{0yj}\\e\_{0zj}\end{array}\right] \~ MVN\left(0,Ω\_{e}\right): Ω\_{e}= \left[\begin{matrix}V\_{e0y}&Cov\_{e0y;e0z}\\COV\_{e0y;e0z}&V\_{e0z}\end{matrix}\right]$$

Eqn 13

where the among-individual variance-covariance matrix contains four variance components: the variance in average level (intercept) of phenotypic attribute *y* (*V*ind0*y*) and *z* (*V*ind0*z*) and the variance in the change (slope) *y* (*V*ind5*y*) and *z* (*V*ind5*z*) as function of age. This matrix also contains six corresponding covariance components. We were mainly interested in the covariance between the slopes of traits *y* and *z* (Covind5*y,*ind5*z*), because this is the term that indicates whether individual differences in plasticity of performance through ageing are correlated.