Phenotypic Covariation And Morphological Diversification In The Ruminant Skull

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Online Appendix A: Additional details on methods and results

Online Appendix B: Simulations exploring the relationship between Average flexibility and rSDE

Dryad files: Data, phylogenetic hypotheses, and annotated R codes for all analyses

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Abstract

Differences between clades in their diversification patterns result from a combination of extrinsic and intrinsic factors. In this study I examined the role of intrinsic factors on the morphological diversification of ruminants, and in particular the differences between bovids and cervids. Using skull morphology, which embodies many of the adaptations that distinguish bovids and cervids, I examined 132 of the 200 extant ruminant species. As a proxy for intrinsic constraints I quantified different aspects of the phenotypic covariation structure within species, and compared them with the among-species divergence patterns of their clades, using phylogenetic comparative methods. My results show that bovids have dispersed into a wider range of directions in morphospace than cervids, and that their overall disparity is higher. Within both bovids and cervids, most species divergence is well aligned with their phenotypic covariance matrices, and those that are better aligned have diverged further away from their ancestor. Bovids' greater disparity and wider range of dispersion is associated with a lower eccentricity of their within-population covariance matrices. These results are consistent with the role of intrinsic constraints in determining amount, range, and direction of dispersion, and demonstrate that intrinsic constraints can influence macroevolutionary patterns even as the covariance structure evolves.

Introduction

Diversity is distributed unevenly across the tree of life; a fact that is at the heart of many research programs in evolutionary biology. This unevenness is the result of both extrinsic and intrinsic factors. While extrinsic factors provide the opportunities for diversification, intrinsic factors determine the variation available for natural selection to work on, and therefore the potential of the population to respond to environmental changes and to take advantage of these opportunities. Studying this potential is therefore crucial for understanding macroevolutionary patterns. A common approach for studying the effect of intrinsic factors is to look at the structure of phenotypic and genetic (co)variation within the population, and compare it to patterns of divergence among populations (Lande 1979; Zeng 1988; Armbruster 1996; Schluter 1996; Arnold et al. 2001; Ackermann and Cheverud 2002; Hansen and Houle 2008; Hohenlohe and Arnold 2008; Marroig et al. 2009; Bolstad et al. 2014). In this study I examine the role of phenotypic covariation and intrinsic constraints in the morphological diversification of the ruminant skull, with particular emphasis on the contrast between bovids and cervids.

According to the quantitative genetics framework (Lande 1979), the rate and direction of short-term evolution depends on the relative alignment between selection and the within-population genetic (**G**) and phenotypic (**P**) covariation, as well as their strength. A closer alignment between the major axis of covariation and selection allows the population to evolve more rapidly in the direction of selection because more variation is available in this direction. A greater angle between them will divert the population further away from the optimum, slowing down its evolution. A direct extension of this framework to the macroevolutionary scale predicts that the divergence of populations will initially be biased by the major axis of their ancestral covariation structure – resulting in a close alignment between the within-population covariation and the among-population divergence – and that this effect will diminish with time (Zeng 1988; Armbruster 1996; Schluter 1996).

Hansen and Houle (2008) expanded this approach to quantify different aspects of the evolutionary potential and provide a null expectation for evaluating the extent of the bias (Hansen and Voje 2011; Bolstad et al. 2014). They defined the evolvability of a single trait as the

expected change in trait value in response to directional selection of unit strength per generation, measured as the mean-scaled trait variance. In a multivariate space, evolvability can vary in different directions and is therefore defined with respect to a specific direction; e.g., that in which selection is acting or that in which divergence has occurred ($e(\mathbf{d}_{SP})$ and $e(\mathbf{d}_{CL})$; see table 1 for details). The conditional evolvability is defined as the expected change in a given direction assuming stabilizing selection in the remaining directions, thus accounting for trait covariances as well as variances. When averaged across random directions these measures provide the null expectation of no bias ($\overline{e}$ and $\overline{c}$ in table 1).

At both the micro- and the macro-evolutionary scales, this framework has focused on the relative alignment between covariation and selection. It measures the amount of variation available in a specific direction and therefore the potential to evolve faster in that direction. However, as the phylogenetic scale and time span of the study increase it becomes more difficult to reconstruct selection and covariation at any given time, and more likely that either or both have changed repeatedly, so that their average estimation (or ancestral reconstruction) becomes less informative. The stability and predictability of **P** and **G** has been a particularly thorny issue when attempting to bridge the micro and macro scales, with the growing understanding that the relevant question is when and how they evolve, rather than if, and that the answer is complex and context-dependent (Arnold et al. 2008; Haber 2015; and references therein). Moreover, on the macro scale, selection is more likely to have shifted often enough and in directions different enough (Uyeda et al. 2011; Jones et al. 2012), presenting the populations with a more diverse array of challenges and opportunities. The probability of going extinct or being outcompeted before reaching the optimum also becomes increasingly relevant (Jablonski 2007; Gomulkiewicz and Houle 2009; Jones et al. 2012). Therefore, we might expect that the long-term evolutionary success of lineages and clades would be largely determined – and therefore better predicted – by their ability to respond effectively to a wide range of selective pressures (Vermeij 1973; Liem 1973; Draghi and Wagner 2008), rather than their ability to respond faster in any particular direction. In this context, 'responding effectively' means reaching close enough to the optimum to avoid extinction or competitive displacement, until selection changes again.

I consider here four measures that could reflect the potential to respond to a wide range of selective pressures: $\bar{e}$, $\bar{c}$, $\bar{f}$, and rSDE(**P**) (see table 1 for details). The average evolvabiliy ($\bar{e}$) and conditional evolvabiliy ($\bar{c}$) developed by Hansen and Houle (2008) measure the variance available in any random direction on average, and thus the average potential to respond to any selection vector. A higher value of $\bar{e}$ or $\bar{c}$ can be interpreted as a greater potential to respond to a wider range of selection vectors, where $\bar{c}$ accounts also for the possibility of stabilizing selection in the remaining directions. Both are proportional to total variance (i.e., matrix size), and $\bar{c}$ accounts also for trait covariances (i.e., matrix shape). Another measure developed based on Hansen and Houle (2008) is the average flexibility ($\bar{f}$; Marroig et al. 2009; Roland 2009), which measures how much the population response is deflected from the direction of selection, on average. A higher value means that the population is less biased by its major axis of covariation and is able to align more closely with a wider range of selection vectors (i.e., more flexible). $\bar{f}$ quantifies matrix shape only, not accounting for the orientation and size of the matrix.

Another metric that quantifies matrix shape only, albeit in a different way, is the relative standard deviation of the eigenvalues (rSDE(**P**) in table 1). This metric, and its variations, has been referred to as integration level in studies of morphological integration (Wagner 1984, Cheverud et al. 1989, Pavlicev et al. 2009, Haber 2011). Its use as a measure of integration has been criticized recently for being merely descriptive with no link to the theory of integration and evolution (Armbruster et al. 2014). However, here I use it to quantify matrix shape – as originally suggested by Van Valen (1974) – and reinterpret it in the context of Hansen and Houle's (2008) model. Since evolvability is defined as the (mean-scaled) variance in a given direction, the eigenvalues of a matrix measure the evolvabilities along its eigenvectors. Therefore, rSDE(**P**) measures the variation in the ability to respond in different directions. Because rSDE(**P**) is standardized by the total variance of the matrix, it captures matrix shape only. When the variation in the sample is distributed more evenly in different directions, matrix shape is less eccentric, and rSDE(**P**) is lower. By definition, matrices with a lower eccentricity are less biased by their major axis of covariation. Therefore, we would expect rSDE(**P**) to have a

tight negative correlation with $\overline{f}$. Indeed, preliminary simulations indicate that this relationship persists for a wide range of matrices that differ in their number of variables, mean correlation, and heterogeneity (see online appendix B). To the extent that the observed covariation matrix reflects underlying integrating factors, a more eccentric matrix would reflect a body-plan that is more strongly integrated overall. However, the link between rSDE(**P**) and integration is not the focus of this study. Instead, I focus here on the link between rSDE(**P**) and macroevolution.

Which variational property best predicts macroevolutionary patterns is still an open question (Hansen 2012; Bolstad et al. 2014). Because $\overline{e}$ and $\overline{c}$ are proportional to matrix size (i.e., total variance), a direct extrapolation to macroevolution assumes a linear relationship between the probability of responding effectively and the variance available to selection at any given time. We might, however, imagine a situation where the relationship is not linear, involving a threshold of variance that needs to be exceeded in order to avoid extinction and/or diverge successfully. When the variation is distributed more evenly across the different dimensions, there would be more directions in which the threshold is likely to be exceeded (for a given matrix size). Therefore, for a given matrix size, a population with a lower eccentricity would be able to respond effectively in more directions, and would be more likely to persist, evolve, and diversify in the long run, regardless of its orientation. This prediction relies on several additional assumptions (see *Discussion*). The extent to which they are warranted in practice and under what conditions is not known, and developing and exploring a comprehensive quantified model is beyond the scope of this study. Here I explore an empirical case in which these additional considerations are likely to be relevant.

Ruminants comprise the bulk of Artiodactyla (Vrba and Schaller 2000; Theodor et al. 2005), and consist of Tragulidae (chevrotains) and Pecora (giraffes, pronghorn, musk deer, bovids, and cervids). Bovids and cervids are currently the most species-rich families within Ruminantia (143 and 51 extant species, respectively). Yet, their taxonomic richness is not too high to be reasonably sampled within the scope of this study, allowing for both good taxonomic coverage and large within-species samples. In addition, their phylogenetic history is relatively well understood (Hernández Fernández and Vrba 2005; Price et al. 2005; Gilbert et al. 2006; Marcot 2007; Agnarsson and May-Collado 2008; Decker et al. 2009). Their fossil record is

135 exceptionally good for vertebrates (Geist 1985, 1987; Janis 1989; Vrba and Schaller 2000;
136 Marcot 2004; Pitra et al. 2004; Ropiquet and Hassanin 2005; Theodore et al. 2005; Gillbert et al.
137 2006; Janis 2008; Heywood 2010), providing ample evidence that ruminants have faced a wide
138 range of selective pressures due mostly to global changes such as Plio-Pleistocene glacial cycles
139 and the opening of grasslands. At the same time, the fossil record reveals that cervids have had
140 about the same opportunities as bovids to exploit open habitats and arid grasslands at least
141 since the late Miocene (Janis 2008; Heywood 2010). Yet, no cervid has evolved into a true
142 grazer. Cervids are mostly browsers, occupying habitats with dense vegetation, whereas bovids
143 exhibit a high diversity of feeding adaptations and a wider range of body size and shape (Allard
144 et al. 1992; Spencer 1997; Sinclair 2000; Marcot 2004; Janis 2008; Heywood 2010). These
145 differences have left researchers puzzled as to why cervids have not taken advantage of the
146 same opportunities as bovids (Janis 2008; Heywood 2010). My results support the role of
147 intrinsic constraints in the morphological diversification of both bovids and cervids, and suggest
148 that the greater diversification of bovids is best explained by their lower within-population
149 eccentricity. I discuss these results in the context of ruminant history and the extrapolation
150 from micro- to macroevolution.
151

Materials and Methods

Data collection and preparation

A total of 2857 skulls were included in this study, representing 5 out of 8 species of tragulids, 3 out of 7 extant species of moschids, 34 out of 51 extant species of cervids, and 87 out of 143 extant species of bovids. All 19 extant cervid genera are represented except *Przewalskium albirostris*, which has been endangered for the last few decades. Of the 50 extant bovid genera, 40 are represented. The remaining 10 consist of only 1 to 3 species each and are all nested within otherwise well-represented clades. All domesticated species were excluded. Taxonomic assignments of specimens were standardized following Grubb (2002). Only prime age adults were measured, as determined by their dentition and cranial sutures. Three-dimensional coordinates were recorded for 43 landmarks using MicroScribe MLX (online table A1). Landmark definition was based on the standard measurements recommended by von den Driesch (1976), as well as other studies of the artiodactyl skull (Janis 1990; Mendoza et al. 2002; Semprebon et al. 2004). Data processing involved unifying the dorsal and ventral aspects of the skull, averaging the left and right, and identifying outliers (see online Appendix A for details). Variances due to measurement error were estimated based on repeated measurements of selected specimens and were found to be between 1 to 3 orders of magnitude lower than the inter-specimen variance (see online Appendix A).

Two datasets of interlandmark distances were created. For the first set ('ILtes'), 107 interlandmark distances were defined based on Delaunay tessellation of the symmetric mean configuration of all specimens, function *delaunayn* in the R package *geometry* (Barber et al. 2012). This procedure maximizes coverage while minimizing redundancy and crossing over spatial modules. The second set ('IL32') included 32 ILMDs selected based on comparability with other studies (e.g., von den Driesch 1974; Janis 1990; Marroig and Cheverud 2004; Mendoza et al. 2002) and interpretability in the context of either function or putative modules (see online table A2). Both datasets were corrected for variation due to subspecies and sex by adding to each value within a subsample the difference between the grand mean and the subsample mean (Sokal and Rohlf 1995; Marroig and Cheverud 2004). No significant effect of sex and subspecies was found on either the orientation or eccentricity of the covariance matrix

181 for most species. Species for which I found a substantial effect, even if non-significant, were
182 reduced to the largest single subspecies sample. A MANOVA test revealed no significant
183 interaction between sex and subspecies for mean shape.

184 ***Quantifying within-population covariation***

185 A **P** matrix was calculated for each species with more than 27 specimens, including 2
186 species of tragulids, 13 species of cervids, and 32 species of bovids (see fig. 2 for details). Three
187 subspecies of white-tailed and mule deer were analyzed separately, bringing the total number
188 of cervid samples to 17. Variables were scaled by the species mean. Scaling by the mean
189 mitigates the isometric effect of size variation among individuals (within and across species), as
190 well as scale differences among variables, and ensures that the evolvability measures are
191 meaningful in the context of Lande's (1979) equation (Hansen et al. 2011). A non-weighted
192 bending procedure was applied to each matrix to ensure that it is positive-definite (Jorjani et al.
193 2003; Pavlicev et al. 2009). Each sample was jackknifed specimen-by-specimen to identify
194 aberrant specimens.

195 The average evolvability ($\bar{e}$), average conditional evolvability ($\bar{c}$), and average flexibility
196 ($\bar{f}$) were calculated using simulations of random selection vectors (Marroig et al. 2009; Rolian
197 2009; Bolstad et al. 2014; see table 1). rSDE(**P**) was calculated based on the eigenvalues (see
198 table 1) and adjusted for the effect of sample size by subtracting the mean of a 1000
199 permutations from the observed value. This is equivalent to the correction suggested by
200 Wagner (1984), but applicable to covariances as well as correlations. Confidence intervals were
201 estimated using a non-parametric bootstrap procedure with a bias correction (BCa; DiCiccio and
202 Efron 1996; Carpenter and Bithell 2000) and 999 iterations. The BCa correction was necessary
203 because the pseudovalues distribution is expected to be biased upward and to depend on its
204 mean when bounded by zero and/or one.

205 The evolution of rSDE(**P**), ($\bar{e}$), and ($\bar{c}$) was explored by fitting several Ornstein-
206 Uhlenbeck models, as well as a Brownian motion model, in order to identify nodes where a shift
207 in the clade's typical values has occurred (interpreted here as selective regime; Hansen 1997;
208 Butler and King 2004). Using R package *maticce* (Hipp and Escudero 2010), I tested five nodes:
209 all ruminants excluding tragulids (node number 8 in Hernández Fernández and Vrba 2005);

210 Bovidae (node 15); Cervidae (node 25); Cervinae (node 27); and Caprinae (node 139). All
211 possible combinations of the five putative transitions were tested, resulting in 32 alternatives of
212 the OU model and one Brownian motion model (see table 2). Values were ln-transformed for
213 this analysis, and branch length was scaled by tree height. Models were selected based on the
214 relative weights of their AICc scores (Anderson et al. 2000). The maximum likelihood estimate
215 for each regime was estimated as an average of the 32 models, weighted by their AICc weights
216 (Anderson et al. 2000).

217 ***Quantifying morphological dispersion***

218 The among-population divergence was measured by the overall amount, rate, and
219 eccentricity of dispersion (table 1). These measures were calculated separately for each clade –
220 Bovidae, Cervidae, Cervinae, and Caprinae, as above – based on its species means. Species
221 means were scaled by the clade's phylogenetically-weighted mean (the inferred root state),
222 assuming a Brownian motion model (function *fastAnc* in the R package *phytools*; Revel 2012).
223 The overall dispersion was calculated as the mean squared morphological distance between
224 each species and the clade's phylognetically-weighted mean (equivalent to Foote 1993's
225 disparity). To facilitate comparisons, the expected distribution under Brownian motion model
226 was generated by simulating a 1000 datasets (function *sim.char* in the R package *Geiger*;
227 Harmon et al. 2008) and recalculating disparity for each simulated dataset. The rate parameters
228 for these simulations were provided by the clade's evolutionary rate matrix ($\mathbf{D}_{IC}$ in table 1). $\mathbf{D}_{IC}$
229 is the covariance matrix of independent contrasts between species means, assuming a
230 Brownian-motion model, and therefore represents the coevolution of traits while taking into
231 account phylogeny (Revell 2007; Revell and Harmon 2008). The rate of dispersion is the trace of
232 $\mathbf{D}_{IC}$. The eccentricity of dispersion is the relative standard deviation of the eigenvalues of $\mathbf{D}_{IC}$
233 (rSDE($\mathbf{D}_{IC}$) in table 1). Thus, this metric measures how evenly species have diverged in
234 morphospace. Confidence intervals for the rates and eccentricity of dispersion were estimated
235 using a parametric bootstrap procedure with 500 replications, using the original sample size
236 and assuming a multivariate normal distribution.

237 ***Evolvability in the direction of divergence***

238 Species divergence was compared with the amount of mean-scaled phenotypic variance
239 (evolvability) available in the direction of divergence, following Hansen and Houle (2008) and
240 Hansen and Voje (2011). I first calculated the amount of variation that each species has along
241 the eigenvectors of its clade's evolutionary rate matrix ($e(\mathbf{d}_{CL})$; see table 1 for details), using its
242 observed **P**. Species whose **P** matrices are more closely aligned with their clade's diversification
243 would have higher evolvabilities along the first eigenvector of $\mathbf{D}_{IC}$ than along other
244 eigenvectors. I then calculated the amount of variation available for species in the direction of
245 their own divergence from their clade's inferred root state (($e(\mathbf{d}_{SP})$ and $c(\mathbf{d}_{SP})$ in table 1; Hansen
246 and Voje 2011), based on the clade's average **P** ($\mathbf{P}_{AV}$). Ideally, **P** here would be averaged over
247 the clade's history while accounting for phylogeny. However, previous analyses (Haber 2015)
248 indicated that the phylogenetic structure of **P** within each clade has been obliterated
249 substantially. Therefore, the simple average – i.e., assuming 'white noise' model – was
250 preferred over other evolutionary models. The observed evolvabilities were compared to the
251 expected values for random directions ($\overline{e}$ and $\overline{c}$; table 1), also calculated here based on $\mathbf{P}_{AV}$
252 (Hansen and Houle 2008, Hansen and Voje 2011). Higher evolvabilities indicate species that
253 have diverged closer to the direction of $\mathbf{P}_{AV}$ than expected by chance (Hansen and Voje 2011).
254 All analyses were repeated for three different phylogenetic hypotheses derived from
255 the literature. Because results were essentially the same regardless of phylogeny, I present
256 below results based on the phylogeny of Hernández Fernández and Vrba (2005) only. Results
257 based on the other two phylogenies are presented in online appendix A. All analyses were
258 carried out using R v.3.0.2 (R development Core Team 2013). The phylogenetic trees were
259 generated and manipulated using packages *ape* (Paradis et al. 2004) and *phytools* (Revell 2012).
260 All R scripts, data, and phylogenetic hypotheses are available on Dryad (###).
261
262 Results
263 ***Within-population covariation***
264 The two datasets (ILtes, IL32) yield largely the same results (online fig. A3), indicating
265 that the smaller dataset captures most of the relevant information with its 32 variables. Values
266 based on the IL32 datasets are consistently lower than those based on the ILtes datasets,

267 probably due to a lower overall level of redundancy in the data, and the signal is often weaker.
268 Adjusting rSDE(**P**) for sample size has little effect (online fig. A4).

269 Average flexibility has a tight inverse correlation with the within-population eccentricity
270 (rSDE(**P**)); average evolvability ($\overline{e}$) is positively but loosely correlated with rSDE(**P**); and average
271 conditional evolvability ($\overline{c}$) is not correlated with rSDE(**P**), nor with $\overline{e}$ (fig. 1). $\overline{c}$ has yielded
272 different results depending on shrinking tolerance, method of matrix inversion, and number of
273 variables (online figure A3), and should therefore be regarded with caution. All rSDE(**P**) values
274 deviate from zero after adjusting for sample size (fig.2), indicating that all species deviate
275 significantly from the null expectation of a random covariation structure. Bovids are in general
276 less variable than cervids (fig. 2); most bovid species do not differ from each other substantially,
277 with the striking exception of Caprinae, whereas cervids show considerable variation
278 throughout the clade and even among conspecific subspecies.

279 The model fitting results indicate that rSDE(**P**), $\overline{e}$, and $\overline{c}$ have not evolved following a
280 Brownian motion process, but rather as a multi-regime OU process (table 2). The most strongly
281 supported transition for rSDE(**P**) is at the base of Caprinae; all models that do not include a shift
282 at this node (models 17-32) have the lowest AICc weights. The best-supported model for all
283 datasets (model 14 in table 2) includes a shift at the base of Cervidae as well as Caprinae. In
284 addition, there is strong evidence against a transition at the base of bovids plus cervids (node
285 8FV in table 2), as well as at the base of all bovids. Therefore, bovids and cervids probably do
286 not share the same typical rSDE(**P**) value. Bovids and tragulids, on the other hand, have the
287 same typical value, which most likely characterized their ruminant ancestor as well. Model 10,
288 which includes a shift for cervines in addition to cervids and caprines, is also relatively well
289 supported (see also online tables A3-A5). Therefore, there is some evidence that the typical
290 rSDE(**P**) value of cervines is higher than that of other cervids. The best-supported model for $\overline{e}$
291 includes a transition for both bovids and caprines (model 8) and none for other clades (table 2),
292 implying that bovids have deviated from the ancestral ruminant state rather than cervids. The
293 best-supported model for $\overline{c}$ includes only a transition for caprine (model 16). Models 14 and 15
294 are well supported in IL32 (table 2) but not in ILtes (online table A3).

295 The parameter estimates for the best-supported models are given in table 3, along with
296 their weighted averages. The shifts inferred for rSDE(**P**) involves an increase for caprines and
297 cervids (and possibly cervines). The shifts inferred for $\bar{e}$ involves a decrease for bovids and an
298 increase for caprines relative to cervids and the ancestral state. The shifts inferred for $\bar{c}$ involves
299 a decrease for caprines based on IL32 and an increase based on ILtes. The alpha estimates for
300 rSDE(**P**) are rather high, yielding a phylogenetic half-life of almost 8% of total tree height
301 (calculated as log(2)/alpha; Hansen 1997). This implies that half of the phylogenetic structure
302 has been obliterated within less than 4 My, out of the 50 My of ruminant history. The sigma-
303 squared estimates for the best OU models are about 4 times higher than that of the Brownian
304 motion model, implying a very strong stabilizing effect. The alpha sigma-squared estimates are
305 even higher for $\bar{e}$ and $\bar{c}$.

306 ***Morphological dispersion***

307 The position of both species of *Alces* in morphospace deviates substantially from all
308 other cervids (online fig. A2). Therefore, all measures were repeated for cervids with and
309 without *Alces*. Bovids' disparity is at the higher end of the expected range based on a Brownian
310 motion model, especially when caprines are excluded, whereas cervids' disparity is at the lower
311 end, especially when *Alces* is excluded (fig. 3). Bovids' rate of dispersion is somewhat lower
312 than that of cervids, although this difference is not significant and disappears when *Alces* is
313 excluded (fig. 3). Cervids' eccentricity of dispersion is significantly higher than that of bovids,
314 especially when *Alces* is excluded (fig. 3). Caprines' eccentricity and total disparity are lower
315 than that of all bovids, but their rate of dispersion is higher. These findings are somewhat more
316 pronounced based on ILtes and the alternative phylogenies (online figures A6-A7)

317 ***Evolvability in the direction of divergence***

318 Most species have substantially higher evolvabilities ($e(\mathbf{d}_{CL})$) along the first eigenvector
319 of their clade's evolutionary rate matrix, $\mathbf{D}_{IC}$, than along other eigenvectors (fig.4). The first
320 eigenvector is associated with 76%-85% of the variation in $\mathbf{D}_{IC}$. The minimal overlap between
321 the range of evovlabilities along the first eigenvector and those along other eigenvectors
322 indicate that the vast majority of species have their **P** matrix more closely aligned with their $\mathbf{D}_{IC}$
323 than expected by chance. At the same time, the wide range of values along the first eigenvector

indicates that species differ greatly in their alignment. Cervids' median value is only slightly higher than that of bovids, and their range is somewhat wider based on IL32 (though not based on ILtes; online fig. A8). Caprines have the same median and range as bovids. Excluding caprines from bovids (online fig. A10) and *Alces* from cervids (online fig. A11) made no difference.

Most of the observed evolvabilities in the direction of species divergence – $e(\mathbf{d}_{SP})$ and $c(\mathbf{d}_{sp})$ – are closer to the maximum value than to the expected value for random directions (fig. 5). The average evolvability of $\mathbf{P}_{AV}$ is 0.31% of trait mean for bovids, 0.19% for cervids, and 0.06% for caprines, whereas the observed $e(\mathbf{d}_{SP})$ are above 0.4%, 0.6%, and 0.29%, respectively. The average conditional evolvability of $\mathbf{P}_{AV}$ is 0.08% for bovids, 0.05% for cervids, and 0.01% for caprines, whereas all the observed $c(\mathbf{d}_{sp})$ are an order of magnitude higher. Many of the bovid $c(\mathbf{d}_{sp})$ values are over 1%, whereas most cervid $c(\mathbf{d}_{sp})$ values are below 0.5%. When caprines are excluded from bovids, all bovid $c(\mathbf{d}_{sp})$ values are lower than 1% (online fig A15). When *Alces* is excluded from cervids, more $c(\mathbf{d}_{sp})$ values exceed 0.5% (online fig A17), thus narrowing the gap between bovids and cervids.

There is a distinct non-linear association between the observed $e(\mathbf{d}_{sp})$ and $c(\mathbf{d}_{sp})$ values and the amount of morphological divergence, d^2 (fig. 5). Species whose divergence is more closely aligned with the direction of maximum evolvability managed to diverge further away from the clade's ancestral state. The curve flattens close to the maximum value of evolvability at about 150% distance, in both bovids and cervids. Only species whose divergence is well aligned with the direction of the major axis of their $\mathbf{P}_{AV}$ (i.e., their observed $e(\mathbf{d}_{SP})$ value is close to the maximum) managed to diverge beyond that threshold.

Discussion

The role of intrinsic constraints in determining macroevolutionary patterns is still an open question in evolutionary biology. The structure of variation and covariation within the population has been used for studying the role of intrinsic constraints on generational scale, but it is still not clear which properties of that structure best predict evolutionary outcomes on the macro scale, and under what conditions. The question of why some clades are more diverse than others is of particular interest for macroevolutionary studies. The contrast between bovids and cervids is such an example. Previous studies have provided ample evidence that bovids are substantially more diverse than cervids, taxonomically and ecologically (Allard et al. 1992; Spencer 1997; Sinclair 2000, Grubb 2002; Marcot 2004; Janis 2008; Heywood 2010). Based on discrete characters of teeth, Marcot (2004) has shown that bovids have been more diverse morphologically at least since the late Miocene (about 10 Mya). Here I provide additional evidence – based on their skull morphology – that bovids have a higher disparity than cervids and have dispersed into a wider range of directions in morphospace. So far, studies of the fossil record have not been able to explain these differences based on extrinsic factors (Janis 2008; Heywood 2010). My findings suggest that intrinsic constraints have played an influential role in the diversification of ruminants in general, and in the differences between bovids and cervids in particular.

The role of intrinsic constraints was assessed here by comparing various properties of the within-population covariation (**P** and $\mathbf{P}_{AV}$; see table 1) with those of the among-population divergence ($\mathbf{D}_{IC}$), where **P** is assumed to reflect the potential to evolve and diversify and $\mathbf{D}_{IC}$ reflects the actual divergence that has occurred. Comparing **P** and $\mathbf{D}_{IC}$ in terms of their relative alignment reveals that most species have their **P** matrices more closely aligned with the major axis of their clade's $\mathbf{D}_{IC}$ than with any other direction (fig. 4). Cervids have lower evolvabilities along directions in which they have diversified less than bovids, and higher evolvabilities in directions in which they have diversified more than bovids (online fig. A12), again implying that intrinsic constraints have influenced the directions in which bovids and cervids have diversified. In addition, species whose divergence is more closely aligned with the direction of maximum evolvability have diverged further away from their clade's ancestral state (fig. 5). At the same

374 time, there is a great variation in how well the **P** matrices of different species are aligned with
375 divergence, implying also a great variation among species in the orientation of their **P** matrices
376 (fig. 4). This is in accord with a previous analysis (Haber 2015), which found that closely-related
377 taxa differ in the orientation of their **P** matrices more than expected from their phylogenetic
378 distance (assuming a single-rate Brownian motion model) and that variation among bovid
379 species in their matrix orientation is similar to that among cervid species.

380 The positive signal in figures 4 and 5 is consistent with a role of intrinsic constraints in
381 ruminant diversification. However, without knowing the exact direction of selection throughout
382 the ruminant history, it is impossible to say whether the close alignment between **P** and $\mathbf{D}_{IC}$ is
383 because covariation has biased divergence or because selection has consistently pushed in the
384 direction of covariation. That said, in the time span included here – 25 My for bovids and 20 My
385 for cervids – it is not likely that selection would be pushing in the direction of **P** for that long
386 unless **P** itself has aligned with selection, and such alignment would likely be due to its
387 constraining effect (Jones et al. 2003; Revell 2007; Arnold et al. 2008). Therefore, although not
388 conclusive, these results suggest that the orientation and size of **P** have likely played a
389 substantial role in determining the direction and magnitude of ruminant divergence. Thus, this
390 study joins others (e.g., Hansen and Voje 2010) in demonstrating that even when covariance
391 structure evolves relatively rapidly, intrinsic constraints could still bias the evolution and
392 divergence of populations. At the same time, these analyses reveal little to no difference
393 between bovids and cervids, and therefore do not provide a good explanation for the finding
394 that bovids' disparity is higher and more evenly distributed than that of cervids.

395 The analyses presented in figures 4 and 5 focus on the relative alignment between
396 covariation and selection, accounting mostly for matrix orientation and size. As the time span
397 and phylogenetic scale of the study increase, it becomes more difficult to reconstruct this
398 relative alignment at any given time, and more likely that either or both have changed enough
399 to obscure their relative contribution. Moreover, from theoretical standpoint, additional
400 considerations might become more relevant on the macro scale, such as the heterogeneity of
401 selection and the probabilities of extinction and speciation (Vermeij 1973; Liem 1973; Jablonski
402 2007; Gomulkiewicz and Houle 2009; Jones et al. 2012). Therefore, we might expect

403 macroevolutionary patterns to be predicted by properties that determine the potential of
404 populations to respond effectively to a wide range of challenges. Here, I considered four such
405 measures: $\overline{e}$, $\overline{c}$, $\overline{f}$, and rSDE(**P**) (see table 1 for details). Each of these measures can be thought
406 of as capturing – in its own way – the potential of the population to respond relatively
407 effectively to a wider range of selective pressures. However, $\overline{c}$ has yielded different results
408 depending on shrinking tolerance, method of matrix inversion, and number of variables (online
409 figure A3), due to its high sensitivity to sample size (relative to number of variables) and
410 strength of covariance. It is therefore considered less reliable in this study, although this is not
411 necessarily the case for conditional evolvabilities along specific directions. $\overline{f}$ has a tight inverse
412 correlation with rSDE(**P**) (fig. 1), in accord with expectations based on the number of variables
413 and heterogeneity of the matrices (see online Appendix B). Therefore, in this study at least,
414 these two metrics capture effectively the same information regarding the potential to evolve
415 into a wide range of directions. $\overline{e}$ is positively but loosely correlated with rSDE(**P**) (fig. 1). Since
416 rSDE(**P**) is scaled by matrix size, this result reflects more than just a scaling association between
417 the mean and variance of the eigenvalues. Instead, it suggests that as matrix size increases,
418 variance tends to be added more in directions with larger eigenvalues (thus increasing the
419 variance of the eigenvalues) rather than randomly or evenly.
420 The model-fitting results indicate that these properties have evolved within a relatively
421 limited range, which has shifted during the phylogenetic history of ruminants (fig. 2 and table
422 2). The main shifts are found at the base of cervids and caprines for rSDE(**P**), and at the base of
423 bovids and caprines for $\overline{e}$ (online fig. A5). The high sigma-squared and alpha values (table 3)
424 imply a great lability and little phylogenetic signal among closely-related taxa. Yet, the fact that
425 the observed patterns are best explained by an Ornstein-Uhlenbeck model with multiple
426 optima implies that these properties have been relatively constrained at the family and
427 subfamily scale in spite of a great variation at the lower scales (Hansen 1997; Butler and King
428 2004). A good fit to the OU model can also occur when a character evolves following Brownian
429 motion with reflective barriers (Harmon et al. 2010). rSDE(**P**) is indeed bound between 0 and 1,
430 and $\overline{e}$ is bound by zero (even if log-transformed for the model fitting), but there is no reason to

431 expect them to be bound within a different range for different subclades. Therefore, these
432 findings suggest that rSDE(**P**) and $\bar{e}$ have been under selection, either directly or indirectly,
433 likely due to their association with morphological diversification.

434 The maximum likelihood values inferred for rSDE(**P**) and $\bar{e}$ imply that bovids and cervids
435 do not share the same typical value for either of them. However, the value of $\bar{e}$ inferred for
436 bovids is very close to that of cervids, and even slightly lower. Based on the current theory, we
437 would expect the greater diversification of bovids to be associated with a higher average
438 evolvability, rather than a lower one, if constraints matter. Therefore, $\bar{e}$ cannot explain the
439 greater diversificaton of bovids. The values inferred for rSDE(**P**), on the other hand, are easier
440 to interpret here, especially in association with rSDE($\mathbf{D}_{IC}$). The value of rSDE(**P**) inferred for
441 bovids – as well as the ruminant ancestor – is lower than that of cervids (and independently,
442 caprines; fig. 2 and table 3), suggesting a greater potential to respond effectively to a wider
443 range of selective pressures. Accordingly, bovids have diversified into a wider range of
444 directions in morphospace (a lower rSDE($\mathbf{D}_{IC}$)), in addition to having a higher overall disparity
445 (fig. 3). The finding that cervids have the same overall rate of evolution as bovids even though
446 their disparity is substantially lower (fig. 3) further suggests that cervids' morphological
447 evolution has been less diffusive than that of bovids, reverting back to previously-explored
448 areas more often. Therefore, these findings support a scenario in which bovids have been able
449 to take advantage of various ecological opportunities because they have retained the low
450 within-population eccentricity (and higher flexibility) that they had inherited from their
451 ancestor. Cervids, on the other hand, have taken the path of increasing eccentricity, which has
452 impeded their ability to take advantage of the same opportunities and channeled their
453 diversification.

454 Caprines dispersion is as spherical as that of other bovids (fig. 3) even though they have
455 the highest within-population eccentricity as a clade (fig. 2 and table 3). This implies that
456 caprines' evolutionary history does not follow the predicted association between rSDE(**P**) and
457 rSDE($\mathbf{D}_{IC}$). However, this apparent conflict may be explained by their early history. Caprines
458 have been identified as one of the most striking examples among ruminants of an explosive

459 radiation followed by high specialization (Geist 1985, 1987; Gentry 2000; Vrba and Schaller
460 2000; Ropiquet and Hassanin 2005). Ropiquet and Hassanin (2005) point out that caprine
461 diversification into tribes concurs with the definition of adaptive radiation given by Schluter
462 (2000): they have diversified rapidly soon after the origination of their common ancestor in the
463 late Miocene; they show great morphological variation that follows a distinct environmental
464 gradient; and their origination is associated with a key innovation - short and stocky
465 metacarpals - that has enabled them to invade mountainous habitats not yet occupied by other
466 herbivores. Thus, the exceptional diversification of caprines is largely due to an early burst of
467 rapid radiation. It is possible, therefore, that the lower eccentricity – and higher flexibility – of
468 their common ancestor had allowed it to take advantage of the opening of a new kind of
469 environment, diversify rapidly, and then specialize into a wide range of climatic conditions.
470 According to this scenario, the high eccentricity that characterizes some caprines today has
471 evolved only after their early burst of diversification, along with their subsequent specialization.
472 The results presented here support the idea that the long-term evolutionary success of
473 lineages and clades is affected by their ability to respond effectively to a wide range of selective
474 pressures (Vermeij 1973; Liem 1973; Draghi and Wagner 2008). In addition, this study suggests
475 that the best predictor of that ability, at least in this case, is their within-population matrix
476 shape, measured as eccentricity (and/or average flexibility). However, the association found
477 here between rSDE(**P**) and macroevolutionary patterns, could also be a mere coincidence. More
478 empirical and theoretical work is required in order to establish the universality of these findings
479 and the validity of the additional assumptions underlying this association. Some empirical
480 evidence comes from research on morphological integration, to the extent that rSDE(**P**) reflects
481 the magnitude of integration. For example, Lower integration was found to be associated with
482 greater functional divergence in humans compared to apes (Rolian 2009; Rolian et al. 2010;
483 Grabowski et al. 2011) and higher module disparity in Carnivora (Goswami and Polly 2011).
484 Some relevant insights come from Draghi and Wagner (2008), who show that populations
485 whose distribution of mutational effects is less eccentric can adapt faster to a wider range of
486 circumstances.

487 Several assumptions underlie the suggested association between matrix shape and
488 macroevolution. The main assumption is that selection changes frequently enough and in
489 directions different enough from the major axis of **P** (or **G**), thus providing the opportunities for
490 testing and realizing the potential reflected in matrix shape. This is ultimately an empirical
491 question. Recent metanalyses provide some evidence that evolutionary patterns across broad
492 taxonomic and time scales follow a model of erratic peak movements within fixed limits (Estes
493 and Arnold 2007; Uyeda et al. 2011). In addition, simulations could reveal how heterogeneous
494 selection needs to be in order for the potential to respond to a wide range of selective
495 pressures to become more relevant than the potential to respond faster in any particular
496 direction. Another assumption is that of a threshold that needs to be exceeded in order for the
497 population to persist long enough for an effective response. Gomulkiewicz and Houle (2009)
498 developed formulae for calculating this threshold, accounting for the structure of the fitness
499 landscape and population dynamics. On the macro scale, other factors probably contribute as
500 well (Jablonski 2005, 2007, 2008). A yet another assumption is that matrix shape (but not
501 necessarily orientation or size) remains effectively stable throughout the clade's history. This,
502 again, is an empirical question for which there is currently too little data. However, there is
503 some evidence for it in the case of ruminants: matrix orientation has varied within 50% of its
504 possible range (Haber 2015), whereas eccentricity has varied within only 33% (figs. 1 and 2).
505 Simulations also indicate that eccentricity tends to vary less than orientation under most
506 combinations of genetic architecture and selection regimes (Jones et al. 2003, 2012).
507 The association found here between matrix shape and ruminants' macroevolutionary
508 patterns implies a trade-off between the ability to respond effectively in a wide range of
509 directions and the ability to respond faster along a specific direction. This, in turn, implies a
510 possible dissociation between macro- and microevolution, where matrix eccentricity is
511 associated with the range and amount of clade dispersion on the macro scale, influenced by the
512 heterogeneity of selection, while matrix orientation and size are associated with the direction
513 and magnitude of population divergence relative to the direction and strength of selection on
514 the generational scale. Again, comprehensive simulations could reveal the range of parameters
515 and conditions necessary for this trade-off to occur. In addition, matrix shape could be linked to

516 macroevolution through taxonomic richness, if the probability of reproductive isolation
517 increases when the population moves in directions further away from the main axis of
518 covariation (regardless of magnitude of change) as opposed to moving along a narrow range of
519 directions. This would be in accord with other studies that point to a decoupling between
520 population-level processes and macroevolutionary patterns (Jablonski 2007 and references
521 therein; Rabosky and Matute 2013). Although the focus here is on macroevolutionary patterns,
522 the same rationale should hold for short-term evolution in highly dynamic environments, an
523 issue that has become increasingly relevant with the advance of global climate change (Kopp
524 and Matuszewski 2013). Therefore, studying variational properties that reflect the potential to
525 respond to a wide range of selective pressures could be useful also for understanding short-
526 term population response to environments with low predictability, as well as macroevoluiton.

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Table 1. Parameters and metrics included in this study, their symbols, and their interpretations

Symbol	Measure		Meaning
P	Pooled within-population phenotypic V/CV matrix; based on individuals and corrected for sex and subspecies mean		Variation and covariation of traits among individuals within a species
$\mathbf{P}_{AV}$	Average pooled within-population phenotypic V/CV matrix; based on individuals and corrected for species mean, as well as sex and subspecies		Variation and covariation of traits among individuals within a species, averaged across species within a clade.
$\mathbf{D}_{IC}$	Among-population phenotypic V/CV matrix; based on species means and corrected for phylogenetic correlation assuming Brownian-motion model (i.e., V/CV of independent contrasts; Revell et al. 2007)		Evolutionary rate matrix; rate of evolution and coevolution of traits among species within a clade
λ	An eigenvalue of **P** or $\mathbf{D}_{IC}$		
β	A vector of p elements, drawn randomly from a normal distribution with mean of zero and SD of one, normed to a unit length		Selection gradient; direction of selection operating on each trait independently of other traits
Average evolvability $\bar{e}$	The average mean-scaled phenotypic variance in **P**; Proportional to matrix size	$E\left[\beta^t \mathbf{P}\beta\right]$ or $E\left[\lambda(\mathbf{P})\right]$	The expected ability of the population to respond to selection in a random direction independently of other directions
Average conditional evolvability $\bar{c}$	The average mean-scaled phenotypic variance in **P**, accounting for trait covariances; Includes both matrix size and matrix shape	$E\left[\left(\beta^t \mathbf{P}^{-1}\beta\right)^{-1}\right]$	The expected ability of the population to respond to selection in a random direction, assuming stabilizing selection in other directions
Average flexibility $\bar{f}$	Cosine of the angle between β and the response vector, averaged over random vectors; Matrix shape only	$E\left[\frac{\beta^t \mathbf{P}\beta}{\sqrt{\Sigma(\mathbf{P}\beta)^2}}\right]$	The expected ability of the population to track in the direction of selection; reflecting the range of random directions into which the population can potentially evolve with relative precision
Within-pop. Eccentricity rSDE(**P**)	Relative standard deviation of the eigenvalues of **P***; Matrix shape only	$\sqrt{\frac{p\sum(\lambda_i-\bar{\lambda})^2}{(p-1)\sum\lambda\sum\lambda}}$	The relative ability to track in different directions; reflecting the range of orthogonal directions into which the population can potentially evolve with relative precision
Among-pop. eccentricity rSDE($\mathbf{D}_{IC}$)	Relative standard deviation of the eigenvalues of $\mathbf{D}_{IC}$		Eccentricity of dispersion; the range of directions in space into which the species have diverged
$\mathbf{d}_{CL}$	An eigenvector of $\mathbf{D}_{IC}$		Direction of clade's dispersion
$\mathbf{d}_{SP}$	Difference vector between a species mean and its clade's phylogenetically-weighted mean (inferred root state) assuming Brownian motion, standardized by that mean and normed to a unit length.		Direction of morphological divergence between a species and its clade's ancestral state
d^2	Squared distance between a species mean and its clade's inferred root	$\mathbf{d}_{sp}{}^t\,\mathbf{d}_{sp}$	Amount of morphological divergence between a species and its clade's ancestral state
Disparity	Average distance between species means and the clade's inferred root	$\frac{\sum d^2}{(N_{sp}-1)}$	Total amount of clade's dispersion
	Trace of $\mathbf{D}_{IC}$		Rate of dispersion
$e(\mathbf{d}_{SP})$	Mean-scaled phenotypic variance in the direction of species divergence	$\mathbf{d}_{sp}{}^t\,\mathbf{P}_{av}\,\mathbf{d}_{sp}$	The variation available for species, on average, in the direction of their divergence
$c(\mathbf{d}_{SP})$	Mean-scaled phenotypic variance in the direction of species divergence, accounting for trait covariances	$E\left[\frac{1}{\mathbf{d}_{sp}{}^t\,\mathbf{P}_{av}{}^{-1}\,\mathbf{d}_{sp}}\right]$	The variation available for species, on average, in the direction of their divergence assuming stabilizing selection in other directions
$e(\mathbf{d}_{CL})$	Mean-scaled phenotypic variance available along the eigenvectors of $\mathbf{D}_{IC}$	$\mathbf{d}_{CL}{}^t\mathbf{P}\mathbf{d}_{CL}$	The variation available for each species in the direction of their clade's diversification

* p is number of traits
** N_{SP} is number of species

Table 2. The different models describing the evolution of of rSDE(**P**), and $\overline{e}$. Based on the IL32 dataset. The best-supported models are in bold. K is the number of parameters in the model.

		Nodes included in the model (1)					rSDE(**P**)		$\overline{e}$	
Model No.	K	8FV*	Cervidae	Cervinae	Bovidae	Caprinae	AICc scores	AICc weights	AICc scores	AICc weights
1	8	1	1	1	1	1	93.24	0.0096	11.11	0.0045
2	7	0	1	1	1	1	90.42	0.0392	8.28	0.0186
3	7	1	0	1	1	1	90.42	0.0392	8.28	0.0186
4	6	0	0	1	1	1	90.07	0.0466	6.08	0.0561
5	7	1	1	0	1	1	91.79	0.0197	8.31	0.0184
6	6	0	1	0	1	1	89.10	0.0759	5.62	0.0707
7	6	1	0	0	1	1	89.10	0.0759	5.62	0.0707
8	5	0	0	0	1	1	89.87	0.0517	**3.50**	**0.2032**
9	7	1	1	1	0	1	90.42	0.0392	8.28	0.0186
10	6	0	1	1	0	1	**87.74**	**0.1497**	8.51	0.0166
11	6	1	0	1	0	1	94.17	0.0060	10.12	0.0074
12	5	0	0	1	0	1	91.65	0.0212	9.35	0.0110
13	6	1	1	0	0	1	89.10	0.0759	5.62	0.0707
14	5	0	1	0	0	1	**86.54**	**0.2728**	5.96	0.0594
15	5	1	0	0	0	1	96.02	0.0024	8.69	0.0152
16	4	0	0	0	0	1	93.73	0.0075	7.81	0.0236
17	7	1	1	1	1	0	98.92	0.0006	12.79	0.0020
18	6	0	1	1	1	0	96.22	0.0022	10.09	0.0075
19	6	1	0	1	1	0	96.22	0.0022	10.09	0.0075
20	5	0	0	1	1	0	95.01	0.0039	7.97	0.0218
21	6	1	1	0	1	0	97.43	0.0012	10.12	0.0074
22	5	0	1	0	1	0	94.85	0.0043	7.54	0.0270
23	5	1	0	0	1	0	94.85	0.0043	7.54	0.0270
24	4	0	0	0	1	0	94.65	0.0047	5.51	0.0747
25	6	1	1	1	0	0	96.22	0.0022	10.09	0.0075
26	5	0	1	1	0	0	93.69	0.0076	9.58	0.0097
27	5	1	0	1	0	0	96.03	0.0024	10.18	0.0072
28	4	0	0	1	0	0	93.73	0.0075	9.15	0.0121
29	5	1	1	0	0	0	94.85	0.0043	7.54	0.0270
30	4	0	1	0	0	0	92.43	0.0144	7.14	0.0330
31	4	1	0	0	0	0	96.83	0.0016	8.50	0.0167
32	3	0	0	0	0	0	94.76	0.0045	7.43	0.0285
BM	2	0	0	0	0	0	102.01	0.0001	36.35	0.0000

*8FV – Node No. 8 in Hernández Fernández and Vrba (2005), including Bovidae plus Cervidae without Tragulidae

Table 3. Maximum likelihood estimates for the best-supported models for the evolution of rSDE(**P**), and $\overline{e}$ (see table 2 and online table A3). Nodes for which a transition was inferred are in bold. Estimates for Brownian motion (BM) model are also given. Average values are weighted by AIC weights. All data are mean-scaled. Branch length is scaled by tree height. Theta values of rSDE(**P**) are adjusted for sample size as in fig. 1.

	Dataset	Model No.	Theta					Alpha	Sigma-squared
			8FV	Cervidae	Cervinae	Bovidae	Caprinae		
Within-pop. Eccentricity rSDE(**P**)	IL32 *	14	0.07	**0.15**	0.15	0.07	**0.16**	9.67	5.23
		10	0.07	**0.13**	**0.20**	0.07	**0.16**	9.61	5.06
		Average	0.09	**0.14**	0.16	0.07	**0.15**	8.96	4.91
		BM			0.08			--	1.38
	ILtes †	14	0.15	**0.23**	0.23	0.15	**0.31**	9.48	2.48
		10	0.15	**0.21**	**0.28**	0.15	**0.31**	9.21	2.36
		Average	0.17	**0.21**	0.24	0.15	**0.31**	8.64	2.29
		BM			0.16			--	0.66
Average evolvability $\overline{e}$	IL32 *	8	0.0057	0.0057	0.0057	**0.0048**	**0.0061**	70.45	7.13
		Average	0.0065	0.0056	0.0057	**0.0049**	**0.0057**	113.62	12.17
		BM			0.0055			--	0.38
	ILtes †	8	0.0050	0.0050	0.0050	**0.0040**	**0.0060**	34.28	3.69
		14	0.0040	**0.0050**	0.0050	0.0040	**0.0060**	33.59	3.75
		Average	0.0054	0.0049	0.0050	**0.0040**	**0.0059**	32.88	3.57
		BM			0.0046			--	0.37

* Reduced dataset of 32 interlandmark distances

† Tessellation-based dataset of 107 interlandmark distances

Figure legends

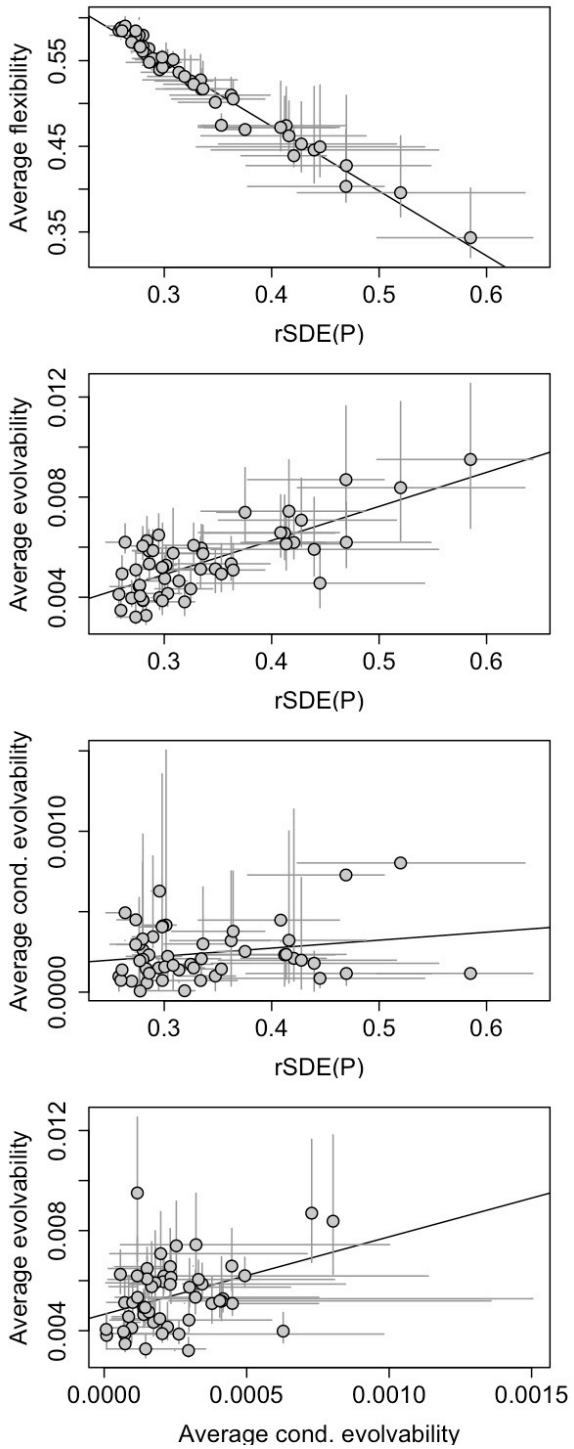
Figure 1: Comparison of **P**-matrix properties based on the IL32 dataset, mean-scaled. See table 1 for details on how these properties are measured and interpreted. Solid line indicates regression line. Grey bars indicate 95% confidence intervals based on non-parametric bootstrap with BCa correction.

Figure 2. The relative standard deviation of eigenvalues (rSDE(**P**)) calculated for the IL32 dataset, mean-scaled. Values were adjusted for sample size by subtracting the mean permutation value from the observed value. Therefore, zero represents the expected value for a random matrix. Sample sizes are given in parentheses. Phylogenetic relationships follow Hernandez-Fernandez and Vrba (2005). Vertical dashed lines represent the maximum likelihood estimates (see tables 2 and 3).

Figure 3. Measures of diversification for the four clades that involve a shift in their typical within-population eccentricity (see figure 1 and table 2), based on the IL32 dataset. Their inferred rSED(**P**) and $\overline{e}$ values are also shown (see table 3). All metrics are proportional to the clade's phylogenetically-weighted mean. Bars in the top panel (disparity) represent the expected distribution under Brownian motion model (95% interval). Bars in the lower two panels (rates and eccentricity) represent 95% confidence interval. Analyses involving Cervidae were repeated with (cross) and without (circle) *Alces*. Analyses involving Bovidae were repeated with (cross) and without (circle) Caprinae.

Figure 4: Evolvabilities in directions of clade's diversification ($e(\mathbf{d}_{CL})$), measured as the amount of variation that each species has in its **P**-matrix in the direction of its clade's eigenvectors. Eigenvectors are ordered by the relative size of their eigenvalues, indicated along the x-axis.

Figure 5: Evolvabilities ($e(\mathbf{d}_{sp})$) and conditional evolvabilities ($c(\mathbf{d}_{sp})$) in the direction of species divergence, calculated based on the average within-species covariance matrix ($\mathbf{P}_{AV}$), plotted against the amount of divergence between each species and its clade's ancestral state (d^2). Everything is proportional to trait mean. d^2 is ln-transformed for clarity. Horizontal bars mark the minimum and maximum evolvabilities (solid), the expected evolvability ($\overline{e}$, dashed) and conditional evolvability ($\overline{c}$, dotted). Caprines are highlighted in black in the top graph. Based on IL32



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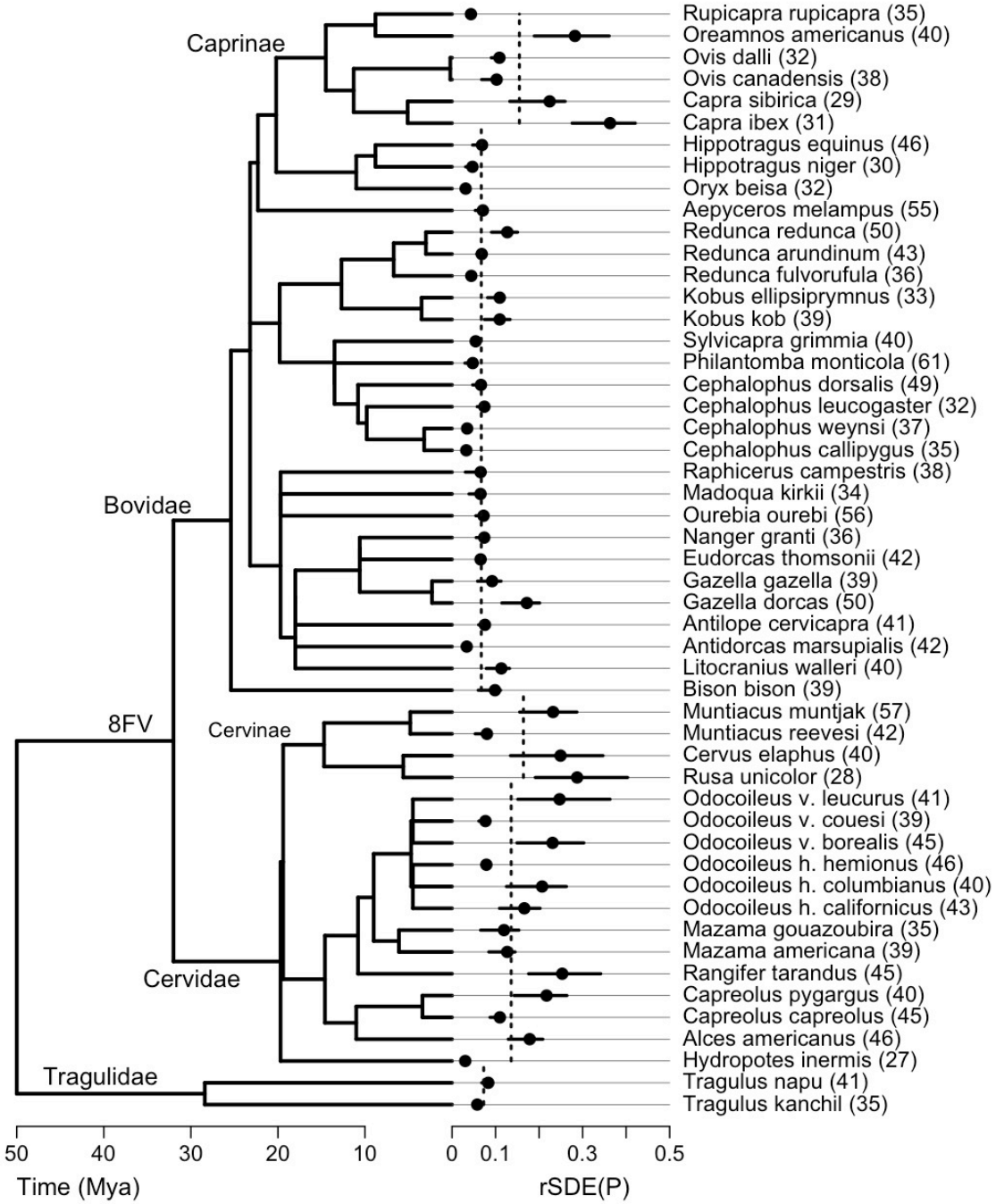

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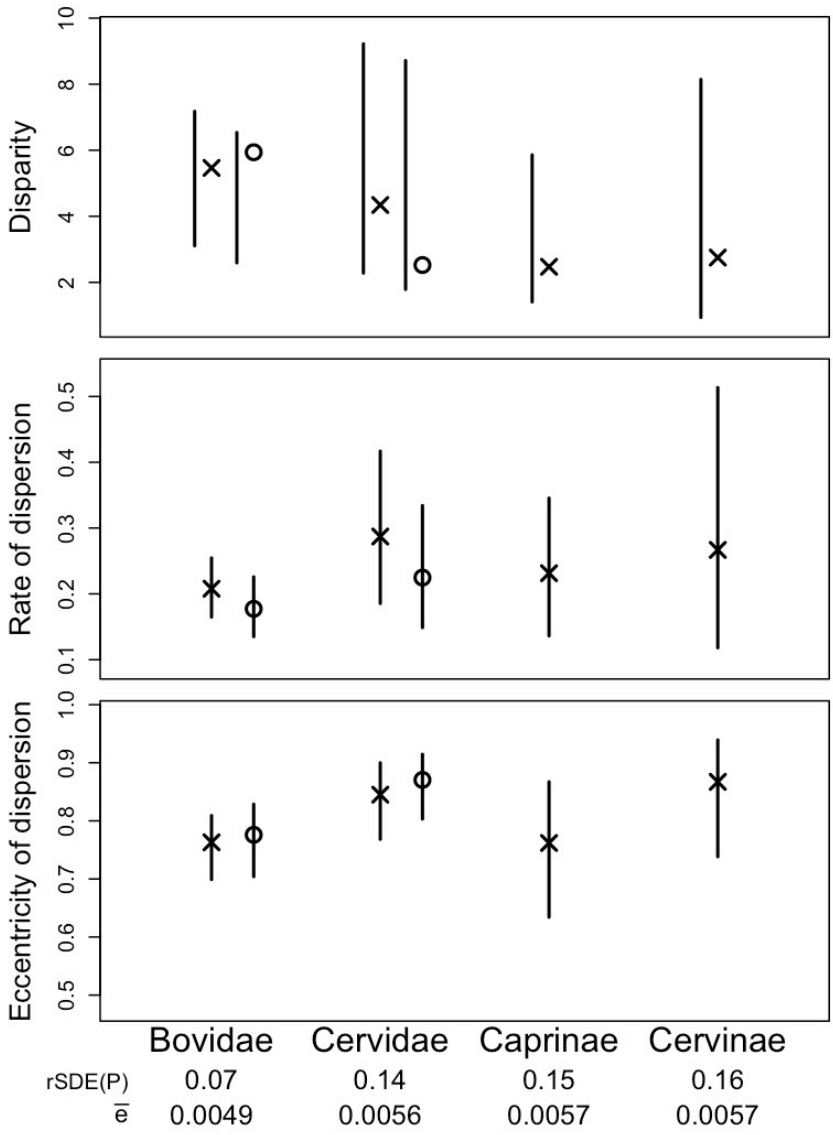

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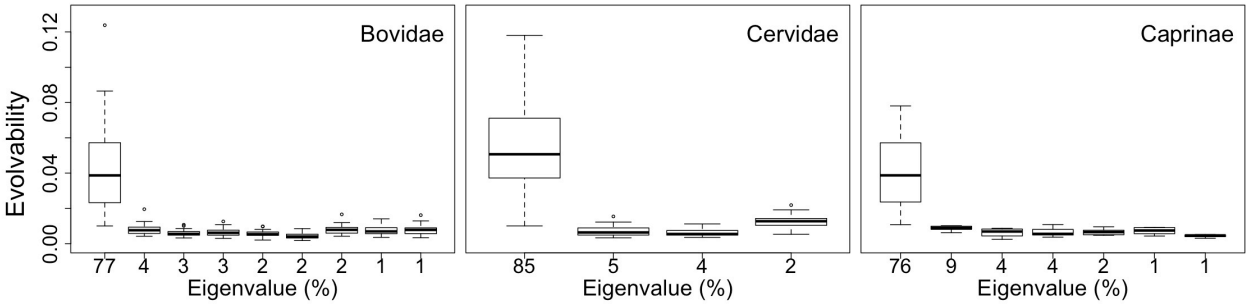

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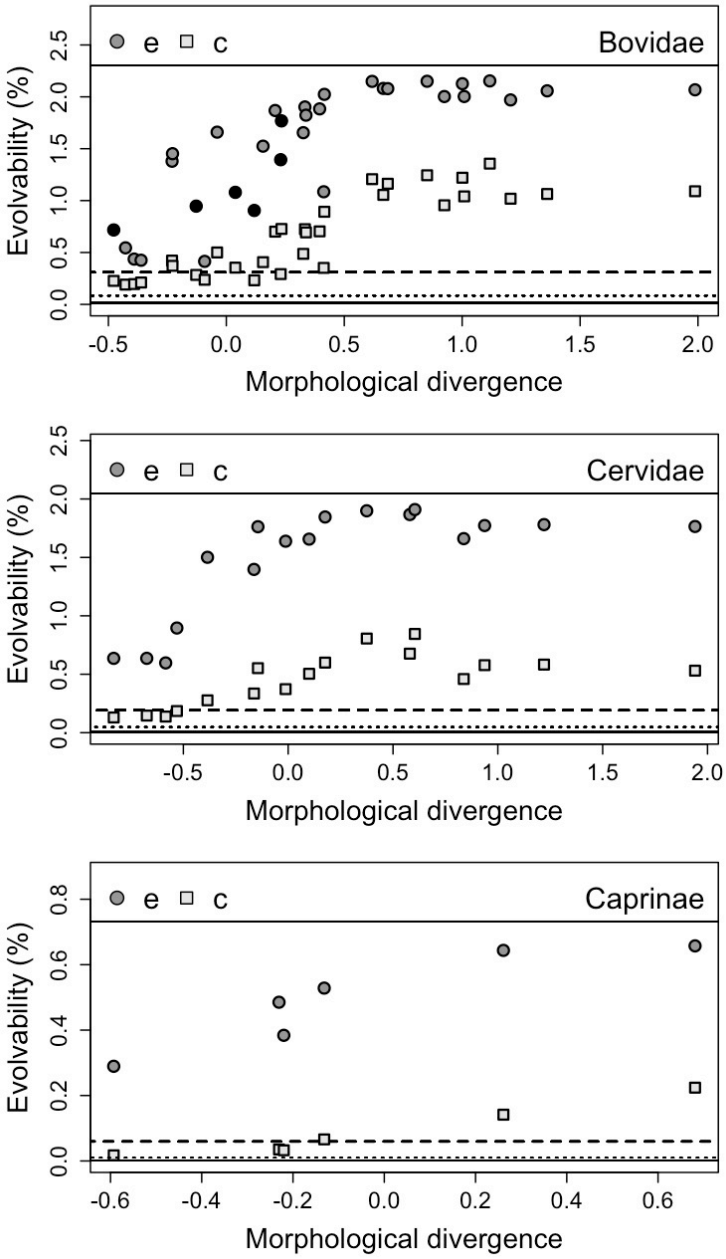

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