



**HAL**  
open science

## How domestication, feralization and experience-dependent plasticity affect brain size variation in *Sus scrofa*

Thomas Cucchi, D. Neaux, L. Féral, Goussard Florent, Hans Adriaensen,  
Elleboudt Frédéric, G. Sansalone, R. Schafberg

► **To cite this version:**

Thomas Cucchi, D. Neaux, L. Féral, Goussard Florent, Hans Adriaensen, et al.. How domestication, feralization and experience-dependent plasticity affect brain size variation in *Sus scrofa*. Royal Society Open Science, 2024, 11 (9), pp.240951. 10.1098/rsos.240951 . hal-04703443

**HAL Id: hal-04703443**

**<https://hal.science/hal-04703443v1>**

Submitted on 20 Sep 2024

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Research



**Cite this article:** Cucchi T, Neaux D, Féral L, Goussard F, Adriensen H, Elleboudt F, Sansalone G, Schafberg R. 2024 How domestication, feralization and experience-dependent plasticity affect brain size variation in *Sus scrofa*. *R. Soc. Open Sci.* **11**: 240951.

<https://doi.org/10.1098/rsos.240951>

Received: 22 March 2024

Accepted: 2 August 2024

**Subject Category:**

Organismal and evolutionary biology

**Subject Areas:**

evolution

**Keywords:**

brain, endocranial volume, domestication, feralization, captivity

**Author for correspondence:**

T. Cucchi

e-mail: [cucchi@mnhn.fr](mailto:cucchi@mnhn.fr)

Electronic supplementary material is available online at <https://doi.org/10.6084/m9.figshare.c.7441721>.

# How domestication, feralization and experience-dependent plasticity affect brain size variation in *Sus scrofa*

T. Cucchi<sup>1</sup>, D. Neaux<sup>1</sup>, L. Féral<sup>1</sup>, F. Goussard<sup>2</sup>, H. Adriensen<sup>3</sup>, F. Elleboudt<sup>3</sup>, G. Sansalone<sup>4,5</sup> and R. Schafberg<sup>6</sup>

<sup>1</sup>Archéozoologie, Archéobotanique: Sociétés, Pratiques et Environnements, Muséum National d'Histoire Naturelle CNRS, Paris UMR 7209, France

<sup>2</sup>Centre de Recherche en Paléontologie – Paris (CR2P), Muséum National d'Histoire Naturelle, Paris, France

<sup>3</sup>PIXANIM, UMR Physiologie de la Reproduction et des Comportements, INRAE, CNRS, Université de Tours, Nouzilly, France

<sup>4</sup>Department of Life Sciences, University of Modena and Reggio Emilia, Modena, Via Campi 213D 41125, Italy

<sup>5</sup>Function, Evolution and Anatomy Research Lab, Zoology Division, School of Environmental and Rural Science, University of New England, Armidale, New South Wales, Australia

<sup>6</sup>Central Natural Science Collections, Martin-Luther University Halle-Wittenberg, Halle (Saale), Germany

TC, 0000-0001-6021-5001; DN, 0000-0001-9465-220X; GS, 0000-0003-3680-8418; RS, 0000-0003-4156-5414

Among domestic species, pigs experienced the greatest brain size reduction, but the extent and factors of this reduction remain unclear. Here, we used the brain endocast volume collected from 92 adult skulls of wild, captive, feral and domestic *Sus scrofa* to explore the effects of domestication, feralization and captivity over the brain size variation of this species. We found a constant brain volume increase over 24 months, while body growth slowed down from month 20. We observed an 18% brain size reduction between wild boars and pigs, disagreeing with the 30%–40% reduction previously mentioned. We did not find significant sexual differences in brain volume, refuting the theory of the attenuation of male secondary sexual characteristics through the selection for reduced male aggression. Feralization in Australia led to brain size reduction—probably as an adaptation to food scarcity and drought, refuting the reversal to wild ancestral brain size. Finally, free-born wild boars raised in captivity showed

a slight increase in brain size, potentially due to a constant and high-quality food supply as well as new allospecific interactions. These results support the need to further explore the influence of diet, environment and experience on brain size evolution during animal domestication.

## 1. Introduction

Brain size evolution in vertebrates is associated with the increase of cognitive performances in ecological and social domains across species [1,2]. The cognitive benefits of larger brain size are linked to spatial memory and the capacity to navigate in a complex and challenging territory, fostering behavioural flexibility and complex foraging techniques to access difficult-to-extract highly nutritious resources [3–6]. Larger brains are also beneficial to live in larger groups, to be more efficient with predation and to deal with complex cooperation [7]. Yet, the brain is one of the most metabolically expensive tissues in the body across all vertebrates, requiring a constant supply of energy. It also implies a longer maturation time, limiting the total lifetime fertility. Evolving a bigger brain to increase cognitive capacities, therefore, is only adaptive when fitness has overcome these trade-offs [2].

Within animal domestication, a new evolutionary force driven by our species has impacted the brain size evolution of vertebrates [8]. Historically, this evolution is seen as a brain size reduction related to the relaxed selection of cognitive capacities in the human environment [9]. The latter would buffer or suppress altogether the need to forage for food, to protect from seasonal and climatic changes, to find mates, to face competition or to avoid predation. This hypothesis attributing brain size reduction with reduced cognitive demands is due to the fact that the increase in brain size, relative brain size (body size corrected) and neuron numbers are associated with increased cognitive capacities [10]. However, more recently, researchers have considered that no universal pattern should be expected in brain size change during domestication [11], while its effect on brain size should be revised altogether [12] and considered as the result of an interaction of drivers and constraints that need to be further understood [13]. Indeed, the brain is the most energy-expensive tissue in the body [2], selection for metabolic investment in faster reproduction, increased fecundity or somatic production (milk, muscle, eggs) are potential components of brain size reduction across different domestic species [13]. Cognitive factors such as behavioural flexibility and learning in a new niche or metabolic factors such as increased stability and enriched diet can also lead to brain size increase in domestic animals [13]. While experience-dependent plasticity within a lifetime could potentially be an important factor in the brain size evolution of domestic mammals, it remains understudied [13].

According to studies performed on domestic species in the 1970s and 1980s, pigs have undergone the greatest brain size reduction up to 40% [8,14]. To explore the different evolutionary, developmental and experiential factors associated with domestication that could influence brain size variation in the *Sus scrofa* species, we used a unique *in vivo* longitudinal record of wild boar skull growth [15] associated with adult population samples of hunted wild boars or those raised in captivity, Australian feral pigs, and pigs from landraces and industrial breeds. To compare these samples, we measured the endocast volume (ECV) as a brain size proxy [16]. To correct for overall body size differences among the *Sus scrofa* populations sampled, we calculated a relative brain size using the foramen magnum breadth (FMB) measured from the skull as a body size proxy [17]. FMB has been used recently to measure the relative brain size in a review on the effect of domestication across several mammalian taxa, *Sus scrofa* included [14]. The advantage of this proxy is the possibility to obtain this data from fossil and sub-fossil crania, when they are well preserved, to explore the relative brain size change across the long temporal depth of the domestication history.

We first assessed the effects of ontogeny, sex differences and ageing in wild and domestic pigs on ECV variation. Second, the effects of domestication over ECV changes were tested by comparing wild boar populations and pig samples with different selective breeding lines—we hypothesized that breeding selection for faster growth and greater muscle mass production would have induced a brain size reduction compared with hunted wild boars. Third, we evaluated the feralization effect over brain size evolution by comparing hunted wild boars, farmed pigs and feral pigs from Australia. The feral pigs are descended from pigs introduced in the mid-nineteenth century. Recent studies have shown that domestic populations returned to the wild retain their small brain [18]. However, exceptions in the feral pigs of Sardinia [19], Australian dingoes [20] and feral minks [21] suggest that the role of adaptation to a shifting niche varies between species and relative contexts [13]. Here, we

hypothesized that 200 years of feralization in an environment the size of Australia with no natural predators could have fostered behavioural flexibility and cognitive demands in feral pig populations that led to an adaptive brain size increase. Finally, we considered the experience/environmental effect of captivity and its plastic response in wild boars relying on an experiment which performed *in vivo* longitudinal computed tomography (CT) scans on 24 male and female wild boars caught in the wild at six months old and raised in captivity until 25 months, when sexual dimorphism is fully expressed (<http://anr-domexp.cnrs.fr/>). Captivity as a factor of brain size reduction has been observed for many mammals that have lived in captivity for generations [22]. In contrast, urban life has been shown to increase cranial capacities in rodents [23], suggesting important plastic changes in brain size. Here, we hypothesized that the drastic reduction in cognitive demand and territoriality challenge during growth in captivity would have induced a plastic reduction of brain size in free-born wild boar piglets raised in captivity until adulthood.

## 2. Material and methods

### 2.1. Sampling and selection of specimens

We assessed the confounding effects of domestication, feralization and environmental plasticity over the brain size variation in *Sus scrofa* using 92 adult specimens aged between 13 and 70 months of age divided into seven grouped samples (electronic supplementary material, file S1; table 1). The first group consisted of 24 wild boars (*Sus scrofa scrofa*) from Northern France; the second and third groups comprised 22 free-born wild boars (*S. s. scrofa*) captured in Northern France and raised in two different captive environments (12 in a 3000 m<sup>2</sup> enclosure and 10 in a 100 m<sup>2</sup> stall; for further detail about the experiment visit <http://anr-domexp.cnrs.fr/>). The fourth, fifth and sixth groups are pigs (*Sus scrofa domesticus*) from different breeding lines. We have included so-called Landraces from Germany [14] and from the Corsican island [7]. According to Merriam-Webster's definition landraces are 'a local variety of a species of plant or animal that has distinctive characteristics arising from development and adaptation over time to conditions of a localized geographic region and that typically displays greater genetic diversity than types subjected to formal breeding practices'. The Corsican Landrace is a small-sized breed adapted to an extensive rearing system based upon the use of local resources like pastureland, chestnuts and acorns [24]. We have also included six Berkshire pigs, a traditional British breed. Finally, the seventh group included 18 feral pigs from the Northern Territory of Australia. The precise origin of these feral populations is still uncertain, but it is accepted that European and Asian domestic pigs were released in Australia by the first European settlers, probably in Sydney in 1788 [25]. In the Northern Territory, pig populations from China were probably introduced during the Gold Rush [25,26]. Pigs were also imported to the Northern Territory from the islands of Timor in 1827 and Kisar in 1838 [25,26]. Some of these domestic pigs were then either released on purpose or escaped and established feral populations [26,27].

Our dataset also includes the *in vivo* longitudinal record of the endocranial growth of the 22 captive wild boars described previously, which include the same male and female ratios. The CT scan for the *in vivo* longitudinal observation (LO) was performed at 6, 8, 11, 14, 20 and 25 months of age. The body weight (kg) has been recorded before each LO for all the specimens. Unfortunately, we have not been able to obtain the endocast of all specimens at each LO, which explains why we do not have 22 specimens for each LO (see electronic supplementary material, file S2).

Experiments using captive wild boars adhered to all the ethical agreements (APA-FIS#5353-201605111133847).

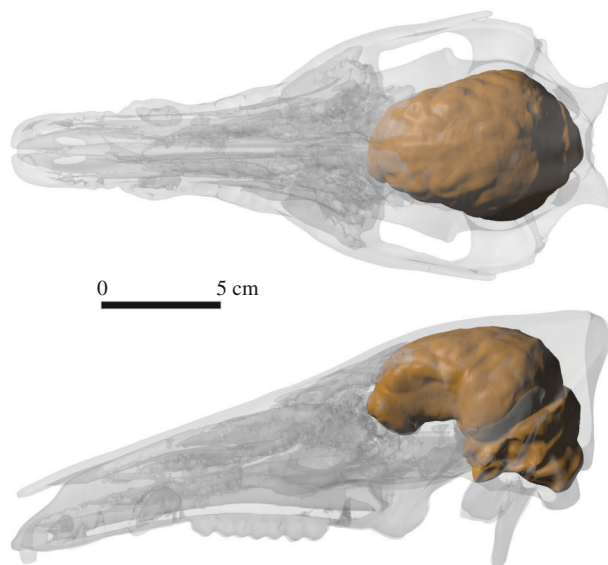
### 2.2. Data acquisition

CT skull scans were undertaken at several facilities (PIXANIM medical CT for French wild boars and experimental specimens, Halle medical CT for the Halle pigs and the I-MED Radiology Network for the feral pigs from Australia).

The three-dimensional skull meshes were obtained with Avyzo 8.

Endocast volume in cm<sup>3</sup> (ECV) were obtained from the three-dimensional skull mesh using the R script from *Endomaker* library (Profico *et al.* [28]) (figure 1).

For each three-dimensional skull mesh, we measured the foramen magnum breadth (FMb) as a body size proxy [17]. To obtain a body size-free brain volume (relative brain size) we used the regression's residuals of the log-transformed brain volume on log-transformed FMb.



**Figure 1.** Volume-rendered skull model and the endocast (brown) of a wild boar (*Sus scrofa*) in dorsal (top) and lateral (bottom) views.

**Table 1.** Origin, sample size and sex ratio of the adult *Sus scrofa* dataset. Abbreviations: WB = hunted wild boars, CWB = captive wild boar, DP = domestic pigs and FP = feral pigs. MNHN = Muséum National d’Histoire Naturelle (Paris, France); NMA = National Museum of Australia (Canberra, Australia); ZNS = Central natural science collection (Halle/Saale, Germany). For specimen details and measurements see electronic supplementary material, file S1.

samples	groups	<i>N</i>	sex ratio	localization	curation
Hunted Wild boars ( <i>S. s. scrofa</i> )	WB	24	13 M, 11 F	France	MNHN
Captive wild boars raised in enclosure ( <i>S. s. scrofa</i> )	CWB	12	5 M, 7 F	France	MNHN
Captive wild boars raised in stall ( <i>S. s. scrofa</i> )	CWB	10	5 M, 5 F	France	MNHN
European pig Landrace ( <i>S. s. domesticus</i> )	DP	14	7 M, 7 F	Germany	MNHN/ZNS
Corsican pig Landrace ( <i>S. s. domesticus</i> )	DP	7	2 M, 5 F	Corsica	MNHN/ZNS
Berkshire pig breed ( <i>S. s. domesticus</i> )	DP	6	4 M, 2 F	UK	ZNS
Australian feral pigs ( <i>S. scrofa</i> )	FP	18	12 M, 6 F	Australia	NMA

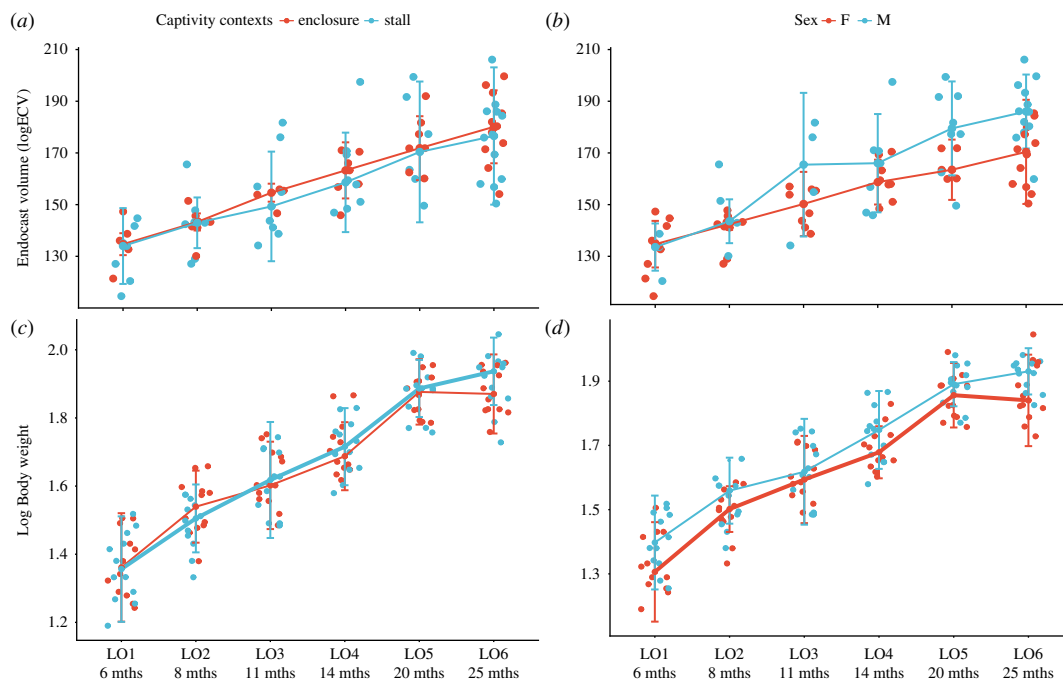
### 2.3. Statistics

Due to the small sample size, we tested the distribution of the logECV using the Shapiro–Wilk’s test in order to choose the appropriate statistical tests. The Shapiro–Wilk’s test performed separately on the adult dataset and on the longitudinal record of growth showed that the logECV distribution did depart from normality for the adult dataset ( $W = 0.96239$ ,  $p$ -value = 0.009972) but not for the longitudinal growth record ( $W = 0.98399$ ,  $p$ -value = 0.3216); therefore, we used non-parametric tests for statistical analyses on the adults’ brain size dataset and parametric statistics for the growth longitudinal dataset.

The percentage of size differences between each group was calculated using the median rather than the mean values due to the difference in sample sizes.

The variation in the endocast volume (logECV) has been graphically displayed on a violin boxplot (figure 3). To assess the differences in brain size and relative brain size variation among the seven groups of the adult dataset, we performed non-parametric Kruskal–Wallis test and Wilcoxon pairwise comparisons between group levels with corrections for multiple testing (Benjamini–Hochberg (BH) adjustment method). To compare ECV variation among the growth stages of the longitudinal dataset, we used a pairwise  $t$ -test comparison with Bonferroni correction.

To assess the relationship between endocast volume and foramen magnum breadth, we used a linear regression model with the logECV as a dependent variable and FmB as independent variable. To evaluate how much domestication has influenced the variation of the volume and relative volume



**Figure 2.** The *in vivo* longitudinal observations (LO) of growth in endocast volume (logECV) and body weight (LogWeight) in wild boars from 6 to 25 months, taking into account (a,c) the captivity contexts (enclosure = 3000 m<sup>2</sup>, stall = 100 m<sup>2</sup>) and (b,d) the difference between males and females.

of the endocast, we used a factorial ANOVA with the logECV as a dependent variable and the three grouping factors (wild boars, European Landrace, English breed/Berkshire) as independent variables.

Statistical analyses were performed with R v. 4.3.2. and R Studio v. 2022 12.2. using the packages ‘dplyr’ v. 2.4.0, ‘ggstaplot’ [29] and ‘ggplot2’ [30].

## 3. Results

### 3.1. Brain size growth in male and female wild boars according to captivity contexts and sexual differences

The *in vivo* longitudinal record of wild boar brain size growth in a controlled environment (figure 2a) shows a 33% increase in the endocranial volume from 6 to 25 months in wild boars without any sign of inflexion during this growth range according to pairwise comparisons (table 2A), while their body mass growth (figure 2c) seems to slow down from 20 months (table 2B).

We found no difference in brain growth between the two contexts of mobility constraints (figure 2a, enclosure versus stall) while a reduction in body mass is observed between the two contexts from 20 months (figure 2c). Sexual difference in brain volume was observed from 11 months (figure 2b) with an 8.4% endocast size reduction in females compared with males reaching 25 months, while body mass differences between the two sexes (figure 2d) are already in place at 6 months and seem to increase from 20 months.

We found no significant influence of age over brain size variation across adult wild, domestic, feral or captive samples (adjusted  $R^2 = 0.002783$ ,  $F$ -statistic = 1.251,  $p$ -value = 0.2663). Age variation in our adults’ dataset is therefore not a confounding factor in the following analyses.

### 3.2. Sexual brain size differences in wild boars, domestic and feral pigs

Overall, we found no sexual brain size difference among the wild and domestic adult dataset (Kruskal–Wallis  $\chi^2 = 0.20025$ , d.f. = 1,  $p$ -value = 0.6545), disagreeing with the results described above for the growth dataset on wild boars, even when assessed separately in adult European and Corsican pigs (Kruskal–Wallis  $\chi^2 = 0.55641$ , d.f. = 1,  $p$ -value = 0.4557), Australian feral pigs (Kruskal–Wallis  $\chi^2 =$



**Table 2.** Pairwise *t*-test comparison with Bonferroni adjustment method between each longitudinal observation (LO) of (A) brain endocast volume (logECV) and (B) body weight (LogWeight) for the experimental captive wild boars (*Sus scrofa scrofa*). Non-significant *p* values are in bold.

A					
	L01	L02	L03	L04	L05
L02	<b>0.8665</b>	—	—	—	—
L03	0.0024	<b>0.5757</b>	—	—	—
L04	$6.30 \times 10^{-7}$	0.0016	<b>1.0000</b>	—	—
L05	$4.70 \times 10^{-11}$	$2.60 \times 10^{-7}$	0.0026	<b>0.3236</b>	—
L06	$3.90 \times 10^{-15}$	$9.60 \times 10^{-11}$	$1.80 \times 10^{-5}$	0.0096	<b>1.0000</b>
B					
	L01	L02	L03	L04	L05
L02	$1.90 \times 10^{-7}$	—	—	—	—
L03	$<2 \times 10^{-16}$	0.00055	—	—	—
L04	$<2 \times 10^{-16}$	$1.00 \times 10^{-12}$	0.00119	—	—
L05	$<2 \times 10^{-16}$	$<2 \times 10^{-16}$	$<2 \times 10^{-16}$	$2.40 \times 10^{-8}$	—
L06	$<2 \times 10^{-16}$	$<2 \times 10^{-16}$	$<2 \times 10^{-16}$	$1.40 \times 10^{-10}$	<b>1.0000</b>

0.30682, d.f. = 1, *p*-value = 0.5796) or in adult wild boars (Kruskal–Wallis  $\chi^2 = 0.30682$ , d.f. = 1, *p*-value = 0.5796).

### 3.3. Brain size differences among wild, captive, feral and domestic *Sus scrofa*

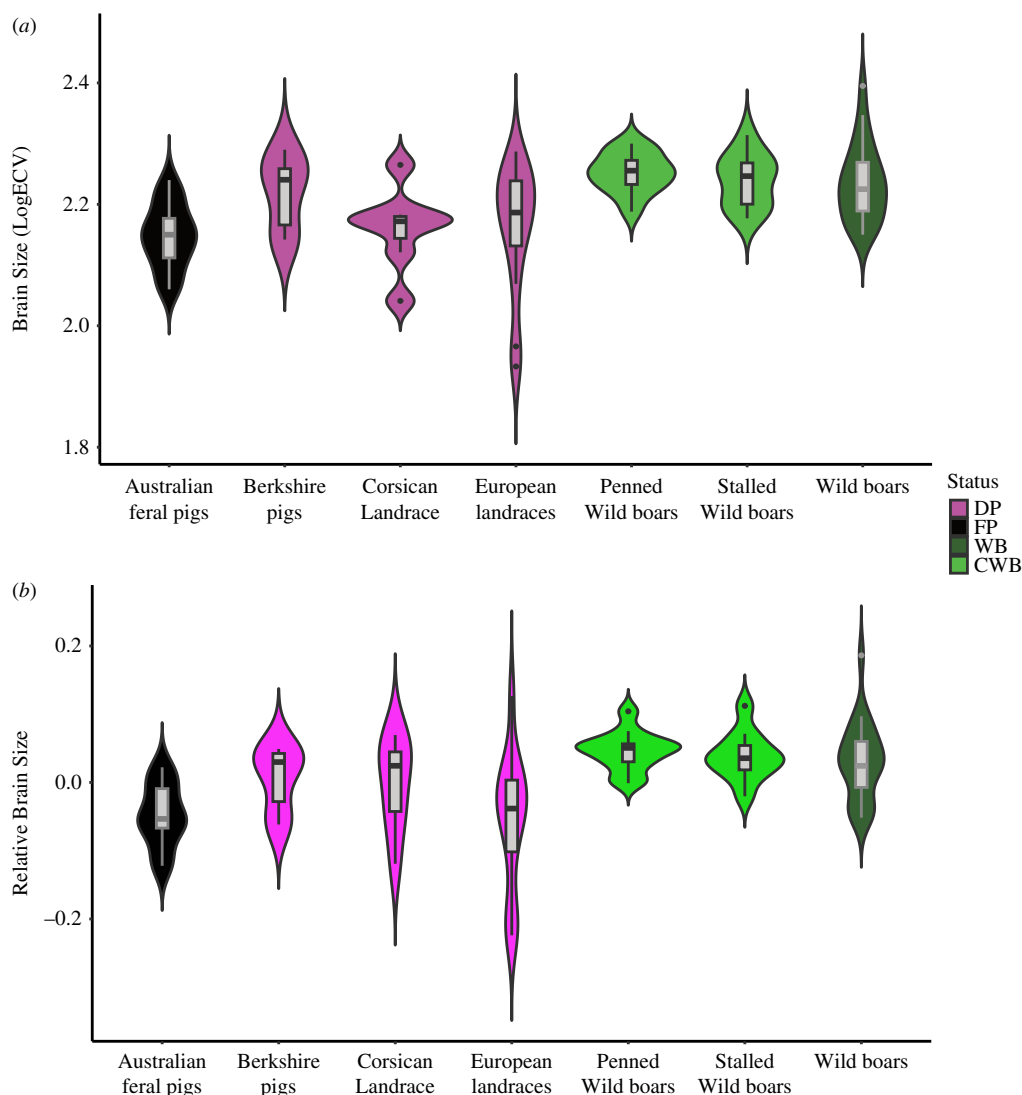
We found significant differences among wild, captive, feral and domestic *Sus scrofa* (figure 3a,b), in terms of both brain volume (Kruskal–Wallis  $\chi^2$  logECV = 30.594, d.f. = 6, *p* < 0.0001) and relative brain volume (Kruskal–Wallis  $\chi^2 = 35$ , d.f. = 6, *p* < 0.0001). We found a 13% brain volume difference between wild boars (hunted and captive) and all domestic pig breeds. This reduction reached 18% when the small Corsican Landrace and captive wild boars are excluded in order to only compare continental hunted wild boars versus non-insular pigs. Despite these overall differences, we found no significant brain or relative brain volume differences between wild boars and domestic breeds when using the Wilcoxon pairwise comparisons (table 3). Significant brain size and relative brain size reduction are only observed between wild boars and the feral pigs from Australia and the small Corsican Landrace (table 3). We observed that Berkshire pigs display an endocast volume that is 12% larger than Landrace pigs, yet this difference is not significant (table 3).

We also found significant (multiple  $R^2 = 0.15$ , *F*-statistic = 15.58, *p* < 0.001) but weak linear relationships between the endocast volume and the cranium size for all the wild, captive, feral and domestic samples (figure 4a). Yet wild boars (hunted or captive) and feral pigs showed a greater brain to body size allometry than domestic pig samples (figure 4b).

ANOVA found a small but significant influence of selective regimen over the brain volume (adjusted  $R^2 = 0.1259$ , *F*-statistic = 3.4, *p* = 0.02524) and the relative brain volume (adjusted  $R^2 = 0.168$ , *F*-statistic = 4.297, *p* = 0.00937) when using wild boars (captive excluded), European domestic Landraces, Corsican Landraces and Berkshire pigs as grouping factors for the linear models.

### 3.4. Feralization and change in brain size

Feral pigs from Australia showed a significant difference in their brain volume (14%) and relative brain volume compared with wild boar samples but no significant reduction of brain volume or relative brain volume compared with pig samples from Landraces, or Berkshire breed (figure 3a,b and table 3).



**Figure 3.** Violin boxplot comparing variation in (a) brain volume (logECV), (b) brain relative volume (regression's residuals of log-transformed brain volume on log-transformed FMB) between hunted wild boars (WB), captive wild boar (CWB), domestic pigs (DP) and feral pigs (FP) samples of *Sus scrofa*.

### 3.5. Captivity experience during growth and brain size change in wild boar

The brain volume variation and the relative brain volume variation of wild boars that were raised in captivity is not significantly different from wild boars hunted in their natural habitat (figure 3a,b). However, we observe that the ECV median of captive specimens is 6% larger than the wild boar ECV.

## 4. Discussion

Differences in brain size between wild and domestic species have been documented in evolutionary science for more than a century, but the relevance of these changes has recently been challenged [31] and many confounding factors remain to be disentangled—such as ageing changes and sexual differences and neuroplastic response to environmental changes. In this study, we explored the effects of these factors on the brain size variation of *Sus scrofa*, a model species considered to have undergone the greatest brain reduction among domesticated mammals [14]. The endocast's volume was extracted automatically from skull CT scans as a proxy of the brain size and we implemented a body size correction using the foramen magnum breadth.



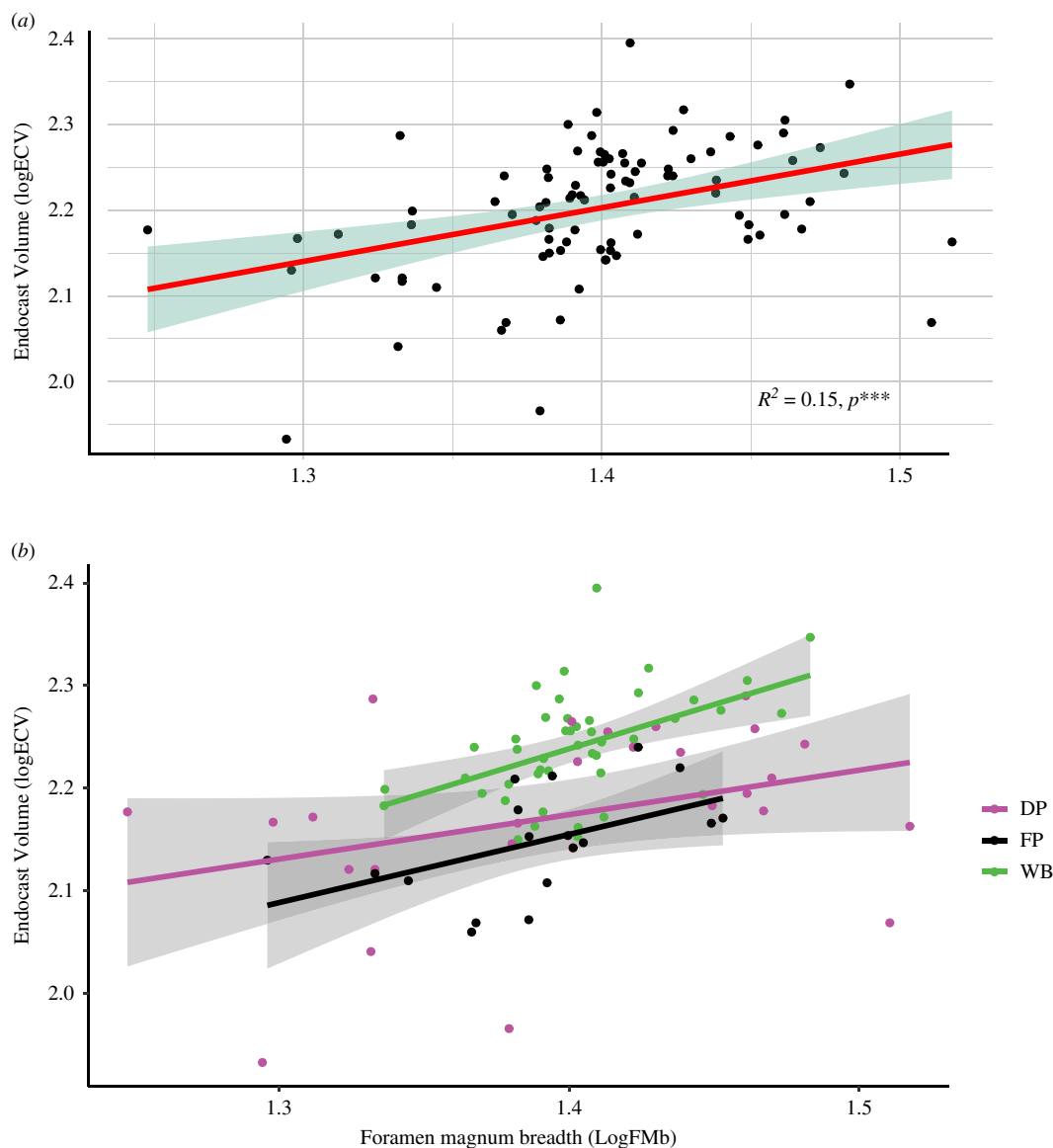
**Table 3.** Wilcoxon pairwise comparisons with BH adjustment method of (A) the brain endocast volume (logECV) and (B) the relative brain size (residuals) between seven *Sus scrofa* groups. Significant differences have been written in bold.

<b>A. brain endocast volume (logECV)</b>						
	Australian feral pigs	Berkshire pigs	Corsican landrace	European landraces	Penned wild boars	Stalled wild boars
Berkshire pigs	0.08166	—	—	—	—	—
Corsican landrace	0.60163	0.44231	—	—	—	—
European landraces	0.37492	0.44231	0.74262	—	—	—
Penned wild boars	<b>0.00058</b>	0.45486	<b>0.01375</b>	<b>0.03045</b>	—	—
Stalled wild boars	<b>0.00121</b>	0.70225	<b>0.03045</b>	0.08166	0.69612	—
Wild boars	<b>0.00077</b>	0.74262	0.07438	0.14568	0.386	0.69612
<b>B. Relative brain size (residuals)</b>						
	Australian feral pigs	Berkshire pigs	Corsican landrace	European landraces	Penned wild boars	Stalled wild boars
Berkshire pigs	0.06731	—	—	—	—	—
Corsican landrace	0.14485	1	—	—	—	—
European landraces	0.81776	0.22961	0.30058	—	—	—
Penned wild boars	<b><math>1.50 \times 10^{-5}</math></b>	0.19382	0.30058	<b>0.00167</b>	—	—
Stalled wild boars	<b>0.00021</b>	0.61895	0.37079	<b>0.00627</b>	0.66612	—
Wild boars	<b><math>5.80 \times 10^{-5}</math></b>	0.57954	0.61895	<b>0.00804</b>	0.37248	0.66612

#### 4.1. Effects of age and sexual differences on brain size

Studies on pig brain development do not go beyond six months [32,33]; in this study, however, we provide the first long-lasting *in vivo* longitudinal record of brain growth in a large mammal until adulthood. Thanks to this record, we found that *Sus scrofa* brain volume increases steadily until 25 months with a sexual difference in brain size already in place from the 11th month. Brain growth and sexual differentiation in brain volume does not seem to be fully aligned with the body mass growth of the captive specimens which slows down from 20 months and shows sexual differences from 6 months. In their natural habitat, wild boars reach 75% and more of their body weight by 24 months and could continue growing in males over 36 months, while sexual difference in body size starts by the 20th month [34]. Unfortunately, our *in vivo* longitudinal record could not be carried out until 36 months so we cannot exclude that the brain growth could slow after 25 months. However, these results suggest that wild boar brain growth is steady between 6 and 25 months, despite sexual maturity and the inflection of the body growth curve from 20 months.

We also found no ageing influence over brain size variation in a cohort of wild and domestic adults, suggesting that age variability should not be considered as a potential bias when comparing the brain size variation of adult *Sus scrofa* across wild and domestic populations.



**Figure 4.** Relative brain size in *Sus scrofa* using the regression of endocast volume (logECV) versus the foramen magnum breadth (logFMb) as body mass proxy: (a) across all the *Sus scrofa* specimens with regression slope and its interval of confidence; (b) separating wild (WB), feral (FP) and domestic (DP) *Sus scrofa* with respective regression slopes and confidence interval.

We found a 6% brain volume difference between 25-month-old male and female wild boars that have grown in captivity for the experiment, but no significant sexual difference was detected in the adult dataset of wild boars, domestic pigs and feral pigs. Sexual differences in the brain volume of the captive wild boars is probably related to the body mass difference (19%) between males and females at 25 months old (see [35] for body mass details). Yet, we did not find significant sexual change in brain volume in wild and domestic *Sus scrofa*, refuting the theory of the attenuation of male secondary sexual characteristics through the selection for reduced male aggression as a driver for brain size reduction in females [13]. The greater sexual expression observed for the experimental dataset could be explained by a reduced access to the food supply for the females, which could be due to greater male aggressiveness; unfortunately, we did not record this information during the experiment. More species-specific empirical studies are therefore required to further address this model.

#### 4.2. Selective regime and brain size changes

To assess the effect of domestication on brain size, we compared brain volume and body size corrected brain volume between European wild boars, European Landraces (German and Corsican) and the

Berkshire breed. We found a significant effect of the selective regime on *Sus scrofa* brain size variation with an 18% reduction trend between European wild boars and European domestic pigs.

Our study cannot answer the important question of whether the smaller brain of pigs compared with wild boars is inherited from the early process of reproductive control during domestication or the result of the recent breeding selection. The Berkshire breed selected for muscle mass production showed a trend towards a 12% increase in brain volume compared with Landraces, contradicting our assumption that selective breeding, leading to the increase of metabolic investment in muscle tissue (meat), tends to reduce the energy investment for brain development [13]. The slight increase in brain size of Berkshire pigs compared with traditional Landraces would suggest that this smaller brain size compared with wild boars could be inherited from the first phase of reproductive control during the early process of pig domestication. Only a bioarchaeological approach could provide the right comparative material to answer this crucial question.

The 18% brain size reduction observed agrees with previous results by Röhrs & Ebinger [36] and Balcarcel *et al.* [14], despite a different brain size approximation and a different statistical approach for brain size differences between wild and domestic animals. This further undermines the brain size reduction between 30% and 40% previously considered for domestic pigs [8]. Yet, the reduction we observed using the volume of the brain endocast is not statistically significant, suggesting that further studies are required with larger samples of wild boar populations across Eurasia and a greater diversity of domestic pigs including Chinese breeds.

### 4.3. Feralization effect on *Sus scrofa* brain size

Despite their great evolutionary interest [37], studies on the effect of feralization on animal phenotypes and especially brain anatomy are still scarce [18]. The seminal work on the feral pig populations from the Galapagos Islands [38], showed that Galapagos pigs had a 30% smaller relative brain size compared with wild boars. This has also been observed for dogs, rodents, birds, fish [39] and even for ungulates that have been feral for thousands of years, such as the Mediterranean sheep [40]. However, some exceptions have recently been reported, such as the dingo [20] or feral populations of mink [21], which both display a reverse movement towards a larger brain. Feral pigs of the island of Sardinia also display a larger brain than wild boar and domestic pigs from the island [19], suggesting that brain size could be one of the reversible traits of domestication through feralization, depending on the species and environmental context.

In this study, we found that the descendants of the first Australian feral pigs did not regain the brain size of continental wild boars. This contradicts our assumption that 200 years of feralization in a new challenging environment [41] the size of Australia, requiring more behavioural flexibility, would require an adaptive increase in the brain size [3], inducing a reverse towards wild boar brain size variation. On the contrary, Australian feral pigs display a brain volume in the range of the small-bodied insular Corsican pig Landrace, smaller than nineteenth-century historical pig Landraces (contemporaneous with the introduction of pigs to Australia). Accordingly, the brain size of Australian feral pigs neither reverted towards a 'wild' brain as we expected nor remained unreversed from their ancestral domestic traits; rather it has further reduced. A skull size reduction has already been observed from the same Australian feral specimens and comparative pigs [42] and fits the body description of Australian feral pigs as smaller and leaner than pigs [43]. This brain reduction in Australian feral pigs could have been adaptive due to the reduction of the energy cost of a small brain in an environment minimizing anti-predator behaviours [44,45]. Yet, it has been reported that dingoes and feral dogs prey on feral pigs [46], which could undermine this assumption. On the other hand, the high mortality of Australian feral pigs is often associated with starvation and drought [47,48], suggesting that the resource scarcity here is probably the strongest selective pressure that the founding populations of feral pigs had to adapt to, and that body and brain size reduction were the most likely adaptive responses.

### 4.4. Lifetime captivity experience effect on wild boar brain size

The few studies on the effect of captivity on mammal brains considers that captivity-induced brain reduction, due to the degradation of the neural network for functions no longer required in captivity, favour a reduction of the brain's energy cost [49]. Studies from captive populations living in zoos or reserves for several generations found brain size reduction in lions and tigers [50]. It has been shown,

however, that enriched environment for captive animals [51] could lead to larger brains, as shown in laboratory rodents [52,53], where the complexity of the captive environment is a key component of the brain size variation in captivity [22]. More recent studies have provided evidence for the role of developmental neuroplasticity in brain morphology [54,55].

In this study, we have provided the first experimental data for the effect of mobility reduction in developmental neuroplasticity in wild boar. We found no brain size or relative brain size reduction in captive wild boars, suggesting that territoriality reduction, a lack of social interaction and a reduction in cognitive demand for resource access with captivity did not induce a plastic brain size reduction in wild boars. Instead, we observed an increase trend of the brain and relative brain size in captive wild boars, suggesting that the plastic response to captivity was actually directed towards an increase in brain size, contradicting our assumption that the loss of cognitive demand in captivity would induce a brain size reduction. One potential explanation for this plastic increase would be the stability and quality (rich in protein) of the food supply in our experimental setting, as suggested by the brain size increase of captive wolves due to high-quality nutrition [56]. Another explanation is that the lack of behavioural flexibility in captivity was balanced by the need to learn in a new niche where the experimental specimens had an enriched environment to prevent stress and were regularly in contact with human carers. This interpretation would be in line with the experiments on laboratory rats where specimens raised in enriched environments had larger brains compared with standard laboratory rats [52] and a greater number of neurons in the hippocampus of house mice raised in stimulating conditions [53]. Therefore, we propose that the stable diet-rich captive environment associated with a new environment and new allospecific interactions could have had neurodevelopmental influence on certain brain region size via synapse formation and cell and synapse pruning [13,57].

## 5. Conclusion

*Sus scrofa*, is considered to be the species that have undergone the greatest brain size reduction among domesticated species. Our study of brain endocast volume supports a brain size reduction up to 18% but rejects previous claims of brain reduction up to 40%. The increase in artificial selection for muscle mass production in this species does not seem to have induced the expected brain size reduction and suggests that reproductive control during the early process of domestication should be further investigated as drivers. Archaeological skulls of *Sus scrofa* from both the Near Eastern and the Chinese domestication centres would undoubtedly help to understand the respective roles of early reproductive control and later breeding selection in the brain evolution of this species. In Australian feral pig populations, the return to natural selection in a challenging environment has not induced the expected return to the wild-sized brain. We propose that an adaptive response to food scarcity for generations has further reduced the brain size inherited from their domestic ancestors. Finally, wild boars raised in captivity until adulthood display a slight increase in brain size, which contradicts the expectation of a cognitively less demanding captive environment. We propose that the constant supply of high-quality food and an enriched environment could have counterweighted the effect of a drastic reduction on cognitive demands by influencing new neurodevelopmental processes. These results suggest that environment and experience are drivers that need further investigations to better understand brain size evolution during domestication.

**Ethics.** The experiment conducted on wild boars has received full approval from the ‘Comité Cuvier d’éthique en matière d’experimentation animale’ of the Natural History Museum of Paris, and the permission to conduct the experiment was granted from the French Ministry of Research with the following licence number: APAFIS#5353-201605111133847.

**Data accessibility.** The data is available at [58].

Supplementary material is available online [59].

**Declaration of AI use.** We have not used AI-assisted technologies in creating this article.

**Authors’ contributions.** T.C.: conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, supervision, visualization, writing—original draft, writing—review and editing; D.N.: formal analysis, investigation, methodology, writing—review and editing; L.F.: formal analysis, writing—review and editing; F.G.: resources, software, visualization, writing—review and editing; H.A.: resources; F.E.: resources; G.S.: data curation, resources, writing—review and editing; R.S.: resources, writing—review and editing.

All authors gave final approval for publication and agreed to be held accountable for the work performed therein.

**Conflict of interest declaration.** We declare we have no competing interests.

**Funding.** This research has been funded by the ANR, through the DOMEXP project (ANR-13-JSH3-0003-01); LabEx ANR-10-LABX-0003-BCDdiv, in the ‘Investissements d’avenir’ programme ANR-11-IDEX-0004-02 and project Emergence SU-19-3-EMRG-02. This project has received financial support from the CNRS through the MITI interdisciplinary programs.

**Acknowledgements.** The authors are most grateful to the staff of the Réserve Zoologique de la Haute-Touche (Christophe Audureau, Jérémy Bernard, Christophe Jubert, Sandrine Laloux, Emmanuel Marechal, Régis Rabier, Patrick Roux and Colin Vion) for their help during the set-up of the experimental structures, the care they provided to the experimental specimens and during the data acquisition.

## References

1. Watanabe S, Hofman MA, Shimizu T. 2017 *Evolution of the brain, cognition, and emotion in vertebrates*. Tokyo, Japan: Springer. (doi:10.1007/978-4-431-56559-8)
2. Heldstab SA, Isler K, Graber SM, Schuppli C, van Schaik CP. 2022 The economics of brain size evolution in vertebrates. *Curr. Biol.* **32**, R697–R708. (doi:10.1016/j.cub.2022.04.096)
3. Sol D, Bacher S, Reader SM, Lefebvre L. 2008 Brain size predicts the success of mammal species introduced into novel environments. *Am. Nat.* **172 Suppl 1**, S63–71. (doi:10.1086/588304)
4. Benson-Amram S, Dantzer B, Stricker G, Swanson EM, Holekamp KE. 2016 Brain size predicts problem-solving ability in mammalian carnivores. *Proc. Natl Acad. Sci. USA* **113**, 2532–2537. (doi:10.1073/pnas.1505913113)
5. Schuppli C, Graber SM, Isler K, van Schaik CP. 2016 Life history, cognition and the evolution of complex foraging niches. *J. Hum. Evol.* **92**, 91–100. (doi:10.1016/j.jhevol.2015.11.007)
6. Powell LE, Isler K, Barton RA. 2017 Re-evaluating the link between brain size and behavioural ecology in primates. *Proc. R. Soc. B* **284**, 20171765. (doi:10.1098/rspb.2017.1765)
7. Dunbar RIM. 1998 The social brain hypothesis. *Evol. Anthropol.* **6**, 178–190. (doi:10.1002/(SICI)1520-6505(1998)6:5<178::AID-EVAN5>3.3.CO;2-P)
8. Kruska D. 1988 Mammalian domestication and its effect on brain structure and behavior. In *Intelligence and evolutionary biology* (eds HJ Jerison, I Jerison), pp. 211–250. Berlin, Germany: Springer. (doi:10.1007/978-3-642-70877-0\_13)
9. Hemmer H. 1990 *Domestication: the decline of environmental perception*. Cambridge, UK: Cambridge University Press.
10. Logan CJ *et al.* 2018 Beyond brain size: uncovering the neural correlates of behavioral and cognitive specialization. *bioRxiv*. (doi:10.1101/145334)
11. Sánchez-Villagra M. 2021 *The process of animal domestication*. Princeton, NJ: Princeton University Press. (doi:10.23943/princeton/9780691217666.001.0001)
12. Hecht EE, Kukekova AV, Gutman DA, Acland GM, Preuss TM, Trut LN. 2021 Neuromorphological changes following selection for tameness and aggression in the Russian farm-fox experiment. *J. Neurosci.* **41**, 6144–6156. (doi:10.1523/JNEUROSCI.3114-20.2021)
13. Hecht EE, Barton SA, Rogers Flattery CN, Meza Meza A. 2023 The evolutionary neuroscience of domestication. *Trends Cogn. Sci.* **27**, 553–567. (doi:10.1016/j.tics.2023.03.008)
14. Balcarcel AM, Geiger M, Clauss M, Sánchez-Villagra MR. 2022 The mammalian brain under domestication: discovering patterns after a century of old and new analyses. *J. Exp. Zool. B Mol. Dev. Evol.* **338**, 460–483. (doi:10.1002/jez.b.23105)
15. Neaux D *et al.* 2021 How changes in functional demands associated with captivity affect the skull shape of a wild boar (*Sus scrofa*). *Evol. Biol.* **48**, 27–40. (doi:10.1007/s11692-020-09521-x)
16. Zollikofer CPE, De León MSP. 2013 Pandora’s growing box: inferring the evolution and development of hominin brains from endocasts. *Evol. Anthropol.* **22**, 20–33. (doi:10.1002/evan.21333)
17. Radinsky L. 1967 Relative brain size: a new measure. *Science* **155**, 836–838. (doi:10.1126/science.155.3764.836)
18. Niego A, Benítez-Burraco A. 2022 Are feralization and domestication truly mirror processes? *Ethol. Ecol. Evol.* **34**, 557–590. (doi:10.1080/03949370.2021.1975314)
19. Maselli V, Polese G, Larson G, Raia P, Forte N, Rippa D, Ligrone R, Vicidomini R, Fulgione D. 2014 A dysfunctional sense of smell: the irreversibility of olfactory evolution in free-living pigs. *Evol. Biol.* **41**, 229–239. (doi:10.1007/s11692-013-9262-3)
20. Smith FA, Elliott Smith RE, Lyons SK, Payne JL. 2018 Body size downgrading of mammals over the late quaternary. *Science* **360**, 310–313. (doi:10.1126/science.aao5987)
21. Pohle AK, Zalewski A, Muturi M, Dullin C, Farková L, Keicher L, Dechmann DKN. 2023 Domestication effect of reduced brain size is reverted when mink become feral. *R. Soc. Open Sci.* **10**, 230463. (doi:10.1098/rsos.230463)
22. O’Regan HJ, Kitchener AC. 2005 The effects of captivity on the morphology of captive, domesticated and feral mammals. *Mamm. Rev.* **35**, 215–230. (doi:10.1111/j.1365-2907.2005.00070.x)
23. DePasquale C, Li X, Harold M, Mueller S, McLaren S, Mahan C. 2020 Selection for increased cranial capacity in small mammals during a century of urbanization. *J. Mammal.* **101**, 1706–1710. (doi:10.1093/jmammal/gyaa121)



24. Casabianca F, Poggioli A, Rossi JD, Maestrini O. 2000 The beginning of collective management for the Corsican pig breed: building up a standard and elaborating the breeders performance recording. *Options Médit. Sér. A. Sémin. Médit.* **41**, 23–34.
25. Pullar EM. 1953 The wild (feral) pigs of Australia: their origin, distribution and economic importance. *Mem. Mus. Vic.* **18**, 7–23. (doi:10.24199/jmmv.1953.18.01)
26. PULLAR EM. 1950 The wild (feral) pigs of Australia and their role in the spread of infectious diseases. *Aust. Vet. J.* **26**, 99–110. (doi:10.1111/j.1751-0813.1950.tb04901.x)
27. Izac AMN, O'Brien P. 1991 Conflict, uncertainty and risk in feral pig management Australian approach. *J. Environ. Manage.* **32**, 1–18. (doi:10.1016/S0301-4797(05)80077-5)
28. Profico A, Buzi C, Melchionna M, Veneziano A, Raia P. 2020 Endomaker, a new algorithm for fully automatic extraction of cranial endocasts and the calculation of their volumes. *Am. J. Phys. Anthropol.* **172**, 511–515. (doi:10.1002/ajpa.24043)
29. Patil I. 2021 Visualizations with statistical details: the 'ggstatsplot' approach. *J. Open Source Softw.* **6**, 3167. (doi:10.21105/joss.03167)
30. Wickham H. 2016 *Ggplot2: elegant graphics for data analysis*. New York, NY: Springer-Verlag.
31. Lord KA, Larson G, Karlsson EK. 2020 Brain size does not rescue domestication syndrome. *Trends Ecol. Evol.* **35**, 1061–1062. (doi:10.1016/j.tree.2020.10.004)
32. Conrad MS, Dilger RN, Johnson RW. 2012 Brain growth of the domestic pig (*Sus scrofa*) from 2 to 24 weeks of age: a longitudinal MRI study. *Dev. Neurosci.* **34**, 291–298. (doi:10.1159/000339311)
33. Fil JE, Joung S, Zimmerman BJ, Sutton BP, Dilger RN. 2021 High-resolution magnetic resonance imaging-based atlases for the young and adolescent domesticated pig (*Sus scrofa*). *J. Neurosci. Methods* **354**, 109107. (doi:10.1016/j.jneumeth.2021.109107)
34. Pedone P, Mattioli S, Mattioli L. 1995 Body size and growth patterns in wild boars of tuscany, central italy. *IBEX JME* **3**, 66–68.
35. Harbers H *et al.* 2020 The mark of captivity: plastic responses in the ankle bone of a wild ungulate (*Sus scrofa*). *R. Soc. Open Sci.* **7**, 192039. (doi:10.1098/rsos.192039)
36. Röhrs M, Ebinger P. 1978 Die Beurteilung von Hirngrößenunterschieden zwischen Wild- und Haustieren. *J. Zool. Syst. Evol. Res.* **16**, 1–14. (doi:10.1111/j.1439-0469.1978.tb00916.x)
37. Gering E, Incorvaia D, Henriksen R, Conner J, Getty T, Wright D. 2019 Getting back to nature: feralization in animals and plants. *Trends Ecol. Evol.* **34**, 1137–1151. (doi:10.1016/j.tree.2019.07.018)
38. Kruska D, Röhrs M. 1974 Comparative-quantitative investigations on brains of feral pigs from the Galapagos Islands and of European domestic pigs. *Z. Anat. Entwicklungsgesch.* **144**, 61–73. (doi:10.1007/BF00518633)
39. Ebinger P, Röhrs M. 1995 Volumetric analysis of brain structures, especially of the visual system in wild and domestic turkeys (*Meleagris gallopavo*). *J. Hirnforsch.* **36**, 219–228.
40. Groves CP. 1989 Feral mammals of the mediterranean islands: documents of early domestication. In *The walking larder* (ed. J Clutton-Brock), pp. 46–58. London, UK: Routledge. (doi:10.4324/9781315746456-8)
41. Marino L. 2005 Big brains do matter in new environments. *Proc. Natl Acad. Sci. USA* **102**, 5306–5307. (doi:10.1073/pnas.0501695102)
42. Neaux D, Sansalone G, Lecompte F, Haruda A, Schafberg R, Cucchi T. 2020 Examining the effect of feralization on craniomandibular morphology in pigs, *Sus scrofa* (Artiodactyla: Suidae). *Biol. J. Linnean Soc.* **131**, 870–879. (doi:10.1093/biolinnean/blaa156)
43. Choquenot D. 1996 *Managing vertebrate pests: feral pigs*. (eds T Korn, JC McIlroy). Canberra, Australia: Australian Govt. Pub. Service.
44. Diniz Filho JAF, dos Santos WJA, Jardim LLCZ. 2018 Integrating macroecology and quantitative genetics: evolution of body size and brain size under island rule. See <http://repositorio.bc.ufg.br/handle/ri/21605>.
45. Kruska DCT. 2005 On the evolutionary significance of encephalization in some eutherian mammals: effects of adaptive radiation, domestication, and feralization. *Brain Behav. Evol.* **65**, 73–108. (doi:10.1159/000082979)
46. Marrant DS, Wurster CM, Johnson CN, Butler JRA, Congdon BC. 2017 Prey use by dingoes in a contested landscape: ecosystem service provider or biodiversity threat? *Ecol. Evol.* **7**, 8927–8935. (doi:10.1002/ece3.3345)
47. Groves C, Giles J, Walton D, Richardson B. 1989 *Fauna of Australia*. Canberra, Australia: AGPS.
48. White TCR. 2008 The role of food, weather and climate in limiting the abundance of animals. *Biol. Rev. Camb. Philos. Soc.* **83**, 227–248. (doi:10.1111/j.1469-185X.2008.00041.x)
49. Clark FE, Greggor AL, Montgomery SH, Plotnik JM. 2023 The endangered brain: actively preserving *ex-situ* animal behaviour and cognition will benefit *in-situ* conservation. *R. Soc. Open Sci.* **10**, 230707. (doi:10.1098/rsos.230707)
50. Yamaguchi N, Kitchener AC, Gilissen E, Macdonald DW. 2009 Brain size of the lion (*Panthera leo*) and the tiger (*P. tigris*): implications for intrageneric phylogeny, intraspecific differences and the effects of captivity. *Biol. J. Linnean Soc.* **98**, 85–93. (doi:10.1111/j.1095-8312.2009.01249.x)
51. Young RJ. 2013 *Environmental enrichment for captive animals*, p. 240. Berlin, Germany: Blackwell Publishing.
52. Krech D, Rosenzweig MR, Bennett EL. 1962 Relations between chemistry and problem-solving among rats raised in enriched and impoverished environments. *J. Comp. Physiol. Psychol.* **55**, 801–807. (doi:10.1037/h0044220)
53. Kempermann G, Kuhn HG, Gage FH. 1997 More hippocampal neurons in adult mice living in an enriched environment. *Nature* **386**, 493–495. (doi:10.1038/386493a0)
54. Brenes JC, Lackinger M, Höglinger GU, Schrott G, Schwarting RKW, Wöhr M. 2016 Differential effects of social and physical environmental enrichment on brain plasticity, cognition, and ultrasonic communication in rats. *J. Comp. Neurol.* **524**, 1586–1607. (doi:10.1002/cne.23842)
55. Pike TW, Ramsey M, Wilkinson A. 2018 Environmentally induced changes to brain morphology predict cognitive performance. *Phil. Trans. R. Soc. B* **373**, 20170287. (doi:10.1098/rstb.2017.0287)



56. Siciliano-Martina L, Michaud M, Tanis BP, Scicluna EL, Lawing AM. 2022 Endocranial volume increases across captive generations in the endangered Mexican Wolf. *Sci. Rep.* **12**, 8147. (doi:10.1038/s41598-022-12371-6)
57. Faust TE, Gunner G, Schafer DP. 2021 Mechanisms governing activity-dependent synaptic pruning in the developing mammalian CNS. *Nat. Rev. Neurosci.* **22**, 657–673. (doi:10.1038/s41583-021-00507-y)
58. Cucchi T. 2024 Data, metadata & R script for How domestication, feralization and experience-dependent plasticity affect brain size variation in *Sus scrofa*. [Dataset]. NAKALA. ()
59. Cucchi T, Neaux D, Feral L, Goussard F, Adriansen H, Elleboudt F *et al.* 2024 Data from: How domestication, feralization and experience-dependent plasticity affect brain size variation in *Sus scrofa*. Figshare. (doi:10.6084/m9.figshare.c.7441721)