Gnanadesikan et al. Supplementary Information

Data

We used all primary *Dognition* measures in this analysis but excluded one task, a contagious yawning experiment, because the dependent measure was binary and therefore not well suited to factor analysis. Genetic breed averages included individuals in the Parker dataset (1) who were from the breed's country of origin, along with those from the United States. In order to make the dog breeds in the two datasets correspond, *Dognition* poodles were assigned as either standard (≥ 40 lbs) or miniature/toy (≤ 20 lbs), as in previous studies (2). The genetic data for miniature and toy poodles was also combined.

Heritability Models

Heritability was estimated using Efficient Mixed Model Association (EMMA) (3). EMMA uses a restricted maximum likelihood algorithm to solve a mixed model with the following form:

$$\mathbf{y} = X\beta + Z\mathbf{u} + \mathbf{e},$$

where $\mathbf{y}$ is a vector of quantitative phenotypes, X is a matrix of fixed effects (in our analyses, either intercepts only or intercept plus breed-average weight), β is a vector of coefficients for those fixed effects, Z is an identity matrix, $\mathbf{u}$ is a vector of random effects, and $\mathbf{e}$ is the residual error vector. The variance of $\mathbf{u}$, the random effects vector, is set to $\sigma_g^2 K$, where K is an n x n relatedness matrix, and n is the number of unique dogs included in the model (here, n = 540). The K matrix was calculated from the genetic data as follows. An identity-by-state (IBS) matrix, representing the proportion of SNPs shared by each pair of individuals, was calculated using *PLINK* (4,5). These values were then averaged for every pair of breeds to generate a breed-average IBS matrix. This breed-level IBS matrix was extrapolated to an individual-level IBS matrix by assuming breed-average similarity between each pair of individuals: for individuals of different breeds, the IBS value was set to the average similarity between those two breeds; for individuals of the same breed, the average similarity of individuals within that breed was used. For example, the following K matrix shows 4 individuals from 2 breeds. Breeds A and B are identical-by-state at 69% of sites. On average, individuals within breed A are identical-by-state at 80% of sites, while individuals within breed B are identical-by-state at 74% of sites.

$$K = \begin{array}{c|cccc} & Breed\ A & Breed\ A & Breed\ B & Breed\ B \\ Breed\ A & 1.00 & 0.80 & 0.69 & 0.69 \\ Breed\ A & 0.80 & 1.00 & 0.69 & 0.69 \\ Breed\ B & 0.69 & 0.69 & 1.00 & 0.74 \\ Breed\ B & 0.69 & 0.69 & 0.74 & 1.00 \end{array}$$

Heritability Sensitivity Analysis: Number of Individuals Per Breed

With the aim of obtaining representative samples, we imposed a threshold (N = 15) as the minimum number of individuals per breed for inclusion in the heritability analyses. Whereas higher thresholds increase the likelihood of obtaining breed-representative samples, they reduce the number of breeds meeting the criterion (Figure S3), reducing overall breed coverage. Conversely, lower thresholds for inclusion increase breed coverage, but potentially yield less reliable/robust samples for each breed. As a sensitivity analysis, we conducted supplemental analyses using thresholds of N = 10, N = 20, and N = 25. The overall pattern of results was consistent across these varying thresholds (Figure S4).

Training History Sensitivity Analysis

Since training is often hypothesized to affect performance on cognitive tasks, we also wanted to explore how controlling for training altered our heritability estimates. We have training history data for only a subset of the individuals included in the main analysis, so we conducted these analyses on the 489 individuals representing 34 breeds for whom we had owner-reported training data and at least 5 individuals per breed, comparing models with no covariates to those with training history, weight, or both. Training history was owner-reported on a scale of 1 – 4, labelled as "None", "Little", "Some", "Substantial", which we collapsed into two categories, "None-Little" and "Some-Substantial". Training history was included in the model as an additional fixed effect. Given the small number of individuals per breed, no resampling was used in this analysis.

Although the addition of training history does shrink the heritability estimates in most cases, the effect appears to be less than that for weight, and the inhibitory control and communication factors remain relatively highly heritable ($h^2 > 0.3$; see figure S6). Unsurprisingly, given the nature of the task, this effect is strongest for the inhibitory control task, which can be seen both in the heritability results (figure S6) and in the model coefficients ($\beta_{\text{Inhibitory Control}} > 0.4$ in both models with training, while for other tasks $\beta < 0.2$, table S4). This analysis indicates that both larger dogs and those with more training generally perform better across tasks.

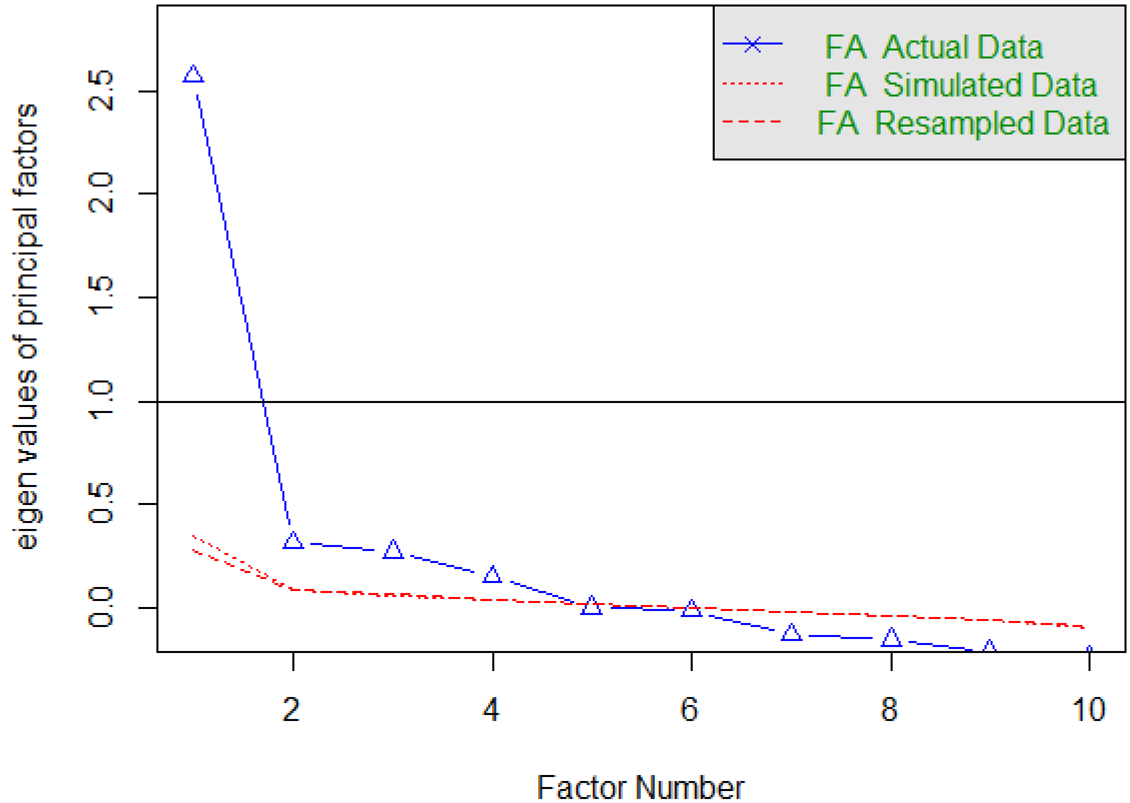

Figure S1: Parallel analysis comparing the actual data to simulated and resampled data, suggesting the presence of four meaningful factors.

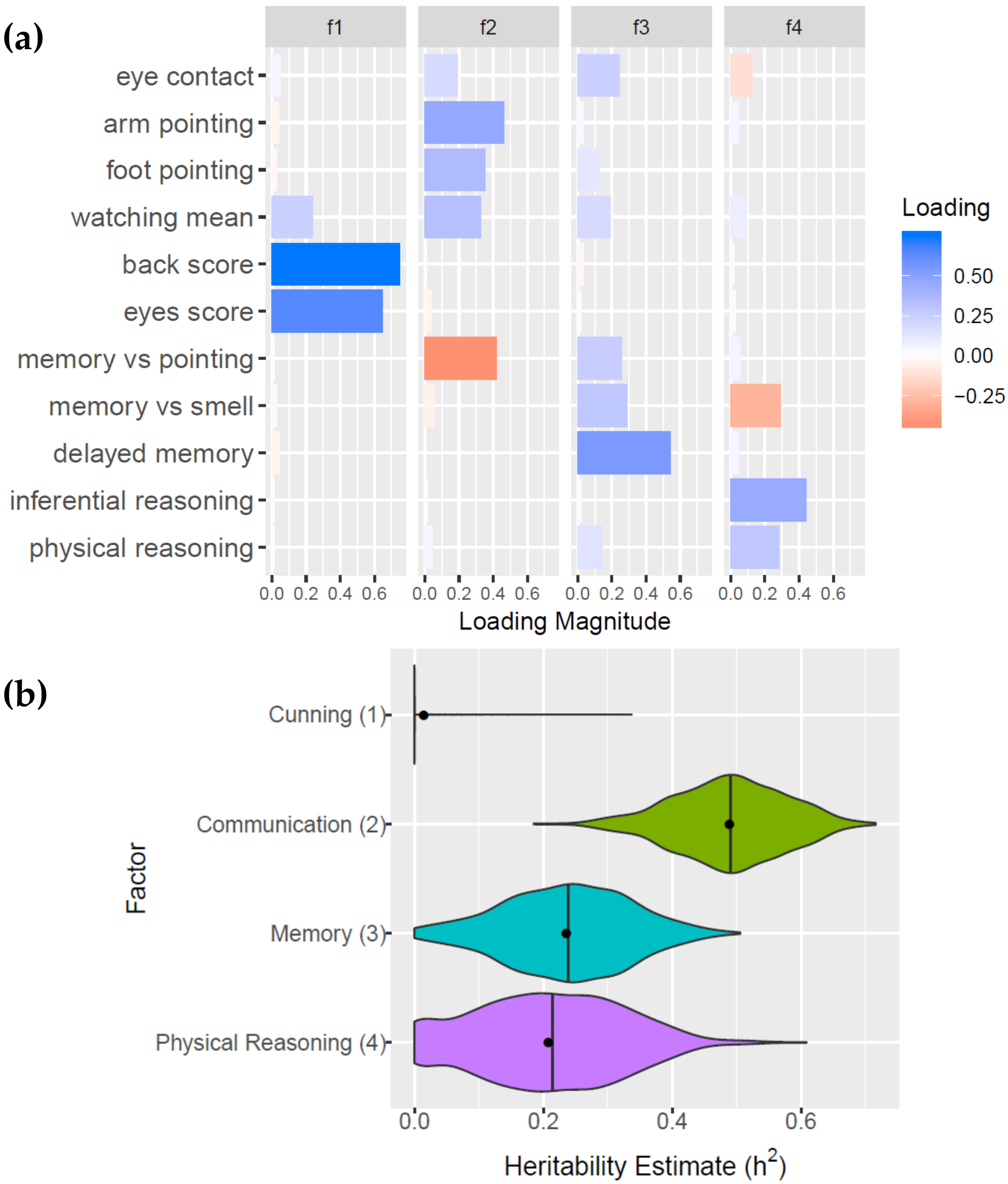

Figure S2: (a) Factor loadings with cunning scores, rather than latencies. The overall pattern is similar to those in the main manuscript (Figure 1), although eye contact loads more significantly on factors 2 and 3 and is therefore retained. **(b)** Heritability analysis for factors calculated with cunning scores, rather than latencies, as showed in a. The cunning factor is not heritable, the communication factor is quite heritable (even more than in the analyses presented in the main paper, presumably due to the contribution of the eye contact task which loads more significantly in this analysis. The memory and physical reasoning factors are intermediately heritable.

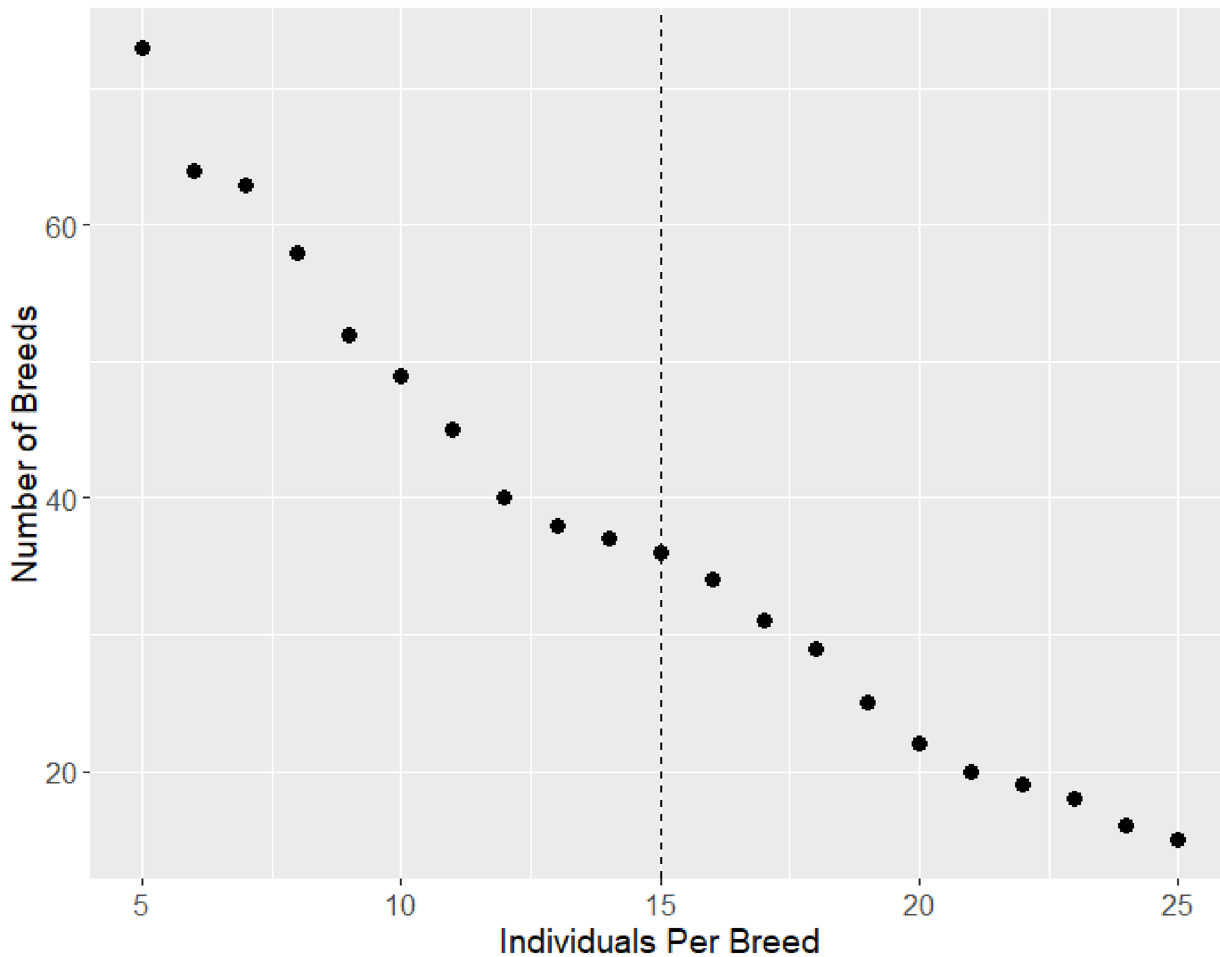

Figure S3: Tradeoff between number of individuals per breed and the number of breeds included in the analysis. Only breeds with genetic data in the Parker dataset are included. The threshold of 15 individuals per breed (dotted line) was ultimately chosen.

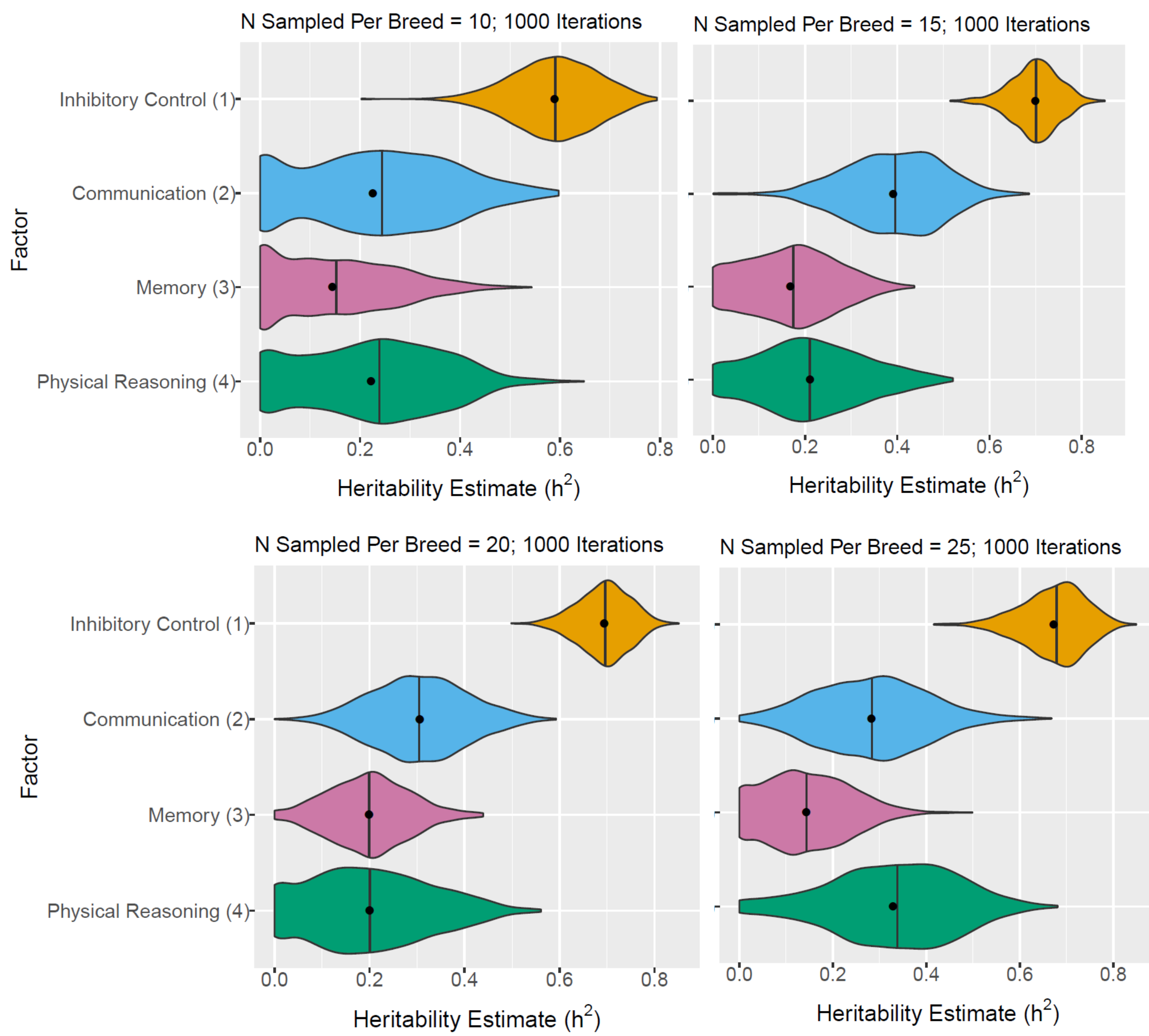

Figure S4: Sensitivity analysis of the inclusion threshold for number of individuals per breed. Although the exact estimates and distributions of estimates changed depending on how many individuals per breed were included, the overall pattern of results remained consistent. Specifically, inhibitory control is always the most heritable, followed by communication and then physical reasoning, with memory the least heritable factor. Thus, a threshold of 15 individuals per breed was ultimately used to maximize the stability of the estimates while also retaining a large number of breeds (see figure S3).

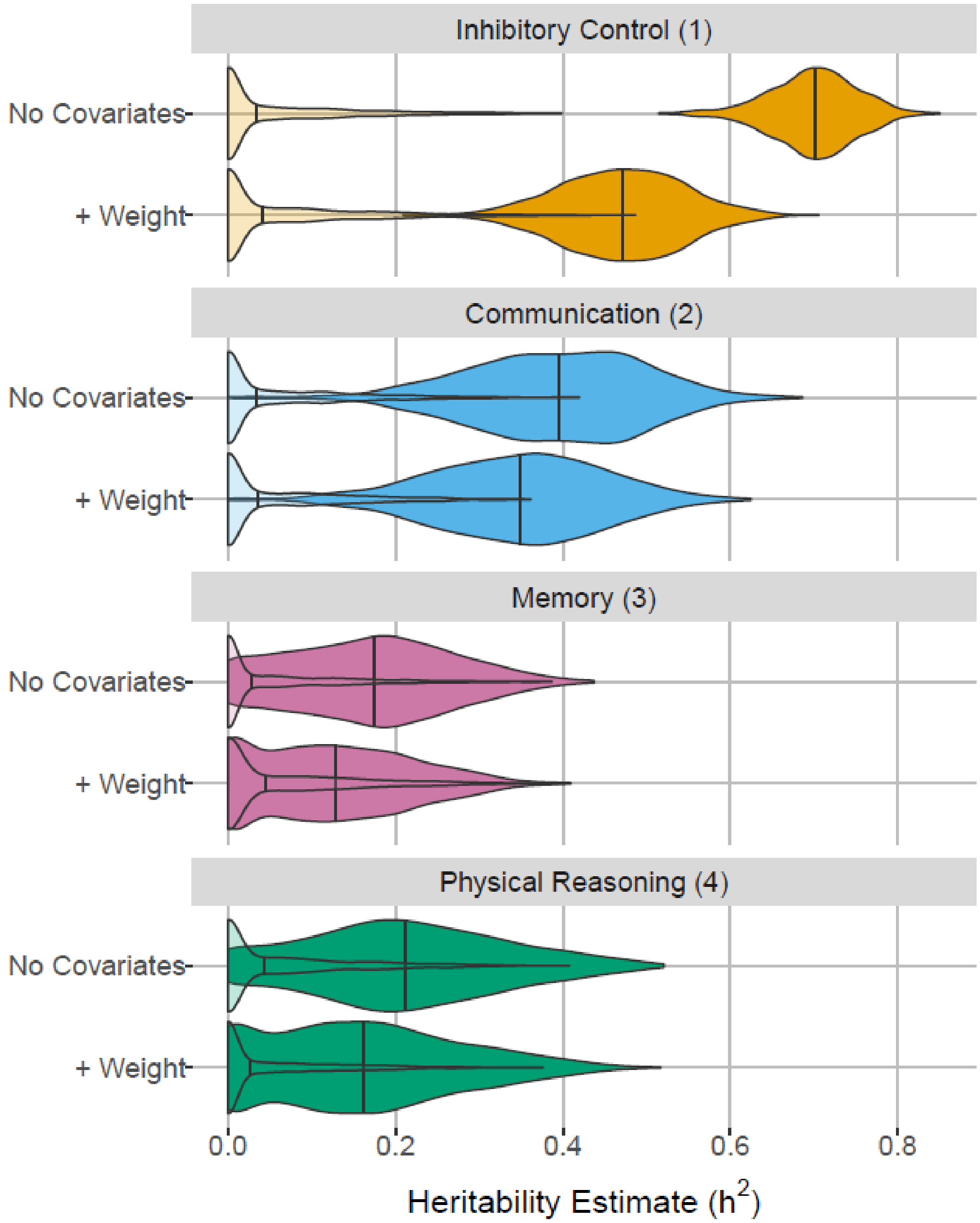

Figure S5: Distribution of narrow-sense heritability estimates for each factor, both without covariates ("No Covariates) and controlling for breed-average weight as a fixed effect ("+ Weight"). The lighter distributions, piled on the y-axis, represent the null distribution in each case, as generated by a randomly permuted association of cognitive and genetic data. Each model was run with resampled cognitive data across 1000 iterations, using 15 individuals per breed at each iteration. The vertical black lines represent the median heritability estimate over these 1000 runs.

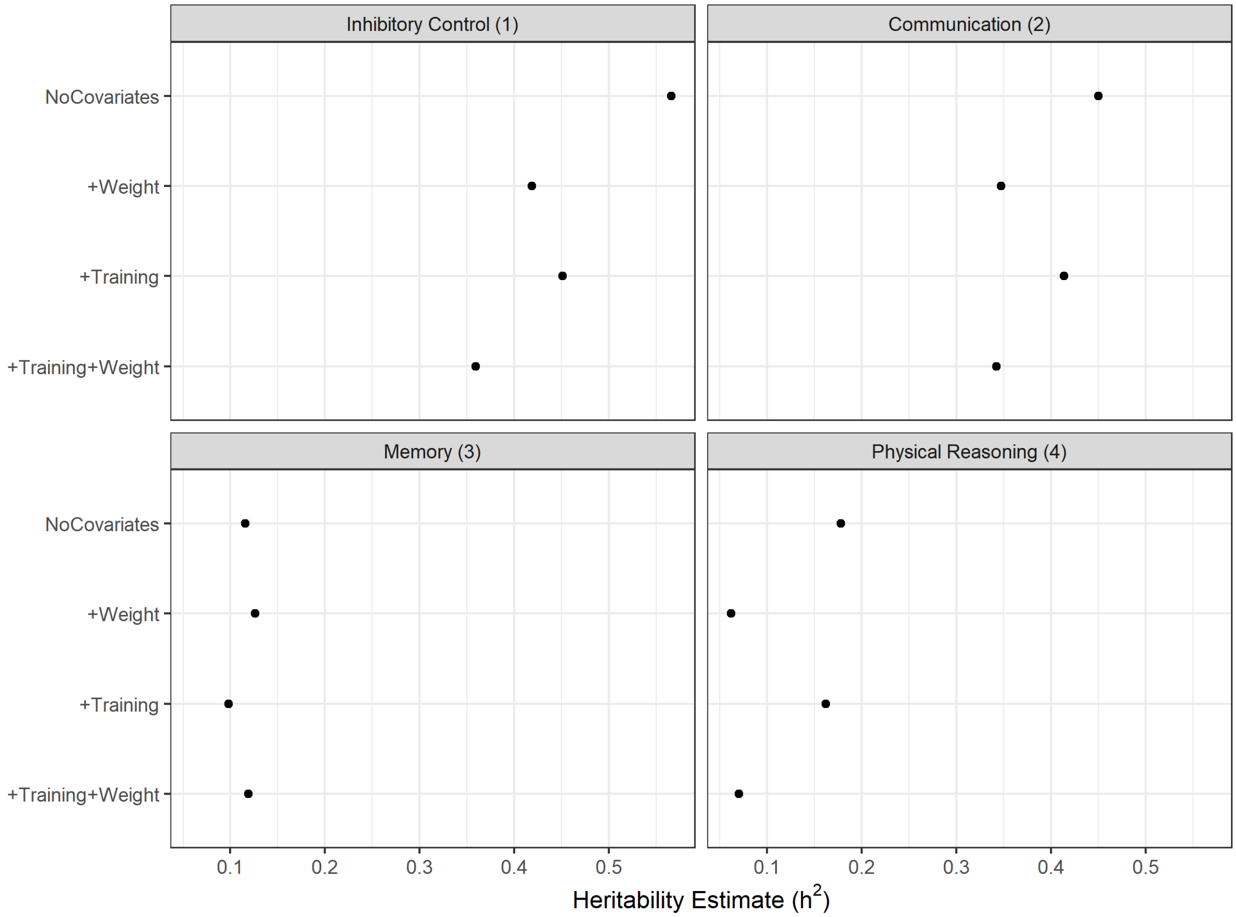

Figure S6: Comparison of heritability results from models controlling for weight, training history, and both versus no covariates. In most cases, the inclusion of additional covariates does shrink the heritability estimate, but the inhibitory control and communication factor estimates remain above 0.3. The effect of training is generally less than that of weight. Model coefficients are given in table S4.

Table S1: Number (N) of individuals and breeds included in the main heritability analysis. The shaded breeds (*Dognition* N < 15) were included in a sensitivity analysis only.

Dognition Breed	*Dognition N*	*Parker Breed Code*	*Parker N*
Labrador Retriever	292	LAB	10
Golden Retriever	162	GOLD	10
German Shepherd Dog	130	GSD	10
Australian Shepherd	88	AUSS	10
Border Collie	83	BORD	10
Irish Water Spaniel	53	IWSP	10
Beagle	41	BEAG	10
Miniature Schnauzer	39	MSNZ	10
Shetland Sheepdog	39	SSHP	10
Boxer	37	BOX	10
Standard Poodle	34	SPOO	10
Miniature/Toy Poodle	30	MPOO/TPOO	10
Dachshund	29	DACH	10
Doberman Pinscher	29	DOBP	10
Pembroke Welsh Corgi	28	PEMB	10
English Springer Spaniel	24	ESSP	10
Chihuahua	23	CHIH	10
Siberian Husky	23	HUSK	10
Shih Tzu	22	SHIH	10
Australian Cattle Dog	21	AUCD	10
Cocker Spaniel	20	ACKR	10
Pug	20	PUG	10
Soft Coated Wheaten Terrier	19	SCWT	4
Vizsla	19	VIZS	7
Yorkshire Terrier	19	YORK	10

Cavalier King Charles Spaniel	18	CKCS	10
Portuguese Water Dog	18	PTWD	10
Rottweiler	18	ROTT	10
West Highland White Terrier	18	WHWT	10
Boston Terrier	17	BOST	10
Havanese	17	HAVA	10
Bulldog	16	BULD	10
French Bulldog	16	FBUL	10
Rhodesian Ridgeback	16	RHOD	9
Belgian Malinois	15	BMAL	6
Weimaraner	15	WEIM	10
German Shorthaired Pointer	14	GSHP	10
Collie	13	COLL	10
Bichon Frise	12	BICH	10
Coton de Tulear	12	COTO	2
American Eskimo Dog	11	AESK	6
Brittany	11	BRIT	10
Jack Russell Terrier	11	JACK	10
Papillon	11	PAPI	10
Shiba Inu	11	SHIB	8
American Staffordshire Terrier	10	AMST	6
Border Terrier	10	BORT	10
Maltese	10	MALT	10
Pomeranian	10	POM	10

Table S2: Breeds included in the factor analysis but excluded from the heritability analysis due to either the small number of individuals per breed in the cognitive data (Dognition N) or a lack of corresponding genetic data. We calculated factors with more breeds than we had sufficient cognitive and genetic data for with the aim of establishing factors that are broadly applicable across breeds and that will therefore be robust to additional data.

Breed	*Dognition N*
American Pit Bull Terrier	23
Australian Labradoodle	17
Bernese Mountain Dog	9
Cairn Terrier	9
Greyhound	9
English Cocker Spaniel	8
Flat-Coated Retriever	8
Miniature Pinscher	8
Rat Terrier	8
Standard Schnauzer	8
Whippet	8
Dalmatian	7
Great Dane	7
Irish Setter	7
Miniature American Shepherd	7
Newfoundland	7
Parson Russell Terrier	7
Samoyed	6
Alaskan Malamute	5
Australian Terrier	5
Bouvier des Flandres	5
Bull Terrier	5
Cardigan Welsh Corgi	5

Miniature Australian Shepherd	5
Nova Scotia Duck Tolling Retriever	5
Old English Sheepdog	5
St. Bernard	5
Staffordshire Bull Terrier	5
Basset Hound	4
Belgian Tervuren	4
Catahoula Leopard Dog	4
Finnish Lapphund	4
German Wirehaired Pointer	4
Irish Terrier	4
Italian Greyhound	4
Mastiff	4
Pyrenean Shepherd	4
Russell Terrier	4
Scottish Terrier	4
Wirehaired Pointing Griffon	4
Akita	3
Beauceron	3
Bluetick Coonhound	3
Chesapeake Bay Retriever	3
Chinese Shar-Pei	3
English Setter	3
Norfolk Terrier	3
Polish Lowland Sheepdog	3
Portuguese Podengo	3
Puli	3
Tibetan Terrier	3

Welsh Springer Spaniel	3
Airedale Terrier	2
Australian Kelpie	2
Basenji	2
Belgian Sheepdog	2
Brussels Griffon	2
Cane Corso	2
Dutch Shepherd	2
Field Spaniel	2
Great Pyrenees	2
Icelandic Sheepdog	2
Kooikerhondje	2
Lagotto Romagnolo	2
Lhasa Apso	2
Manchester Terrier	2
Norwegian Buhund	2
Norwich Terrier	2
Schipperke	2
Silky Terrier	2
Spinone Italiano	2
Tibetan Spaniel	2
Toy Fox Terrier	2
Treeing Walker Coonhound	2
"Cirneco dell"Etna"	1
Afghan Hound	1
American English Coonhound	1
American Water Spaniel	1
Bearded Collie	1

Bedlington Terrier	1
Berger Picard	1
Black and Tan Coonhound	1
Boerboel	1
Boykin Spaniel	1
Briard	1
Bullmastiff	1
Canaan Dog	1
Chow Chow	1
Czechoslovakian Vlcak	1
Danish-Swedish Farmdog	1
Entlebucher Mountain Dog	1
Eurasier	1
Finnish Spitz	1
French Spaniel	1
German Longhaired Pointer	1
German Pinscher	1
Giant Schnauzer	1
Glen of Imaal Terrier	1
Gordon Setter	1
Greater Swiss Mountain Dog	1
Ibizan Hound	1
Irish Red and White Setter	1
Irish Wolfhound	1
Karelian Bear Dog	1
Keeshond	1
Kerry Blue Terrier	1
Leonberger	1

Norwegian Elkhound	1
Perro de Presa Canario	1
Petit Basset Griffon Vendeen	1
Plott	1
Pointer	1
Portuguese Pointer	1
Redbone Coonhound	1
Schapendoes	1
Small Munsterlander Pointer	1
Smooth Fox Terrier	1
Spanish Water Dog	1
Stabyhoun	1
Swedish Vallhund	1
Tosa	1
Welsh Terrier	1
Wire Fox Terrier	1

Table S3: Inter-factor correlations. The highest correlation is between factors 1 and 3, inhibitory control and memory, respectively.

	F1	**F2**	**F3**	**F4**
F1	1.00	0.14	0.28	0.17
F2		1.00	-0.01	0.14
F3			1.00	0.10
F4				1.00

Table S4: Model Coefficients for the training sensitivity analysis.

Model	*Factor*	*Parameter*	*Beta*	*SE*	*p*
No Covariates	Inhibitory Control	Intercept	0.01459	0.74264	0.98433
No Covariates	Communication	Intercept	0.03132	0.43188	0.94219
No Covariates	Memory	Intercept	-0.05047	0.19181	0.79245
No Covariates	Physical Reasoning	Intercept	-0.01134	0.21527	0.95800
+ Training	Inhibitory Control	Intercept	-0.26639	0.61015	0.00000
+ Training	Inhibitory Control	Training	0.48789	0.10190	0.00000
+ Training	Communication	Intercept	-0.04962	0.40725	0.11837
+ Training	Communication	Training	0.13651	0.07235	0.11837
+ Training	Memory	Intercept	-0.14646	0.17968	0.03454
+ Training	Memory	Training	0.17168	0.07211	0.03454
+ Training	Physical Reasoning	Intercept	-0.10104	0.20669	0.02559
+ Training	Physical Reasoning	Training	0.15976	0.06417	0.02559
+ Weight	Inhibitory Control	Intercept	-0.44331	0.59993	0.00255
+ Weight	Inhibitory Control	Weight	0.01950	0.00605	0.00255
+ Weight	Communication	Intercept	-0.16051	0.37165	0.09769
+ Weight	Communication	Weight	0.00793	0.00403	0.09769
+ Weight	Memory	Intercept	-0.11811	0.21611	0.81561
+ Weight	Memory	Weight	0.00281	0.00340	0.81561
+ Weight	Physical Reasoning	Intercept	-0.17983	0.13999	0.01152
+ Weight	Physical Reasoning	Weight	0.00779	0.00282	0.01152
+ Training + Weight	Inhibitory Control	Intercept	-0.56832	0.53313	0.00005
+ Training + Weight	Inhibitory Control	Training	0.44416	0.10358	0.00005
+ Training + Weight	Inhibitory Control	Weight	0.01418	0.00582	0.00005
+ Training + Weight	Communication	Intercept	-0.19495	0.36844	0.24676
+ Training + Weight	Communication	Training	0.11374	0.07382	0.24676
+ Training + Weight	Communication	Weight	0.00660	0.00410	0.24676

+ Training + Weight	Memory	Intercept	-0.17212	0.21067	0.07457
+ Training + Weight	Memory	Training	0.16610	0.07403	0.07457
+ Training + Weight	Memory	Weight	0.00110	0.00345	0.07457
+ Training + Weight	Physical Reasoning	Intercept	-0.22487	0.14857	0.09650
+ Training + Weight	Physical Reasoning	Training	0.12928	0.06545	0.09650
+ Training + Weight	Physical Reasoning	Weight	0.00650	0.00291	0.09650

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