Supplementary material

Linking cognition with fitness in a wild primate: Fitness correlates of problem-solving performance and spatial learning ability

Franziska Huebner, Claudia Fichtel, Peter M. Kappeler

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Figures

Figure S1: The food extraction task: Body width of a mouse lemur corresponds to the width of one compartment (5 x 4.5cm).

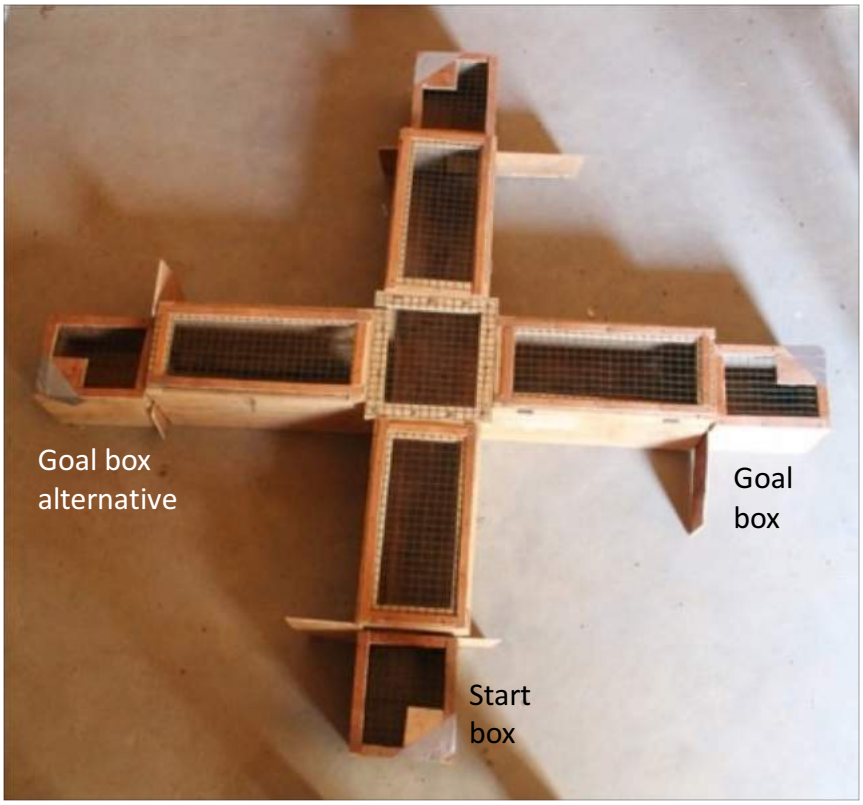

Figure S2: The maze: Body size of a mouse lemur corresponds approximately to one quarter of the start box (20cm x 17cm)

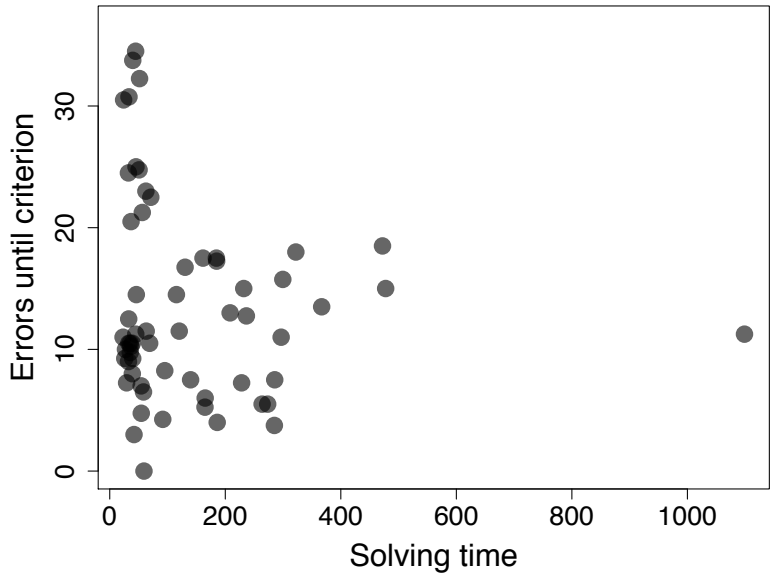

Figure S3: Correlation between the two main measures of cognitive performance: solving time (in seconds) in the FE task and number of errors until criterion in the maze.

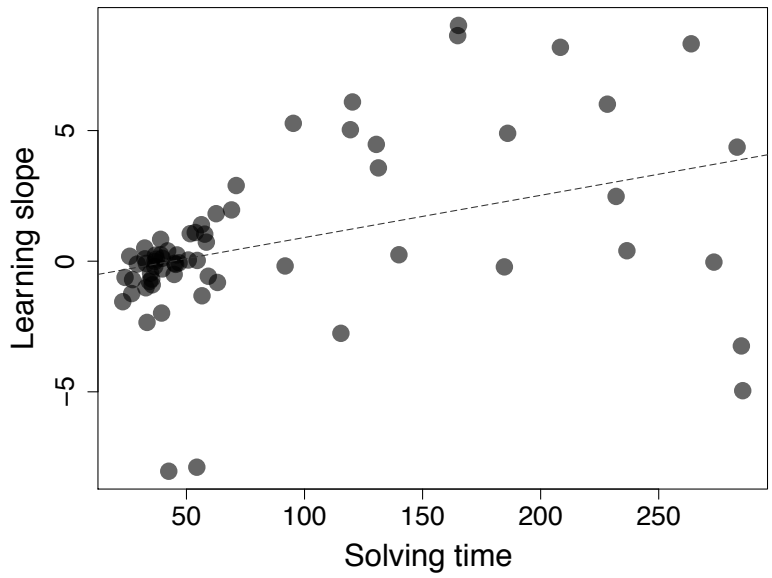

Figure S4: Correlation between individual learning slopes and mean solving time (in seconds) for subjects that opened at least five lids in the FE task. Learning slopes were calculated from individual regression lines of successive latencies until lid openings from first success until fifth or sixth success (i.e. time intervals between successes). Negative slopes reflect a decrease in solving latencies and suggest learning across lid openings. Spearman rank correlation ($r= 0.46$, $S= 25784$, $P< 0.001$, $N= 66$) revealed that individuals' mean solving time and learning slopes correlated positively, thus supporting the notion that for subjects with low solving times, learning is involved during the repeated opening

of lids in the FE task and that individuals' mean solving times are an adequate measure to compare among subjects that differed in the number of lid opened.

Tables

Table S1: Overview of studies linking cognitive performance and fitness proxies

Species	**Cognitive performance**	**Fitness proxy**	**Sample size**	**Relationship**	**Fitness measured in**	**Reference**
Bumble bee, *Bombus terrestris*	Associative learning	Foraging success	12 colonies	positive	wild	Raine & Chittka 2008
Bumble bee, *Bombus terrestris*	Associative learning	Lifetime foraging performance	85	negative	wild	Evans et al. 2017
Rose bitterling, *Rhodeus ocellatus*	Spatial learning	Reproductive success	16 males	Positive; depending on mating tactic	captivity	Smith et al. 2015
Great tit, *Parus major*	Problem solving	Clutch size	368 females	positive	wild	Cole et al. 2012
Great tit, *Parus major*	Problem solving	Nest success	368 females	negative	wild	Cole et al. 2012
Great tit, *Parus major*	Problem solving	Adult survival	698	none	wild	Cole et al. 2012
Great tit, *Parus major*	Problem solving	Fledgling number, clutch size, nestling survival	26 pairs	positive	wild	Cauchard et al. 2013
Great tit, *Parus major*	Problem solving; 2 tasks	Hatching success, Fledgling number	55 pairs	Positive for 1 problem solving task	wild	Preiszner et al. 2016
Great tit, *Parus major*	Problem solving; 2 tasks	Clutch size	55 pairs	none	wild	Preiszner et al. 2016
House sparrow, *Passer domesticus*	Problem solving	Nestling survival	80	None for females, positive for males (N= 41)	wild	Wetzel et al. 2017
Satin bower bird, *Ptilonorhynchus violaceus*	Problem solving, 2 tasks	Mating success	33 (25) males	positive	wild	Keagy et al. 2009

Spotted bower bird, *Ptilonorhynchus maculatus*	PC score* from 6 tasks (Motor task, color and shape discrimination, reversal learning, spatial memory)	Mating success	11	none	wild	Isden et al. 2013
Australian magpie, *Cracticus tibicen dorsalis*	PC score* from 4 tasks (inhibitory control, associative learning, reversal learning, spatial memory)	Number of clutches and fledglings per year	22 females	Positive	wild	Ashton et al. 2018
African striped mouse, *Rhabdomys pumilio*	Spatial memory	Survival until breeding season	20 males, 22 females	Positive for males, negative for females	wild	Maille & Schradin 2016

* Scores from principal component analysis used for the further analysis

Table S2: Results of the repeatability tests for measures of the FE tasks

Performance measure	**Test**	**Result**	**Sample size**	**Interpretation**
Success yes/ no	Cohen's kappa	Kappa= 0.42	13	Moderate agreement
Latency success	Intraclass correlation	ICC= 0.34	12	Poor agreement
Solving time	Intraclass correlation	ICC= 0.63	8	Good agreement

Subjects were tested in the same task with a delay of 10 to 30 days. On the group level, subjects improved in performance: Latency to success decreased by 205$\pm$ 500 sec (mean$\pm$ sd), solving time decreased by 72$\pm$ 65 sec (mean$\pm$ sd). Interpretation of Cohen's kappa and intraclass correlation coefficients according to Hallgren 2012.

Table S3: Food extraction task: results of the Generalized Linear Model (GLM) fitting the influence of BMI on success probability (success y/n)

Predictor variable	Estimate	SE	z	P
Intercept	2.83	0.70	4.03	<0.001

BMI[a]	-1.13	0.41	-2.77	0.006
Sex (male)	-0.93	0.82	-1.13	0.258

Reference category for categorical predictor is indicated in brackets, SE: Standard error, N= 96.
[a] Covariate was z-transformed to a mean of= 0 and sd= 1; original mean of BMI (sd)= 2.66 (0.39).

Table S4: Food extraction task: results of the Generalized Linear Mixed Model (GLMM) testing the influence of BMI on individuals' number of successes

Predictor variable	**Estimate**	**SE**	**z**	**P**
(Intercept)	5.70	1.45	3.92	<0.001
BMI[a]	-2.26	0.77	-2.94	0.003
Sex (male)	-1.10	1.38	-0.80	0.423

Reference category for categorical predictor is indicated in brackets, SE: Standard error, N= 94.
[a] Covariate was z-transformed to a mean of= 0 and sd= 1; original mean of BMI (sd)= 2.66 (0.39).

Table S5: Results of the Cox proportional hazards model fitting the effects of body mass index on latency to solve in the food extraction task

Predictor variable	**coeff**	**Exp(coeff)**	**SE(coef)**	**z**	**P**
BMI[a]	-0.35	0.71	0.12	-3.03	0.002
Sex (male)	-0.28	0.76	0.23	-1.19	0.234

Positive coefficients indicate a higher hazard (here solving), i.e., shorter solving latencies. Exponentially transformed coefficients are the hazard ratios and give the effect size on the hazard of predictor variables. Reference category for categorical predictor is indicated in brackets, SE: Standard error, N= 96.
[a] Covariate was z-transformed to a mean of= 0 and sd= 1; original mean of BMI (sd)= 2.66 (0.39).

Table S6: Food extraction task: results of the linear model testing the effect of body mass index at time of testing on individuals' solving time.

Predictor variable	**Estimate**	**SE**	**t**	**P**
Intercept	4.35	0.17	25.14	<0.001
BMI[a]	0.11	0.12	0.92	0.359
Sex (male)	0.10	0.24	0.43	0.667

Reference category for categorical predictor is indicated in brackets, SE: Standard error, N= 76.
[a] Covariate was z-transformed to a mean of= 0 and sd= 1; original mean of BMI (sd)= 2.61 (0.37).

Table S7: Maze: results of the Generalized Linear Model (GLM) fitting the effect of predictors on subjects' probability to reach the learning criterion

Predictor variable	**Estimate**	**SE**	**z**	**P**
Intercept	1.34	0.45	2.98	0.003
BMI[a]	-0.17	0.28	-0.59	0.558

Sex (male)	-0.73	0.58	-1.26	0.209

Reference category for categorical predictor is indicated in brackets, SE: Standard error, N= 73.
[a] Covariate was z-transformed to a mean of= 0 and sd= 1; original mean of BMI (sd)= 2.56 (0.35).

Table S8: Maze: results of the Cox proportional hazards model fitting the effect of predictors on individuals' number of errors until reaching the learning criterion

Predictor variable	**coeff**	**Exp(coeff)**	**SE(coef)**	**z**	**P**
BMI[a]	-0.09	0.91	0.13	-0.71	0.479
Sex (male)	-0.20	0.82	0.28	-0.69	0.488

Positive coefficients indicate a higher hazard (here reaching the learning criterion), i.e., fewer errors. Exponentially transformed coefficients are the hazard ratios and give the effect size of predictor variables on the hazard. Reference category for categorical predictor is indicated in brackets, SE: Standard error, N= 73.
[a] Covariate was z-transformed to a mean of= 0 and sd= 1; original mean of BMI (sd)= 2.56 (0.35).

Table S9: Relationships between performances in the maze and in the food extraction tasks tested with Spearman rank correlations and Cohen's Kappa tests.

	FE: Latency success	FE: N of successes	FE: solving time	FE: success y/n
Maze: Errors until criterion	R_s= 0.13 P= 0.27 N= 71	R_s= -0.08 P= 0.49 N= 69	R_s= -0.08 P= 0.56 N= 61	/
Maze: criterion y/n	/	/	/	Cohens Kappa= 0.019, N= 71

Table S10: Results of the linear models (LM) fitting the effects of test performance in food extraction task and maze on BMI change from the rainy to the end of dry season

	Predictor variable	**Estimate**	**SE**	**t**	**P**
Model 1: Food extraction N= 31	Intercept	0.48	0.08	5.73	<0.001
	Solving time[a]	0.12	0.05	2.18	0.038
	Sex (male)	-0.48	0.11	-4.35	<0.001
	Age (juvenile)	-0.01	0.11	-0.13	0.900
Model 2: Maze N= 31	Intercept	0.64	0.10	6.33	<0.001
	Number of errors[b]	-0.12	0.06	-1.97	0.059
	Sex (male)	-0.54	0.11	-4.89	<0.001
	Age (juvenile)	-0.18	0.12	-1.57	0.129

Reference categories for categorical predictors are indicated in brackets, SE: Standard error.

[a] Covariate was log transformed and afterwards z-transformed to a mean of= 0 and sd= 1; original mean of log(solving time) (sd)= 4.49 (0.96).
[b] Covariate was z-transformed to a mean of= 0 and sd=1; original mean (sd)= 13.61 (9.43).

Table S11: Results of the Cox proportional hazards model fitting the relationship between test performance in the food extraction task and survival.

Predictor variable	**coeff**	**Exp(coeff)**	**SE(coef)**	**z**	**P**
Solving time[a]	0.09	1.10	0.15	0.62	0.534
Sex (male)	-0.72	0.49	0.31	-2.35	0.019
Age (juvenile)	1.87	6.50	0.44	4.28	<0.001

Positive coefficients indicate a higher hazard (risk of death), i.e., a lower survival probability. Exponentially transformed coefficients are the hazard ratios and give the effect size on the hazard of predictor variables. Reference categories for categorical predictors are indicated in brackets, SE: Standard error, N= 64.
[a] Covariate was log transformed and afterwards z-transformed to a mean of= 0 and sd= 1; original mean of log(solving time) (sd)= 4.42 (0.93).

Table S12: Results of the Cox proportional hazards model fitting the relationship between test performance in the maze and survival.

Predictor variable	**coeff**	**Exp(coeff)**	**SE(coeff)**	**z**	**P**
Number of errors[a]	-0.04	0.97	0.16	-0.23	0.824
Sex (male)	-0.75	0.47	0.31	-2.45	0.014
Age (juvenile)	1.69	5.41	0.46	3.63	<0.001

Positive coefficients indicate a higher hazard (risk of death), i.e., a lower survival probability. Exponentially transformed coefficients are the hazard ratios and give the effect size on the hazard of predictor variables. Reference categories for categorical predictors are indicated in brackets, SE: Standard error, N= 62.
[a] Covariate was z-transformed to a mean= 0 and sd= 1; original mean (sd)= 14.81 (9.27)

References

Ashton BJ, Ridley AR, Edwards EK, Thornton A. 2018. Cognitive performance is linked to group size and affects fitness in Australian magpies. *Nature* **554**, 364–7. doi:10.1038/nature25503.
Cole EF, Morand-Ferron J, Hinks AE, Quinn JL. 2012. Cognitive ability influences reproductive life history variation in the wild. *Curr Biol* **22**, 1808–12. doi:10.1016/j.cub.2012.07.051.
Cauchard L, Boogert NJ, Lefebvre L, Dubois F, Doligez B. 2013. Problem-solving performance is correlated with reproductive success in a wild bird population. *Anim Behav* **85**, 19–26. doi:10.1016/j.anbehav.2012.10.005.
Evans LJ, Smith KE, Raine NE. 2017. Fast learning in free-foraging bumble bees is negatively correlated with lifetime resource collection. *Sci Rep* **7**, 1–10. doi:10.1038/s41598-017-00389-0.
Hallgren KA. 2012. Computing Inter-Rater Reliability for Observational Data: An Overview and Tutorial. *Tutor Quant Methods Psychol* **8**, 23-34.

Isden J, Panayi C, Dingle C, Madden J. 2013. Performance in cognitive and problem-solving tasks in male spotted bowerbirds does not correlate with mating success. *Anim Behav* **86**, 829–38. doi:10.1016/j.anbehav.2013.07.024.

Keagy J, Savard J-F, Borgia G. 2009. Male satin bowerbird problem-solving ability predicts mating success. *Anim Behav* **78**, 809–17. doi:10.1016/j.anbehav.2009.07.011.

Maille A, Schradin C. 2016. Survival is linked with reaction time and spatial memory in African striped mice. *Biol Lett* **12**, 20160346.

Preiszner B, Papp S, Pipoly I, Seress G, Vincze E, Liker A, Bokony V. 2016. Problem-solving performance and reproductive success of great tits in urban and forest habitats. *Anim Cogn* **20**, 53–63. doi:10.1007/s10071-016-1008-z.

Raine NE, Chittka L. 2008. The correlation of learning speed and natural foraging success in bumble-bees. *Proc R Soc Lond B Biol Sci* **275** (1636), 803–808.

Smith C, Philips A, Reichard M. 2015. Cognitive ability is heritable and predicts the success of an alternative mating tactic. *Proc R Soc Lond B Biol Sci* **282**, 20151046. doi:10.1098/rspb.2015.1046.

Wetzel DP. 2017. Problem-solving skills are linked to parental care and offspring survival in wild house sparrows. *Ethology* **123**, 475–83. doi:10.1111/eth.12618.