Genet. Res., Camb. (1984), **43**, *pp.* 289–298
Printed in Great Britain

The effect of selection on brain and body size association in rats

By WILLIAM R. ATCHLEY

Department of Genetics, University of Wisconsin, Madison, Wisconsin 53706

(*Received 19 July 1983 and in revised form 4 January 1984*)

SUMMARY

Changes in brain size, body size and their covariance are reported from a long-term replicated directional selection experiment on body weight gain in rats. Two strains had been selected for increased and two for decreased weight gain between 3 and 9 weeks of age, and there were two randomly selected control lines. Selection produced significant changes in body weight in all selected lines. Divergence from the controls occurred in brain size in those strains selected for increased weight gain; no significant divergence was found for the strains selected for decreased weight gain. Divergence among unselected control lines suggests that genetic drift occurred in expression of brain size. Sexual dimorphism in response to selection results from sex differences in heritabilities and genetic correlations in relevant traits. In spite of considerable change in body size and brain size, no significant change in their covariation occurred either between the selection lines or between sexes. The relevance of these results to a brain and body size 'scaling effect' during evolutionary divergence is discussed.

INTRODUCTION

Change in cranial capacity is a conspicuous trend in vertebrate evolution. Studies of evolutionary changes in brain size appear frequently in the literature of a number of fields (Jerison, 1973; Sacher & Staffeldt, 1974; Gould, 1966, 1975, 1977; Radinsky, 1977, 1978; Hahn, Jensen & Dudek, 1979; Lande, 1979; Szarski, 1980; Martin, 1981). Many authors have suggested that changes in cranial capacity represent an important measure of evolutionary divergence in primates.

Published studies on evolutionary change in cranial capacity often describe variation in brain size in terms of its covariation with other traits such as body size, rate of development or duration of gestation, by means of the regression equation

$$\log Y = \log a + b \log X,$$

where Y is brain size and X is another trait. This relationship can be (i) *allometric* or *ontogenetic* (relationships between traits in a single growing individual); (ii) *static* or *intraspecific* (between different individuals all at the same stage of growth); or (iii) *interspecific* or *evolutionary* (between different species at the same stage of growth) (Huxley, 1932; Gould, 1966, 1975, 1977; Lande, 1979; Wood, 1978). Many

writers have used the term 'allometry' to include all of these associations and the regression formula given above is often defined as the 'allometry equation' where the coefficient b is the 'allometry coefficient'. In this paper, I have followed a more classical approach and confined the use of the term allometry to ontogenetic relationships; therefore, I use the term 'regression coefficient' instead of 'allometric coefficient' in discussing b.

It is widely held that evolution of brain size has occurred as a correlated response to evolutionary change in other traits. As a result, many studies focus on the quantitative relationship of brain size to body size or other traits within and between taxa, speculate about the underlying causes of the associations, and discuss potential evolutionary consequences. Unfortunately, experimentation to test these evolutionary hypotheses or to estimate rélevant genetic parameters is lacking.

Natural selection for body size or rate of development is a common phenomenon which can produce multivariate evolutionary divergence (Atchley, Rutledge & Cowley, 1982). Altering rates of development is a common mechanism for adaptive change in body size and it is to be expected that change in developmental rate will have diverse morphogenetic consequences including potential effects on brain size.

A prevailing hypothesis is that a 'scaling effect' exists where evolutionary change by selection for increased or decreased body size or rate of development in vertebrates produces correlated change in brain size (Jerison, 1973; Gould, 1975; Lande, 1979). There is a large literature about brain and body size relationships in a variety of animals dating from the early studies of Dubois (1897) and Lapique (1898, 1907). However, Martin (1981) suggested that there is no empirical foundation for the concept of scaling brain size to body size.

This paper examines the following questions. First, is there a significant positive genetic correlation between brain and body size within populations, i.e. existence of the genetic 'scaling effect'? This question can be answered by determining if single trait selection at different intensities or in different directions for body size or rate of development will produce parallel change in brain size. If two traits are genetically correlated, evolutionary change in one trait should produce parallel change in the other. Second, will single trait selection change the degree of correlation between brain and body size? In other words, will the quantitative relationship between brain and body size within taxa be maintained in the face of strong divergent selection for body size or rate of development? Third, do the same quantitative relationships exist within and between taxa undergoing rapid and divergent evolutionary change?

METHODS AND MATERIALS

A long-term replicated selection experiment was carried out on rats where selection was practiced on body weight gain between 3 and 9 weeks of age (Baker & Chapman, 1975; Baker, Chapman & Wardell, 1975; Atchley & Rutledge, 1980). Body weight gain in rodents is a highly heritable trait and is correlated genetically and phenotypically with body size (Atchley, 1983, 1984; Riska, Atchley &

Rutledge, 1984). In this paper, body weight is equated to body size. A cross of 4 inbred lines of rats comprised the original founding population and 6 separate genetic stocks were then produced from randomly chosen progeny. Selection within families was carried out for 23 generations for increased weight gain (U_1, U_2), for decreased weight gain (D_1, D_2), and random selection constituted the controls (R_1, R_2) (Baker & Chapman, 1975; Baker *et al.* 1975; Atchley & Rutledge, 1980). Attempted effective population number for each replicate at each generation was 72. For the results reported here, sample sizes were U_1 (67), U_2 (87), D_1 (73), D_2 (67), R_1 (138), and R_2 (86) for a total of 518 rats. Litters from 100 families were standardized at birth to 3 male and 3 female progeny and the pups raised in a crossfostering design where a random half of each litter was nursed by an unrelated dam which had pupped on the same day (Atchley & Rutledge, 1980). Forced weaning occurred at 21 days.

All rats were weighed at 189 days of age, sacrificed, and skeletonized. Brain size was determined by filling the brain case with alfalfa seeds and the seeds weighed to the nearest one-hundredth of a gram. Brain size was measured twice on each rat and repeatability was over 97 %.

All data were transformed to logarithms to the base 10 prior to analysis. Narrow-sense heritability and genetic correlation estimates are computed for brain and body size based on the linear model and statistical procedures described by Atchley & Rutledge (1980). Because of the size limitations of this experiment, genetic parameters could not be estimated for each line and sex combination. Thus, assessment of the effects of selection on the genetic variances and genetic covariances is not possible. Therefore, estimates of the heritabilities and genetic correlations for each sex are reported where the data have been corrected for the effects of selection. By correcting for the effects of selection, the results should estimate the genetic parameters in the randomly-selected control animals. While the heritability and genetic correlation values computed in this manner are only estimates of the population parameters for the original base population, they do provide considerable insight into the results obtained in this particular selection experiment.

Bivariate relationships between brain and body size were analysed by a least squares regression model

$$\log \text{brain size} = \log a + b \log \text{body weight},$$

where brain and body weight always refer to 189 days of age. Tests for the homogeneity of regression slopes were carried out using the procedure described by Zar (1974).

Phenotypic regression coefficients were calculated (i) within each sex and genetic strain; (ii) between sexes within strains; and (iii) between strains, i.e. based on the brain and body size means for the various genetic stocks. The divergence in body weight produced in this selection experiment is considered similar in magnitude to that found between different species, so that the between-strain regression can be given an evolutionary interpretation.

RESULTS

Strain divergence

Table 1 provides means and standard deviations of $\log_{10}$ body weight and $\log_{10}$ brain size at 189 days of age for each sex and stock and the analysis of variance of strain differences. The sexes differ significantly at $P < 0{\cdot}01$ for both brain and body size in each replicate and genetic strain. The degree of divergence between the sexes is consistent over the six strains. For log body weight, the average sex difference and its standard deviation is 0·21 (±0·02) while that of brain size is 0·03 (±0·01).

Table 1. *Log body weight, log brain size and their standard deviations for 6 genetic strains of laboratory rats at 189 days of age*

(Results of a protected LSD test are given at the bottom of the table. Strains not differing from each other for log body weight or log brain size at $P < 0{\cdot}05$ are underlined.)

	Males			Females		
Strain	Body weight	Brain size	*N*	Body weight	Brain size	*N*
U_1	2·644±0·038	0·217±0·025	33	2·413±0·045	0·185±0·025	34
U_2	2·651±0·038	0·237±0·022	42	2·429±0·024	0·196±0·018	48
R_1	2·566±0·046	0·187±0·026	69	2·350±0·050	0·152±0·025	69
R_2	2·501±0·034	0·148±0·019	44	2·301±0·033	0·121±0·024	44
D_1	2·519±0·060	0·160±0·028	35	2·302±0·078	0·122±0·022	40
D_2	2·444±0·038	0·153±0·027	37	2·261±0·028	0·130±0·021	33

Log body weight

Males						Females					
$\underline{U_1}$	$\underline{U_2}$	R_1	$\underline{D_1}$	$\underline{R_2}$	D_2	U_2	U_1	R_1	$\underline{D_1}$	$\underline{R_2}$	D_2

Log brain size

U_2	U_1	R_1	$\underline{D_1}$	$\underline{D_2}$	$\underline{R_2}$	U_2	U_1	R_1	$\underline{D_2}$	$\underline{D_1}$	$\underline{R_2}$

Estimates of genetic parameters in data corrected for the effects of selection suggest considerable sexual dimorphism in that males consistently show higher heritabilities. The heritability of log brain size at 189 days in males is 0·64 (±0·23) while for females the value is 0·36 (±0·18). Log body weight heritabilities at 14 and 189 days of age in males were 0·61 (±0·19) and 0·81 (±0·26). For females, these values are 0·29 (±0·14) and 0·29 (±0·20). The heritability of 14 day weight is also the heritability of body weight gain prior to 14 days of age (Riska *et al.* 1984). The genetic correlation between log brain size at 189 days with log body weight at these three intervals in males is 0·65 (±0·14) and 0·44 (±0·18). In females, the correlations are 0·36 (±0·30) and −0·44 (±0·46).

The genetic correlation not different from zero between brain and body size at 189 days in females of these rats results from a marked phase of compensatory growth in body weight in females which occurs over a several week period beginning at about 28 days of age. The compensatory growth phenomenon is

described in detail by Atchley (1984) and Riska *et al.* (1984). The impact of sexual dimorphism in genetic parameters on brain and body size evolution in these organisms is considered in the Discussion of this paper.

Body weight. Males of the up-selected lines are 3·5 standard deviation units larger while the down-selected strains are 1·3 units smaller than the controls (Atchley *et al.* 1982). Up-selected females are 1·4 standard deviation units larger than the controls while the down-selected rats are 1 unit smaller. Asymmetry in response to selection in different directions within a sex is not uncommon and the underlying causes are described by Falconer (1981). Sexual dimorphism in response to selection in this instance probably stems from sex differences in additive genetic variance and heritability for body weight (Atchley, 1984).

Up-selected replicates do not differ from each other in males but do in females. Down-selected replicates differ significantly as do the random replicates. Lines R_2 and D_1 unfortunately do not differ significantly from each other but both are significantly below the other random replicate, R_1, and above the other down-selected replicate, D_2. Strains R_2 and D_1 differ in 9 week weight in both sexes, i.e. at the end of the selection period; however, by 189 days of age, these differences have become less marked (Atchley & Rutledge, 1980; Atchley *et al.* 1982).

An examination of growth curves for body weight showed rats in all strains reach the period of maximum growth rate (inflection point of the growth curve) at approximately the same time. However, at the inflection point, the up-selected rats (U_1, U_2), are much heavier than the controls while the down-selected strains (D_1, D_2) weigh considerably less.

Brain size. For log brain size, the up-selected lines differ significantly from the controls. One control line (R_1) is significantly greater than the down-selected lines but there is no significant difference among D_1, D_2 and R_2 in either sex at 189 days of age (Table 1). The up-selected lines diverge from the controls by about 2·5 standard deviation units in each sex. Thus, significant correlated divergence in brain size clearly occurs in the up-selected rats but less clearly in the down-selected rats. Replicates R_1 and R_2 differ significantly and the divergence must have occurred as a result of genetic drift over the duration of the experiment.

Regression analyses

Within strains and sexes. Regression coefficients of log brain size on log body weight size at 189 days of age for each sex are given in Table 2. In males, the values range from 0·46 ($\pm$0·08) for U_1 to 0·15 ($\pm$0·08) for D_1 and all except D_1 differ from zero at $P < 0·05$. There is no significant difference between replications of the same selection regime.

For females, the coefficients vary from 0·30 ($\pm$0·08) in U_1 to 0·08 ($\pm$0·06) in R_1. Only 3 strains have regression coefficients significantly different from zero, i.e. U_1 ($P < 0·01$), D_1 and D_2 (both $P < 0·05$). There is no significant difference between replications of the same selection regime. There is no significant sex difference within any one strain with regard to the regression coefficient, e.g. U_1 (males) with U_1 (females). However, the average regression for males (0·30) is greater than the average value for females (0·13).

A test for homogeneity of regression coefficients indicates no significant difference

among genetic strains in females and the average coefficient is 0·13. In males, however, there is statistical heterogeneity among the coefficients with U_1, U_2, R_2, and D_2 being homogeneous and differing from R_1 and D_1. The average coefficient for the first 4 taxa is 0·37. The ranked order of the coefficients is identical in the two sexes except for D_1 in females. There is no statistical difference in regression coefficients between replicates U_1 and U_2, R_1 and R_2 nor between D_1 and D_2. The divergence of R_1 and D_1 from the remaining taxa in males may be due, in part, to stochastic effects such as genetic drift.

Table 2. *Phenotypic regression coefficients (b) and their standard errors of log body size and log brain size at 189 days of age in 6 genetic strains of laboratory rats*

(Results of tests for homogeneity of regression coefficients are given at the bottom of the table. Strains not differing from each other at $P < 0{\cdot}05$ are underlined.)

Strain	Males	Females
U_1	0·46 ± 0·08	0·30 ± 0·08
U_2	0·30 ± 0·08	0·10 ± 0·11
R_1	0·17 ± 0·07	0·08 ± 0·06
R_2	0·35 ± 0·07	0·12 ± 0·11
D_1	0·15 ± 0·08	0·11 ± 0·05
D_2	0·37 ± 0·10	0·27 ± 0·13

Males

$\underline{U_1 \quad D_2 \quad R_2 \quad U_2} \quad R_1 \quad D_1$

Females

$\underline{U_1 \quad D_2 \quad R_2 \quad D_1 \quad U_2 \quad R_1}$

Between strain regression. Regression analysis of the strain means gives an equation for males of

$$\log \text{brain size} = -0{\cdot}90\ (\pm 0{\cdot}19) + 0{\cdot}42\ (\pm 0{\cdot}07) \log \text{body weight},$$

and for females

$$\log \text{brain size} = -0{\cdot}93\ (\pm 0{\cdot}18) + 0{\cdot}46\ (\pm 0{\cdot}08) \log \text{body weight}.$$

For both sexes, the coefficient differs from zero at $P < 0{\cdot}01$. A test for homogeneity of the regression coefficients in the two sexes indicates they do not differ significantly and the average coefficient is 0·44 (± 0·07).

Lande (1979) raised the important question of whether the regression coefficient within groups differs significantly from the coefficient between groups, i.e. do the same relationships hold within and between taxa. For females in this experiment, the average regression coefficient within groups differs from the between groups coefficient at $P < 0{\cdot}01$. The average coefficient within all male taxa differs from the between groups coefficient at $P < 0{\cdot}001$. However, those 4 taxa in males which are statistically homogeneous, i.e. U_1, U_2, R_2, and D_2, do not differ significantly from the between groups coefficient.

Between sex regressions. As noted earlier, there are consistent statistical differences

https://doi.org/10.1017/S0016672300026070 Published online by Cambridge University Press

between sexes for both brain and body size. However, we must inquire about the effect of selection on the covariance between sexes. The regression coefficient between sexes is estimated here as $(Y_M - Y_F)/(X_M - X_F)$ where Y_M = mean log brain size in male and X_F = mean log body size in females. The regression coefficients are quite stable ranging from 0·13 for D_2 to 0·18 for U_2. The average coefficient and its standard deviation is 0·15 ($\pm$0·02).

To examine the effects of selection on the brain:body size association, I estimated relative brain size, y_{ij}, for the ith replicate and jth sex such that

$$y_{ij} = Y_{ij} - X_{ij},$$

where Y and X are as described in the previous paragraph. Thus, y provides an estimate of the log of brain size relative to body size. Divergence in y in up-selected from randomly-selected rats is −0·054 and −0·042, for males and females, respectively. The divergence of down-selected from randomly-selected rats is 0·041 and 0·034, for males and females, respectively. Divergence in relative brain size between sexes within replicates computed as y_{males} minus y_{females} is −0·190 for up-selected, −0·177 for randomly-selected and −0·170 for down-selected.

These results, together with the between-strain regression slope being less than unity, suggests that the up-selected strains have acquired relatively smaller brains than the down-selected strains in both sexes. Further, males have smaller brains per unit of body weight than females.

DISCUSSION

These overall results indicate that selection for differential body weight gain between 3 and 9 weeks produced significant divergence among strains in adult body weight. In three strains, there is significant divergence in adult brain size as well. Twenty-three generations of directional selection for rate of body weight gain generated a correlated increase of about 2·5 standard deviation units in brain size in those rats selected for increased weight gain. Evidence of genetic drift in brain size is noted between the replicates of the randomly selected lines. Genetic drift is commonly observed between replicates in long-term selection experiments.

Within the power of this experiment to detect differences, selection for rate of development did not alter significantly the regression relationships between brain and body size among the various taxa. The results suggest some divergence possibly due to genetic drift, but there is no evidence of a clear-cut phenotypic change in regression coefficients due to selection for rate of development in body size.

Initially, I set out to test three specific hypotheses about brain and body size relationships. First, is there a significant genetic correlation within strains between brain size and body size? The results of the present selection experiment, together with the selection experiment of Roderick, Wimer & Wimer (1976), indicate a significant genetic correlation between brain and body size because, at least in some of the strains, there is a parallel change in both brain and body size when selection is carried out on body size and rate of development. A genetic analysis indicates that the genetic correlation is highest early in development when brain and body

size are both undergoing simultaneous rapid growth (Atchley *et al.* in preparation). The reason for the absence of significant divergence in brain size between the down-selected strains and one of the control lines is unclear at the present time, although this may have been due to random genetic drift. However, it is also possible that the potential decrease in brain size correlated with smaller body size is being counteracted by some minimal physiological value whose identity is not known at this time.

The second question dealt with the effect of single trait selection on the correlation between that trait and a related one within the selected populations. The present analysis suggests no significant phenotypic change has occurred in the regression relationships of the two traits during the course of selection. These phenotypic results are in agreement with several previous studies on the effect of selection on correlation structure (for references, see Lande, 1979). Unfortunately, we do not have the necessary experimental data or statistical power to examine the more relevant question of whether the selection altered the genetic correlation in the various lines.

Finally, with regard to the question of homogeneity of the regression relationship within and between taxa, there is a sexually dimorphic result. The coefficients within a taxon for females differ significantly from those between taxa, while in males the within taxon slopes for 4 taxa do not differ from the between taxa slope.

There is sexual dimorphism in divergence in body weight and its covariance with brain size. Males exhibit greater response to selection for body weight and rate of development. Further, selection appears to have produced smaller brains per unit body weight in males compared to females, and males exhibit more diversity in the regression coefficients between brain and body size. Some of these results are at least partially explained by the sexual dimorphism in genetic variances and correlations.

The level of direct response to selection by a single trait, X, (DR_X) is defined by

$$DR_X = ih_X^2 s_p,$$

where i = the intensity of selection, h_X^2 = the heritability of trait X and s_p = the phenotypic standard deviation. The correlated response in some other trait, Y, ($CR_{Y.X}$) is given by

$$CR_{Y.X} = ih_X h_Y r_G s_p,$$

where r_G = the genetic correlation between X and Y and s_p in this instance relates to trait Y (Falconer, 1981).

In these rats, males have heritabilities almost twice those of females for log body weight at 189 days and rate of weight gain prior to 14 days of age. The magnitude of the genetic variance for log body weight is considerably higher in males between 14 and 189 days of age (Atchley, 1984). Thus, it is not surprising that a greater response to selection for body weight and weight gain occurs in males.

With regard to the covariance between brain and body size, Kobayashi (1963) has shown that the rat brain reaches maturity by approximately 14 days of postnatal growth after which time little change in size occurs. Thus, the amount of genetic variance for rate of early development together with the genetic correlation between brain and body weight early in postnatal development are very

important in defining any subsequent association between these traits. Reiterating the dimorphism in genetic statistics given previously, the heritability of body weight gain prior to 14 days of age is 0·61 (±0·19) in males but only 0·26 (±0·12) in females. Further, the heritability of mature brain size is almost twice as large in males as in females (0·64 (±0·23) versus 0·36 (±0·18)). Finally, the genetic correlation between mature brain size (189 days of age) and body weight gain prior to 14 days of age is 0·65 (±0·14) in males and 0·36 (0±0·03) in females.

Using the formula for correlated response to selection and setting the intensity of selection and the phenotypic standard deviation each equal to unity, the sexual differences in expected correlated response to selection in brain size are evident. If selection is focused on body weight gain prior to 14 days of age when almost all of brain growth occurs, the expected correlated response in males is 0·50 but only 0·18 in females. If selection is focused on 21 day body weight then the expected correlated response in brain size in males is 0·41 and females is 0·20. Thus, in each instance, the expected response in females is only half that for males. Selection for weight gain may also be selection for gain in previous intervals since body weight at any particular time is the sum of previous correlated gains. Thus, selection for 3–9-week body weight gain, which was the selection criterion in this experiment, would also include a component for rate of development up to 14 days of age. The latter is the interval when the brain develops. These differences in expected correlated response may explain the lack of statistical divergence in within strain regression slopes in females relative to that seen in males.

In conclusion, these results provide experimental evidence for the genetic relationship between rate of development, body size and brain size. There would seem to be a significant genetic component to a 'scaling effect' relationship between body size and brain size. Selection for changes in rate of development and body size tends to produce parallel changes in brain size, at least in some of the genetic strains of rats examined here.

I am indebted to my colleagues Bruce Riska and J. J. Rutledge for their helpful discussions on this topic. Maria Van Horn recorded the brain data. Bruce Riska, Ken Bennett, Jennifer Kitchell, and Judy Silverstein provided critical comments on the manuscript. I am grateful to an anonymous reviewer for making several suggestions to improve the manuscript. The research was supported by grants from the National Science Foundation (DEB-7906058 and DEB-8109904) and by the College of Agriculture and Life Sciences of the University of Wisconsin, Madison. Contribution number 2732 from the Department of Genetics, University of Wisconsin.

REFERENCES

Atchley, W. R. (1983). Some genetic aspects of morphometric variation. In *Numerical Taxonomy* (ed. J. Felsenstein), pp. 346–363. Berlin: Springer-Verlag.

Atchley, W. R. (1984). Ontogeny, timing of development and genetic variance-covariance structure. *American Naturalist* **123**, 519–540.

Atchley, W. R. & Rutledge, J. J. (1980). Genetic components of size and shape. I. Dynamics of components of phenotypic variability and covariability during ontogeny in the laboratory rat. *Evolution* **34**, 1161–1173.

Atchley, W. R., Rutledge, J. J. & Cowley, D. E. (1981). Genetic components of size and shape. II. Multivariate covariance patterns in the rat and mouse. *Evolution* **35**, 1037–1055.

Atchley, W. R., Rutledge, J. J. & Cowley, D. E. (1982). A multivariate statistical analysis of direct and correlated response to selection in the rat. *Evolution* **36**, 677–698.

BAKER, R. L. & CHAPMAN, A. B. (1975). Correlated response to selection for postweaning gain in rats. *Genetics* **80**, 191–203.

BAKER, R. L., CHAPMAN, A. B. & WARDELL, R. T. (1975). Direct response to selection for postweaning gain in the rat. *Genetics* **80**, 171–189.

DUBOIS, E. (1897). Sur le rapport du poids de l'encéphale avec la grandeur du corps chez les mammifères. *Bulletin de la Société d'anthropologie de Paris* **8**, 337–376.

FALCONER, D. S. (1981). *Introduction to Quantitative Genetics*, 2nd ed. London: Longman.

GOULD, S. J. (1966). Allometry and size in ontogeny and phylogeny. *Biological Reviews* **41**, 587–640.

GOULD, S. J. (1975). Allometry in primates, with emphasis on scaling and the evolution of the brain. *Contributions in Primatology* **5**, 244–292.

GOULD, S. J. (1977). *Ontogeny and Phylogeny*. Cambridge: Belknap Press.

HAHN, M. E., JENSEN, C. & DUDEK, B. C. (eds.) (1979). *Development and Evolution of Brain Size*. New York: Academic Press.

HUXLEY, J. S. (1932). *Problems of Relative Growth*. London: MacVeagh.

JERISON, H. J. (1973). *Evolution of Brain Size and Intelligence*. New York: Academic Press.

KOBAYASHI, T. (1963). Brain-to-body ratios and time of maturation of the mouse brain. *American Journal of Physiology* **204**, 343–346.

LANDE, R. (1979). Quantitative genetic analysis of multivariate evolution applied to brain: body size allometry. *Evolution* **33**, 402–416.

LAPIQUE, L. (1898). Sur la relation du poids de l'encéphale au poids du corps. *Comptes rendus de la Société de biologie filiales* **50**, 62–63.

LAPIQUE, L. (1907). Tableau générale des poids somatiques et encéphaliques dans les espèces animales. *Bulletin de la Société d'anthropologie de Paris* **8**, 248–262.

MARTIN, R. D. (1981). Relative brain size and basal metabolic rate in terrestrial vertebrates. *Nature* **293**, 57–60.

RADINSKY, L. (1977). Brains of early carnivores. *Paleobiology* **3**, 333–349.

RADINSKY, L. (1978). Evolution of brain size in carnivores and ungulates. *American Naturalist* **112**, 815–831.

RISKA, B., ATCHLEY, W. R. & RUTLEDGE, J. J. (1984). A genetic analysis of targeted growth in mice. *Genetics*. (In the Press.)

RODERICK, T. H., WIMER, R. E. & WIMER, C. C. (1976). Genetic manipulation of neuroanatomical traits. In *Knowing, Thinking and Believing* (eds. L. Petrinovich and J. L. McGaugh). New York: Plenum Press.

SACHER, G. A. & STAFFELDT, E. F. (1974). Relation of gestation time to brain weight for placental mammals: Implication for the theory of vertebrate growth. *American Naturalist* **108**, 593–616.

SZARSKI, H. (1980). A functional and evolutionary interpretation of brain size in vertebrates. *Evolutionary Biology* **13**, 149–174.

WOOD, B. A. (1978). Allometry and hominid studies. In *Geological Background to Fossil Man* (ed. W. W. Bishop), pp. 125–138.

ZAR, J. H. (1974). *Biostatistical Analysis*. Englewood Cliffs: Prentice-Hall.