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Paleoneurological Studies in Honor of Ralph L. Holloway
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NUMBER 4

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THE HUMAN BRAIN EVOLVING:

Paleoneurological Studies
in Honor of Ralph L. Holloway



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FRONT COVER CAPTIONS

Center: Portrait of Ralph L. Holloway.

Upper left: A modern human brain.

Upper right: Ralph measuring landmarks on an endocast ca. 1976.

Lower right: Homo habilis cranium KNM-ER-1813 from Koobi Fora, Kenya (photo by Holloway).

Lower left: Ralph with an endocast of the Flores "hobbit" cranium.

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CHAPTER 2

THE MATERNAL ENERGY HYPOTHESIS OF BRAIN EVOLUTION: AN UPDATE

ROBERT D. MARTIN AND KARIN ISLER

ABSTRACT

Bivariate scaling analyses can reveal interesting correlations between individual biological variables, but inference of actual causal links in complex networks requires multiple tests to satisfy the criterion of isolation. Mammalian brain tissue has high energy demands, so energy supply is inevitably a key issue in evolution of the primate brain, especially for large-brained hominids. Various hypotheses have proposed a direct link between brain size and metabolic turnover in adults, but the author's Maternal Energy Hypothesis (MEH) instead focuses on energy supplied by the mother during brain development up to weaning. This hypothesis is supported by various empirical findings, but it has also been challenged, particularly on the basis that these findings do not survive tests conducted to eliminate effects of phylogenetic inertia. New comparative analyses of brain size in mammals with improved datasets have, however, confirmed links to both basal metabolic rate and gestation period, complying with core predictions of MEH. The evidence now available in support of MEH is reviewed and some implications for brain evolution are explored. A widely recognized general trend towards increase in average relative brain size during mammalian evolution has recently been challenged by a study of brain size in bats that inferred, exclusively through analysis of data from extant species, that brain size has actually undergone reduction in numerous lineages. It is shown that the statistical test used to test for directionality of evolution was inappropriate. A review of fossil evidence for brain evolution in primates, cetaceans and carnivores confirms the generally accepted trend towards increased average brain size through the Tertiary. Progressive increase in

mammalian relative brain size over time is at least partially attributable to increases in the level and efficiency of maternal investment. Energetic aspects, including those invoked in the MEH, are of special importance for outstandingly large-brained mammals such as hominids.

INTRODUCTION

Analysis of non-linear scaling relationships between individual variables and body size (allometric analysis) is now a standard tool in biology. The basic approach is bivariate analysis in which the X -axis is usually some measure of body size (e.g. body mass) and the Y -variable is a parameter of interest (e.g. brain mass). The standard allometric scaling formula is a power function $Y = kX^\alpha$, in which α is the scaling exponent and k is the scaling coefficient. Scaling relationships can be examined both within species (growth allometry; intraspecific scaling among adults) and between species (interspecific allometry). In the following text, attention will be directed exclusively at interspecific allometric relationships in which paired X and Y values represent means for individual species. A classic example of such an allometric relationship is provided by the scaling of basal metabolic rate (BMR) to body mass across placental mammal species, for which an empirically determined scaling exponent value of 0.75 is now widely (although not universally) accepted. Logarithmic conversion of the two variables transforms the scaling formula into a linear relationship with the equation $\log Y = \alpha * \log X + \log k$, such that the values of α and k can be determined by fitting a best-fit line. Basic concepts, methods and issues in allometric analysis have been extensively reviewed elsewhere (e.g. Gould, 1966, 1975; Harvey and Mace,

1982; Schmidt-Nielsen, 1984; Martin, 1989; Martin and Barbour, 1989; Reiss, 1989; Harvey and Pagel, 1991; Martin et al., 2005; Bonner, 2006).

Despite the relative simplicity of the standard bivariate approach to allometric scaling, it has been progressively recognized that allometric analysis is beset with complex problems. Three such problems involve statistical issues. The first of these, choice of an appropriate best-fit line, has long been recognized and is covered by an extensive literature. The least-squares regression is most widely used to determine a best-fit line in allometric analysis, but it entails two basic assumptions that are unlikely to be met with interspecific datasets: (1) The X -variable is measured without error; (2) The Y -variable is clearly dependent on the X -variable. For this reason, various authors have preferred to use alternative approaches that avoid these assumptions, such as the major axis or reduced major axis. However, the basic model underlying all of these parametric line-fitting techniques (least-squares regression, reduced major axis and major axis) is the bivariate normal distribution, yet interspecific datasets commonly do not conform to such a distribution. For this reason, a non-parametric, iterative method was developed as an alternative for fitting a line to bivariate data in allometric analyses (Isler et al., 2002).

A second widespread problem that has regrettably received far less attention is the potential existence of structural heterogeneity in datasets. Quite often, individual subsets in a sample of species show different scaling relationships, commonly showing similar values for the allometric exponent (α) but dissimilar values for the allometric coefficient (k). Separate scaling relationships for such subsets can be referred to as grades, and vertical separation of best-fit lines for those subsets in a bivariate plot can be said to involve grade distinctions or shifts. An illustrative example is provided by scaling of BMR in marsupials and placentals. The best-fit line for marsupials has essentially the same slope as that for placentals ($\alpha \approx 0.75$ in both cases), but the value of the allometric coefficient is lower. In other words, marsupials generally tend to have a lower BMR value at any given body mass than placentals. On average, for any given body mass the basal energy consumption of a marsupial will be about 30-35% less than that of a placental (MacMillen and Nelson, 1969; Dawson and Hulbert, 1970; Martin, 1990). Numerous examples of such grade distinctions are known, but there is no widely recognized method for their objective detection in any given dataset. As a rule, grade distinctions are identified in practice because the investigator decides to conduct separate analyses for selected subsets of data (e.g. for taxonomic groups suspected on *a priori* grounds to be potentially divergent with respect to the variable investigated). In primates, for instance, it is well known that there are several fundamental differences between strepsirrhines (lemurs and lorisiforms) and haplorhines (tarsiers and higher primates). It is therefore advisable to check for grade distinctions between these two groups in any analysis of

allometric scaling in primates.

In fact, the non-parametric line-fitting method reported by Isler et al. (2002) has an incidental benefit in providing a direct indication of the existence of clear-cut grades in a given dataset (Martin et al., 2005). This property was explored with respect to distinct grade distinctions in the scaling of gestation period in placental mammals and of neonatal body mass in primates. With the former, placental mammals with well-developed precocial offspring generally have distinctly longer gestation periods relative to adult body mass than those with poorly developed altricial offspring. With the latter, among primates, individual neonatal body mass relative to maternal mass is distinctly greater in haplorhines than in strepsirrhines. However, the signal yielded by the non-parametric line-fitting method is weak even in cases where such clearly marked grades are present, underlining the difficulty facing objective detection of grade distinctions within a dataset. Failure to recognize the existence of grades within a dataset can lead to erroneous interpretations, as a single best-fit line determined for an entire dataset will usually indicate substantially different values for α and k compared to those inferred for the individual grades. In the case of gestation periods in placental mammals, for example, the empirical value for α indicated by a line fitted to the entire sample is ≈ 0.25 , whereas separate best-fit lines for altricial and precocial mammals yield an α value of ≈ 0.15 . It is reasonable to regard the latter as biologically meaningful and the former as an artefact arising from grade confusion.

A third, relatively recently recognized statistical problem involved in interspecific allometric studies is a potential biasing influence exerted by phylogenetic relatedness. As noted in a seminal paper by Felsenstein (1985), data points for individual species may not be statistically independent because of their differential degrees of relatedness within the phylogenetic tree. In principle, phylogenetic inertia might distort empirically determined scaling relationships. A possible remedy for this potential problem is calculation and analysis of differences (“independent contrasts”) between values for sister taxa in the phylogenetic tree (Harvey and Pagel, 1991; Purvis and Rambaut, 1995). This method is now widely used, but it has a number of drawbacks (Martin et al., 2005). In particular, the method of calculation leads to marked exaggeration of effects of error terms in the data (Ricklefs and Starck, 1996). Ironically, because closely related species tend to have very similar body mass and hence similar values for any correlated variables, a comprehensive sample with many sister taxa will generate contrast values in which error terms are particularly prevalent. As there is no means of distinguishing between measurement error and “error” due to adaptive biological deviation from an idealized scaling relationship, the implications for analyses conducted using independent contrasts are difficult to decipher. However, one practical conclusion that can be drawn is that adequate monitoring of data quality to reduce observa-

tional errors to a minimum is absolutely crucial for any analysis using independent contrasts.

Quite apart from these three largely statistical problems, particular caution is required in any attempt to infer causality from any correlations that emerge from scaling analyses. It cannot be emphasized enough that correlation should not be simply equated with causality. Moreover, the value of the correlation coefficient (r) for a bivariate relationship is not a reliable guide to the likelihood of a direct causal link between the variables concerned. In any biological context, one very good reason for this is that networks of variables are commonly involved, such that analysis of just two variables in isolation may well yield a statistically strong correlation in the absence of any underlying causal link. An exquisite example of invalid extension from correlation to causality is provided by a report that the frequency of citation of authors declines across the alphabetical sequence of surnames (Tregenza, 1997). The title of that report (“Darwin a better name than Wallace?”) playfully reflected the inference that the observed significant negative correlation reflected some causal connection. However, it was subsequently pointed out that the frequency of surnames beginning with any given letter also declines across the alphabetical sequence. Once this confounding factor is taken into account, the apparent correlation between the alphabetical sequence of surnames and citation frequency becomes non-significant (Shevlin and Davies, 1997). The authors of that rectification emphasized the importance of compliance with the criterion of isolation (i.e. excluding all potential confounding variables) when attempting to proceed from observed correlation to inference of a likely causal relationship. One useful approach in tackling networks of biological variables is analysis using partial correlations, which can theoretically permit identification of a persistent correlation between any two variables after excluding the effects of all others. However, the success of such an approach depends upon reliable identification of all variables that should be considered in the analysis.

THE MATERNAL ENERGY HYPOTHESIS

Formulation of the Maternal Energy Hypothesis (MEH) with respect to the relationship between brain size and body size in placental mammals (Martin, 1981, 1983) was initially prompted by two complementary sets of findings: (1) The scaling relationship between brain and body size in placental mammals is comparable to that for basal metabolic rate (BMR). (2) There are convincing indications of a link between brain size and gestation. Hofman (1983a) reached similar conclusions from these same lines of evidence. The brain is unusual compared to most other bodily organs in that most of its growth is achieved relatively early in ontogeny. In all mammals, a large part of brain development is completed by weaning, so it is clearly heavily dependent on resources provided by the mother. Accordingly, the

MEH postulates that the size of the brain in an adult may be linked not to that individual’s own BMR but to that of its mother (Figure 1).

It was long held that the empirical exponent value for the scaling relationship between brain size and body size is ≈ 0.67 (von Bonin, 1937; Jerison, 1973; Gould, 1975). An exponent value of $2/3$ was interpreted as indicating some kind of connection between brain size and body surfaces, fitting the interpretation that brain size is linked to information flow to and from surface effectors and/or receptors. Interestingly, it had also been argued in earlier studies that the exponent value for scaling of basal metabolic rate to body size is ≈ 0.67 (Rubner, 1883). This was similarly interpreted as reflecting a relationship to body surface area. However, analysis of larger, improved datasets revealed that the value of the scaling exponent for BMR is actually ≈ 0.75 , although small-bodied mammals are a special case (Brody and Procter, 1932; Brody, 1945; Kleiber, 1932, 1947, 1961; Hemmingsen, 1960; Schmidt-Nielsen, 1984; McNab, 1986, 1988). In comparable fashion, analysis of expanded datasets for placental mammal species eventually revealed that the exponent for brain:body size scaling actually has an empirical value of ≈ 0.75 , similar to that for basal metabolic rate (Bauchot, 1978). For instance, Martin (1981) reported the following scaling formula derived by fitting a major axis to data for 309 placental mammal species:

$$\log_{10} E = 0.76 * \log_{10} P + 1.77 \quad (r = 0.96)$$

(where E = brain mass in mg and P = body mass in g)

Broadly similar findings were reported from a series of other studies (e.g. Eisenberg, 1981; Armstrong, 1982, 1983, 1985, 1990; Hofman, 1982, 1983a,b). The sample analysed by Martin (1981) was subsequently expanded to 477 species, yielding a closely similar result (Martin, 1998):

$$\log_{10} E = 0.77 * \log_{10} P + 1.66 \quad (r = 0.98)$$

(where E = brain mass in mg and P = body mass in g)

For comparability with other studies, this formula can be converted into the following form using natural logarithms and g instead of mg for brain mass:

$$\log_e E_M = 0.77 * \log_e P - 3.08$$

(where E = brain mass in g and P = body mass in g)

Most recently, a greatly enlarged dataset including 1129 placental mammal species from all 18 extant orders (Isler and van Schaik, in review) has almost tripled the available sample size. Analysis of this expanded dataset, taking the reduced major axis as a best-fit line (Figure 2), yields a result very close to those reported by Martin (1981, 1998):

$$\log_e E = 0.77 * \log_e P - 3.03 \quad (r = 0.98)$$

(where E = brain mass in g and P = body mass in g)

It is hence established beyond reasonable doubt that the empirical value of the scaling exponent for the relationship between brain mass and body mass across placental mammals, taking raw data for individual species, exceeds 0.67 and is ≈ 0.75 . However, it could be argued

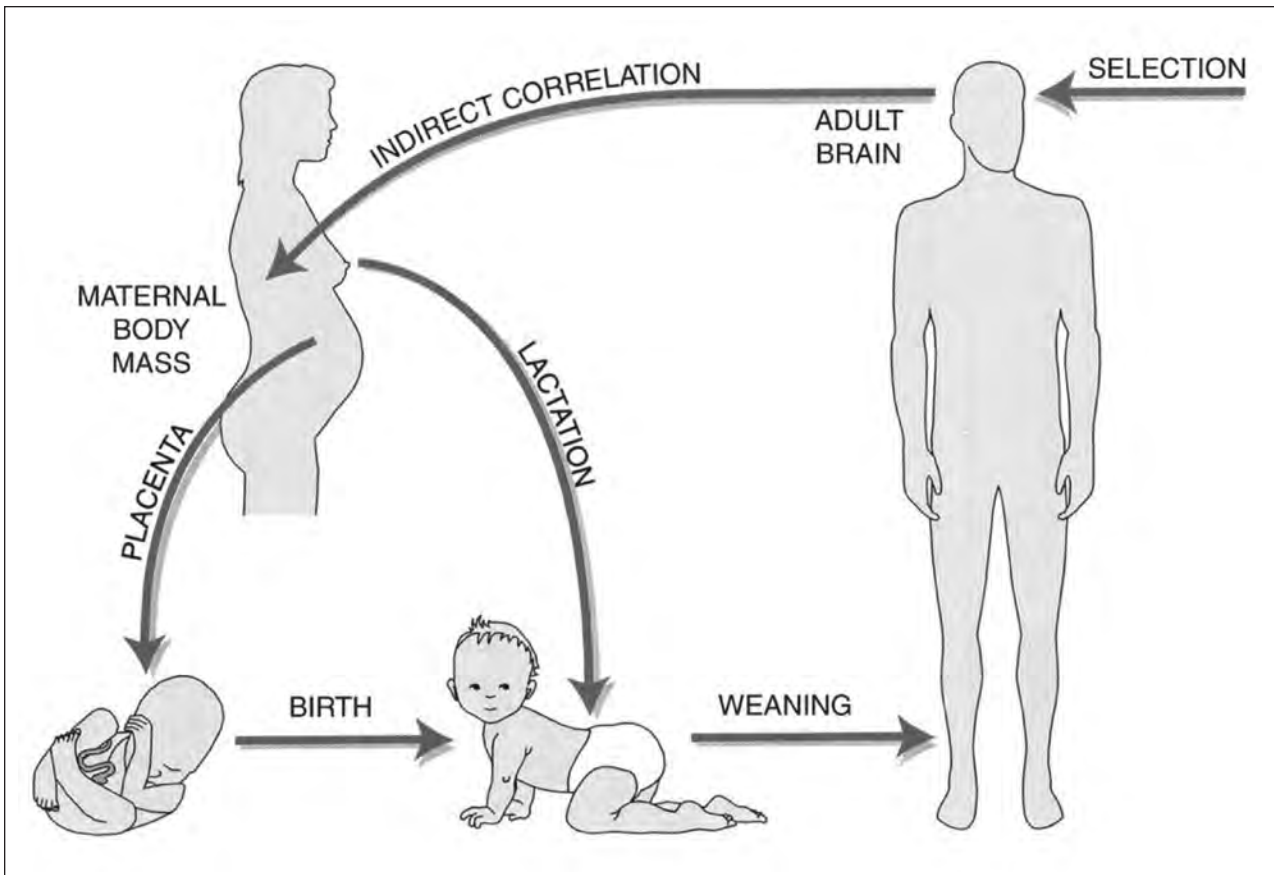


Figure 1 Schematic illustration of the Maternal Energy Hypothesis (MEH). Maternal resources provide for brain development prenatally via the placenta throughout gestation and postnatally through lactation up until the time of weaning. The eventual size of the adult brain is then determined by limited post-weaning growth. Correlations between brain size in an adult individual and other variables such as basal metabolic rate may hence be indirect, reflecting the body size of the mother rather than the body size of the adult itself. In addition to the mother's metabolic capacity, the eventual size of the adult brain can be influenced by variables such as gestation period and the duration of lactation.

that this result is biased by over-representation of particular orders of mammals. Bats ($n = 315$) and rodents ($n = 340$) together make up over half of the sample of 1129 placental mammal species, while at the other extreme 8 orders are represented by only 1-4 species (Dermoptera, Hyracoidea, Macroscelidea, Pholidota, Proboscidea, Scandentia, Sirenia, Tubulidentata). One simple pragmatic approach to offset this problem is to take over-all average logarithmic values for brain and body mass for individual orders of mammals. This approach in fact yields a very similar result, with a slight reduction in the value of the allometric exponent value to 0.75 and a small improvement in the correlation coefficient (Figure 3):

$$\log_e E = 0.75 * \log_e P - 3.08 \quad (r = 0.99)$$

(where E = brain mass in g and P = body mass in g)

In a more systematic approach designed to counteract the potential problem posed by species-rich taxa, Martin and Harvey (1985) presented logarithmic averages for brain and body weights calculated through successively higher taxonomic levels, ranging from genera up to orders. They obtained a scaling exponent value of

0.72 (95% confidence limits: 0.68-0.77). A scaling exponent value of ≈ 0.75 is therefore not attributable to a bias arising from the influence of species-rich orders.

Similarity in the empirically determined exponent values for scaling of BMR and adult brain size across placental mammals indicates a broadly isometric relationship between these two variables, i.e. simple proportionality regardless of body size (Mink et al. 1981; Hofman, 1983b; Martin, 1998; Fig. 4). Of course, such similarity in scaling could be merely coincidental. Moreover, it is well known that the exponent value for scaling of brain mass to body mass in mammals changes with taxonomic level of analysis (Martin and Harvey, 1985), and it is difficult to decide on the appropriate value for comparisons (Martin, 1990). Demonstration of a causal relationship requires extensive additional testing to ensure compliance with the criterion of isolation. Moreover, even if the existence of a connection between adult brain size and BMR is convincingly established, different interpretations are possible. One immediate possibility is that there is some direct connection between adult brain size and BMR. In this vein, Armstrong (1982, 1983) suggested that the size of the brain may be con-

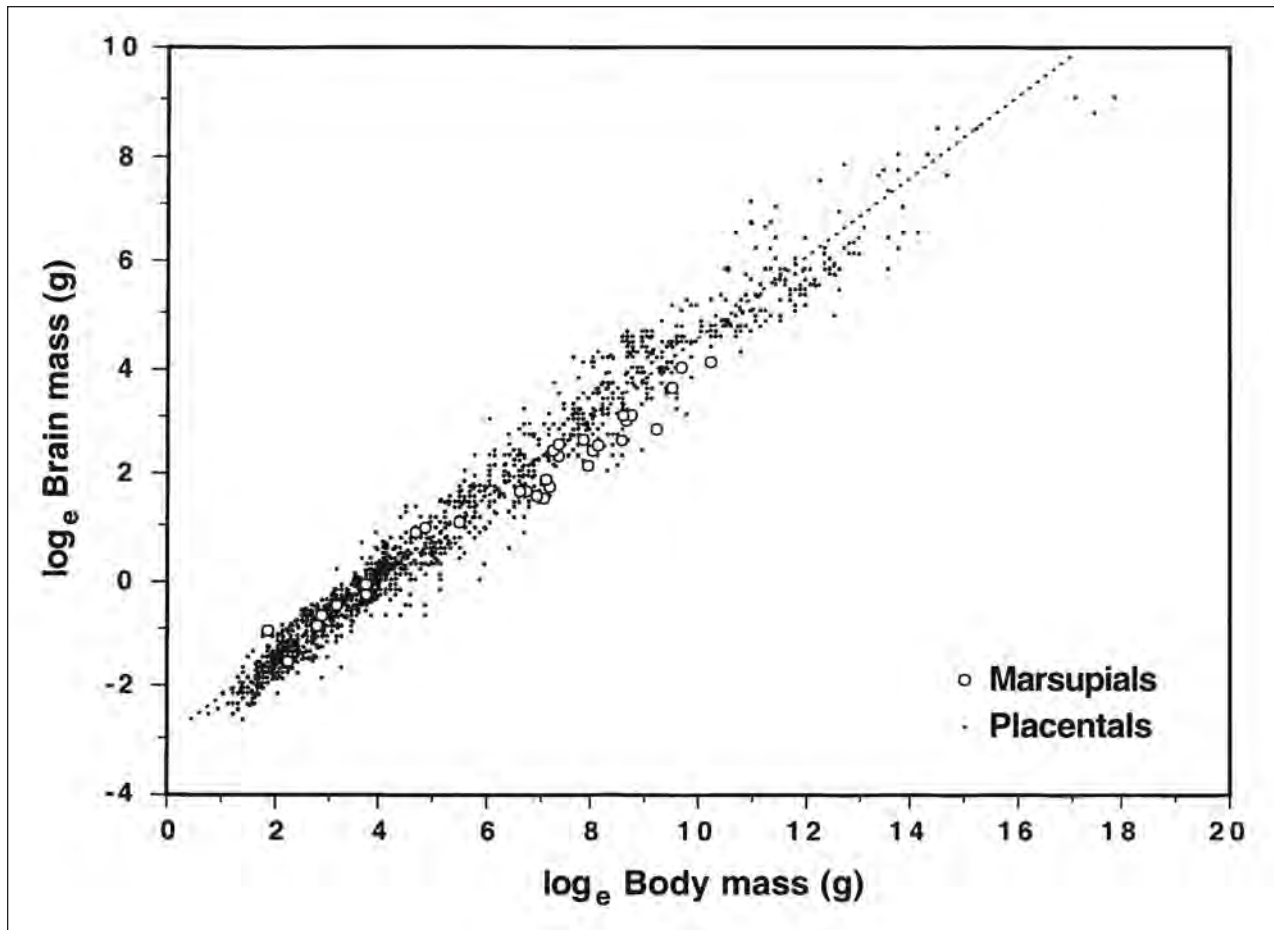


Figure 2 Scaling of brain mass (g) to body mass (g) for 1129 placental mammal species including representatives from all 18 extant orders. The scaling formula indicated by the best-fit line (reduced major axis) is: $\log_e E = 0.77$, $\log_e P = -3.03$ ($r = 0.98$). For comparison, data for 31 marsupial species (not included in calculation of the best-fit line) have been superimposed on the graph. (Dataset for placental mammals compiled by Karin Isler and Carel van Schaik; dataset for marsupials from Haight and Nelson, 1987.)

strained by the size of systems delivering oxygen and glucose and the rate of oxygen turnover, while Hofman (1983b) noted the need for compatibility between the energy demands of the brain and production and transport of oxygen by the body as a whole. In support of her interpretation, Armstrong explicitly cited the broadly isometric relationship between adult brain size and BMR shown in Figure 4.

However, postulation of a direct link between brain size and BMR in the adult conflicts with a number of other findings. First of all, for mammals generally the range of variation in relative brain size greatly exceeds the range of variation in BMR relative to body size (Martin, 1998). Overall, brain size shows a 25-fold range of variation relative to body size, whereas relative variation in BMR shows only a 4-fold range. There is hence considerable variation in adult brain size that cannot be explained by a direct relationship with BMR. There is also conflict with an observed grade shift towards higher values in the distribution of relative brain sizes among primates compared to other placental mammals. This grade distinction is not matched by a corresponding shift in the distribution of BMR values relative to body size

(Mink et al., 1981; Leonard and Robertson, 1992; Leonard et al., 2003, 2007; Martin, 1998). Hence, the larger average brain mass of primates (Martin and Harvey, 1985; confirmed here in Fig. 3) is not explicable on the basis of a higher average BMR level. Armstrong (1982) in fact acknowledged that primates have larger brains than expected from their BMR values in comparison to other mammals, and a clear grade shift towards larger brains in primates is seen in a plot of residual values for adult brain mass against residual values for BMR, both determined relative to body mass (Armstrong, 1983). Armstrong proposed that primates allocate a larger proportion of available energy to the brain, but did not explain how primates can seemingly escape a constraint that supposedly limits brain size in other mammals. This same point applies even more emphatically to the human brain. Humans have an exceptionally large brain (the largest relative to body size recorded among placental mammals), yet the human BMR value relative to body size is quite close to the average condition for placental mammals generally. Finally, the absence of a direct connection between adult brain size and BMR is also indicated by data for marsupials. As already noted, BMR

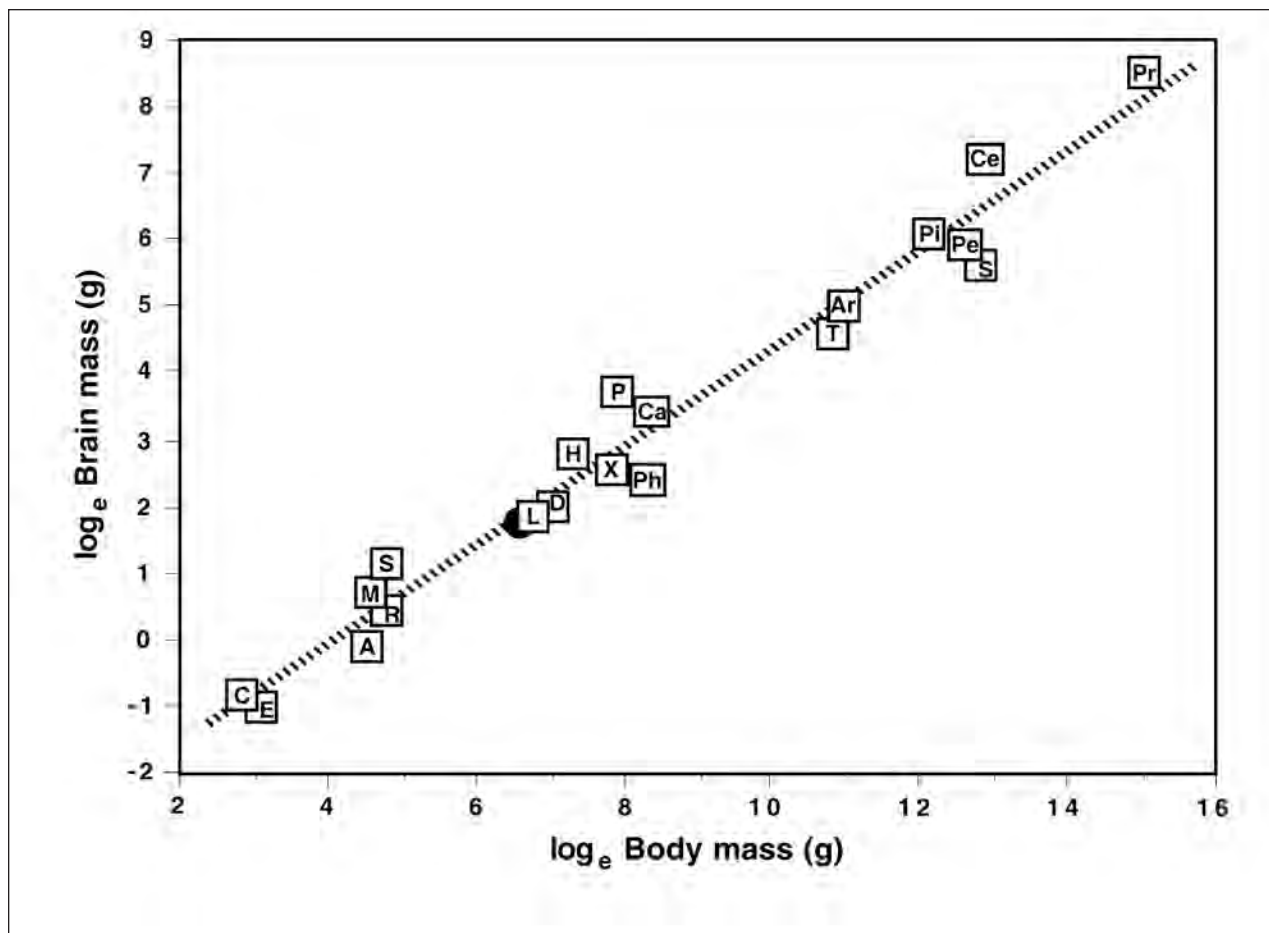


Figure 3 Scaling of brain mass (g) to body mass (g) for placental mammals using the dataset shown in Fig. 2 but taking mean values for 20 ordinal groupings. Key: A = Afrosoricida; Ar = Artiodactyla (part of Certartiodactyla); C = Chiroptera; Ca = Carnivora; Ce = Cetacea (part of Certartiodactyla); D = Dermoptera; E = Eulipotyphla; H = Hyracoidea; L = Lagomorpha; M = Macroscelidea; P = Primates; Pe = Perissodactyla; Ph = Pholidota; Pi = Pinnipedia (part of Carnivora); Pr = Proboscidea; R = Rodentia; S = Scandentia; Si = Sirenia; T = Tubulidentata; X = Xenarthra. The scaling formula indicated by the best-fit line (reduced major axis) is: $\log_e E = 0.75 * \log_e P - 3.08$ ($r = 0.99$). Note that the point for primates (P) is the highest relative to the best-fit line. (Dataset for placental mammals compiled by Karin Isler and Carel van Schaik.)

relative to body mass in marsupials is approximately 30-35% below the average condition for placental mammals. Other things being equal, therefore, the existence of a direct link between adult brain size and BMR would surely predict distinctly smaller average relative brain size in marsupials than in placentals. However, there is complete overlap between individual values for marsupials and placentals in a plot of brain mass against body mass (Fig. 2), and the average condition for marsupials lies almost directly on the best-fit line determined for ordinal average values of placental mammals (Fig. 3). There is nonetheless an intriguing differentiation among marsupials in that small-bodied species tend to have relatively large brains compared to the average condition for placentals, whereas large-bodied species tend to lie below the best-fit line for placental mammals (Fig. 2). This may indicate that, compared to placentals, marsupials experience increasing constraints on brain development with increasing body size. Overall, however, it cannot be

argued that the lower average BMR level in marsupials is associated with uniformly smaller brain size than in placentals. Indeed, small-bodied marsupials have quite large brains compared to placentals of comparable body size. Clearly, marsupials must have adaptations that permit them to develop quite large brains despite their generally lower BMR level.

An alternative approach that might potentially avoid the problems posed by inference of a direct link between adult brain size and BMR is the notion that there is a trade-off between the size of the brain and the size of other organs with high energy demands in the adult body. A prominent example of this is the Expensive Tissue Hypothesis (ETH) proposed by Aiello and Wheeler (1995; see also Aiello et al. 2001), which specifically invokes a trade-off in the adult individual between brain size and gut size. In principle, such a trade-off could explain why some species can have larger brains than others with equivalent energy resources in the adult con-

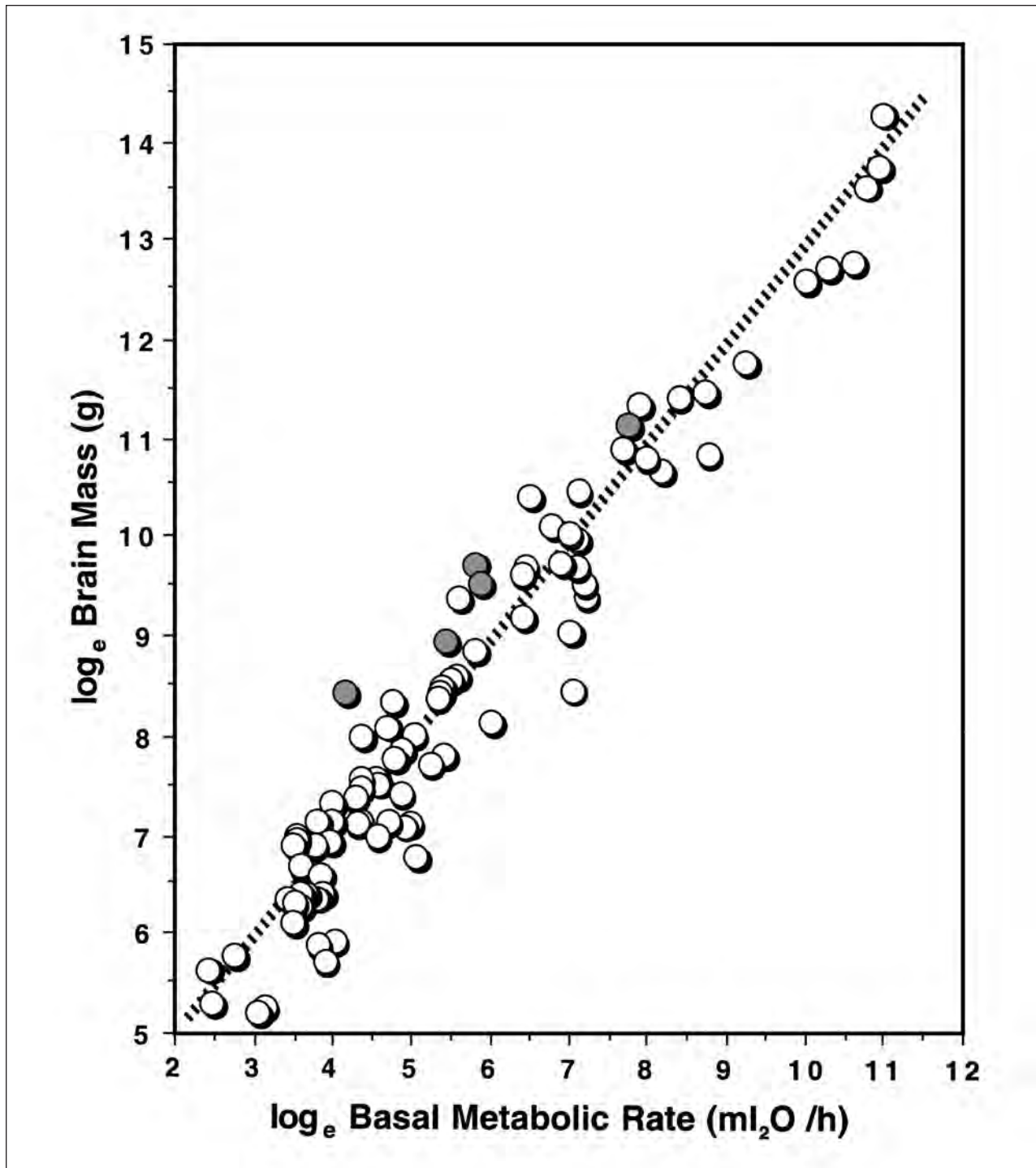


Figure 4 Scaling of brain mass (g) to basal metabolic rate (ml O₂/h) for 88 placental mammal species. Grey symbols indicate primates in the sample ($n = 5$); white symbols indicate other mammals. The reduced major axis yields an empirical value of 1.01 for the scaling exponent, confirming the isometric relationship (dirty proportionality) indicated by the line.

dition. One prediction of the ETH is that there should be a negative relationship between residual values for brain mass and gut size relative to body mass. Aiello and Wheeler (1995) tested this prediction with a sample of primates and reported that there is, indeed, the expected negative relationship. However, as with any result from a bivariate comparison, alternative explanations are pos-

sible. For instance, efficient digestion of leaves requires a resident population of symbiotic bacteria in the gut, either in the stomach or in the caecum, so folivorous (leaf-eating) mammals would be expected to have a relatively large gut. There are also indications that folivorous mammals have lower BMR than fruit-eating mammals (Clutton-Brock and Harvey, 1980; McNab,

1980, 1986), so the MEH would predict that leaf-eaters should have relatively small brains compared to fruit-eaters (frugivores) because low maternal BMR would limit fetal brain growth. Hence the reported negative relationship between residuals for brain size and gut size in primates is compatible with the MEH as well as with the ETH. Clearly, further testing is necessary to assess the relative merits of the two hypotheses. It should also be noted that primates do not have systematically smaller gut sizes than other mammals to compensate for their generally larger brains, as would be predicted from the ETH (Snodgrass et al., 2007). Leonard et al. (2003, 2007) have proposed instead a trade-off between brain mass and muscle mass in primates, notably in humans. In light of results from various comparative studies, Barton (2006) has suggested that the concept of trade-offs against brain size should be considered in relation to energetically expensive tissues generally rather than exclusively in relation to other cases involving scaling relationships among primates, one possibility is to extend comparisons to other mammal groups. A suitable test case is provided by bats. Eisenberg and Wilson (1978) identified a marked grade distinction in the scaling of brain size to body size in bats, with frugivorous species having larger brains than insectivorous (arthropod-eating) species. This finding was replicated for a much larger sample of bat species by Jones and MacLarnon (2004). However, arthropod-eating mammals generally have smaller guts relative to body size than fruit-eating species, so frugivores would be expected to have relatively larger guts as well as relatively larger brains. Accordingly, it was pointed out that a direct trade-off of the kind predicted by the ETH would not be expected in this case (Martin, 1996). Jones and MacLarnon (2004) subsequently confirmed this expectation, showing that relative brain size in bats shows a positive rather than negative correlation with relative gut size. It should be noted, incidentally, that insectivorous bats typically have lower BMR relative to body mass than frugivorous bats. Hence, the difference in relative brain size between these two dietary categories could be explained by the MEH.

A test of the ETH was also conducted using data for 21 bird species (Isler and van Schaik, 2006a). Taking residuals calculated from raw values for gut mass and brain mass relative to body size, non-significant negative correlations were found for both individual species and family-level averages ($p = 0.53$ and $p = 0.43$, respectively). A significant negative correlation was found with the contrast values for species ($p < 0.03$), but this result was not confirmed by analysis of a larger dataset with intestine lengths for 192 bird species. By contrast, Isler and van Schaik (2006a) found a significant negative correlation between brain mass and pectoral muscle mass, interpreted as indicating a trade-off between brain size and locomotor costs in birds.

The second stimulus that led to formulation of the MEH was evidence for a connection between gestation period and brain size in mammals. Such a link was first

clearly indicated by the seminal finding of Sacher and Staffeldt (1974) that there is a tighter correlation for the relationship between neonatal brain mass and duration of gestation than for the relationship between neonatal body mass and gestation period. Their reported result is replicated in Figure 5 by an analysis conducted with a similar dataset for 92 placental mammal species. The value of the coefficient of determination (r^2) for the relationship between neonatal brain mass and gestation period is 0.84, whereas that for the relationship between neonatal body mass and gestation period is only 0.72. In other words, only 16% of variation in neonatal brain mass cannot be attributed to variation in gestation period, whereas 28% of variation in neonatal body mass is attributable to factors other than gestation. Taken in isolation, this difference is suggestive but not compelling. However, partial correlations from a 4-way analysis of adult body mass, gestation period, neonatal body mass and neonatal brain mass reveal an even clearer distinction. The partial correlation between gestation period and neonatal brain mass is 0.71, whereas that between gestation period and neonatal body mass is only 0.12. By contrast, the partial correlation between neonatal brain mass and adult body mass is 0.176, whereas that between neonatal body mass and adult body mass is 0.75. Hence, neonatal brain mass seems to be associated primarily with gestation period, whereas neonatal body mass is linked more particularly to adult body mass. In light of their original finding of a tighter correlation between neonatal brain mass and gestation period, Sacher and Staffeldt (1974) suggested that the brain might serve as a pacemaker for mammalian development. However, this is only one possible interpretation of the observed correlation, and it is noteworthy that this finding is entirely compatible with the MEH.

Another key observation is that there is a clear grade distinction between primates and other placental mammals with respect to the relationship between neonatal brain and body mass. It has already been noted that a plot of ordinal averages for the scaling of brain mass to body mass in adults indicates larger relative brain size in primates compared to other mammals (Figure 3). However, there is considerable overlap between individual primate species and other mammal species in the adult condition. By contrast, there is very little overlap between primates and other mammals in a plot of brain mass against body mass for neonates. In primates, brain mass at birth is approximately twice as large as in other placental mammals, relative to neonatal body mass (Sacher, 1982; Martin, 1983, 1996). On the one hand, this reveals that the larger average brain sizes relative to body size found in adult primates can be traced to a marked difference in prenatal development, squarely placing the emphasis on the maternal contribution. On the other hand, the weakening of the distinction between primates and other mammals by the time that the adult condition is attained indicates that factors intervening after birth can influence the ultimate outcome. It is important to recognize that the distinctly larger brain sizes of primates at birth,

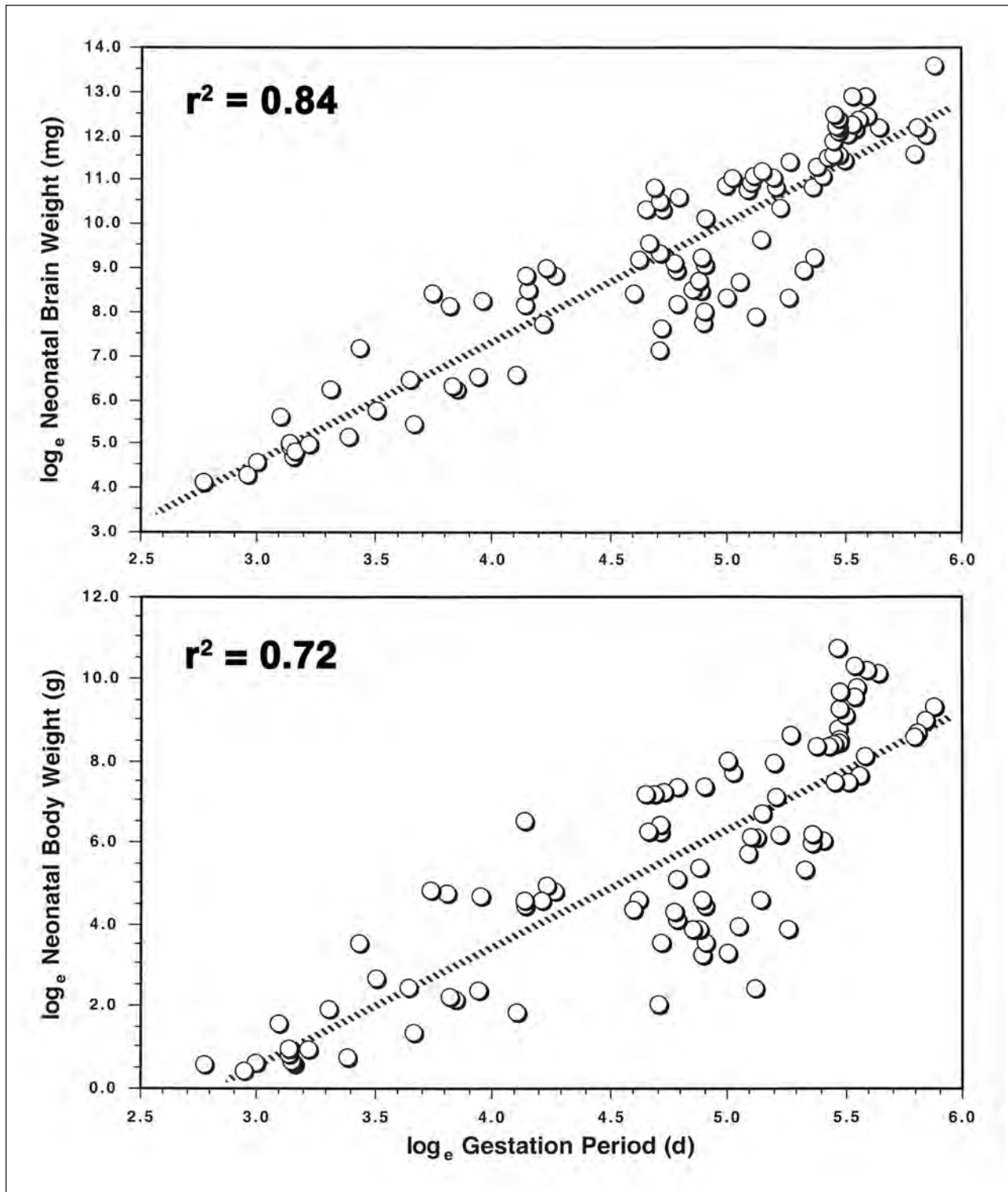


Figure 5 Plots of neonatal brain (mg) and body mass (g) against gestation period (d) for 92 placental mammal species. Best-fit lines are least-squares regressions (provided for visual orientation only). The wider scatter of points around the line in the plot for neonatal body mass against gestation period is reflected by the lower value for the coefficient of determination (r^2).

relative to neonatal body mass, could be attained in two different ways. One possibility is that development of the fetal brain in primates is comparable to that in other mammals and that development of the rest of the body is restricted. Alternatively, it is possible that primate mothers actually invest more resources in development of the infant brain. These alternatives can be tested by plotting neonatal brain and body mass separately against adult body mass (Figure 6). As can be seen, primates overlap completely with other mammals with respect to the overall size of the neonate relative to adult body mass, but there is a clear grade distinction with respect to the size of the neonatal brain relative to adult body mass. Hence, the evidence shows that, in comparison to other mammals, primate mothers do actually invest more resources in the development of the fetal brain. It should be emphasized that brains of fetal primates are uniformly larger (relative to body mass) than those of other mammals throughout development, showing that increased maternal investment is consistently maintained during pregnancy in primates (Sacher, 1982; Martin, 1983).

Predictions of the MEH are also supported by combined analysis using partial correlations of adult brain size, adult body size, BMR and gestation period for the sample of 51 placental mammal species mentioned above (Martin, 1996, 1998). This analysis revealed persistent positive associations linking BMR to both body mass and brain mass, and linking gestation period to brain mass. Brain mass also showed a persistent positive association with body mass. However, the positive correlation between gestation period and BMR originally seen with the raw values was eliminated and replaced by a negative partial correlation. These results have now been confirmed with a much larger dataset for 320 placental mammal species. The results hence confirm that BMR and gestation period are both correlated with brain weight after eliminating the effect of body size (partial correlation coefficients: BMR—brain weight 0.214, gestation period—brain weight 0.307). At the same time, the negative partial correlation between gestation period and BMR (-0.233) indicates that relatively large brain sizes in mammals may be attributable either to longer gestation periods or to elevated BMR but not to both factors in combination. It should also be noted that, in a study restricted to primate genera, Little (1989) used path analysis to infer that gestation period and estimated metabolic rate are both connected to adult brain size.

In a study specifically focussing on bats, Jones and MacLarnon (2004) took data for 313 species to conduct a comparative test of three hypotheses concerning the rôle of energetics in the evolution of larger brains: (1) direct metabolic constraint; (2) ETH; (3) MEH. Their analyses provided virtually no support for the proposed link with basal metabolic rate invoked by any of the three hypotheses, but they did show that independent effects of gestation length and body mass can account for 95.9% of the variance in brain mass in bats. These authors hence demonstrated that the duration of maternal investment

in bats plays an important part in the attainment of adult brain mass. They aptly noted that their results underline the crucial need to test the general applicability of any evolutionary hypothesis developed for a single clade in isolation by examining other clades with different evolutionary backgrounds. It should be noted, incidentally, that some bats are highly unusual with respect to the relationships between hibernation, BMR and reproductive parameters, so this may explain why no overall association between BMR and brain size was found in this case.

The maternal energy hypothesis focusses on the part played by maternal resources in brain development and the likelihood that they place constraints on the ultimate size of the brain in adulthood. However, selection to meet particular functional requirements will also exert an influence on brain size. Ideally, the concept of maternal energy constraints and that of selection favouring particular brain functions should be combined in a single model. A possible candidate is provided by the 2-phase hypothesis of brain size evolution proposed by Aboitiz (1996). This hypothesis proposes that brain size is influenced by both “passive” growth (general adjustment to body size) and “active” growth (adaptation in response to particular behavioural needs). The MEH can at least partially account for passive adjustment of overall brain size to body size, while selection of individual brain components to serve particular brain functions would eventually translate into increased brain size. Recognition of maternal investment as a key feature of “passive” brain growth permits refinement of the Aboitiz model in that an increase in overall brain size can result from an increase in maternal metabolic turnover or from an increase in the duration of gestation. Another implication of the model is that the quest for links between particular behavioural developments and increased brain size should focus particularly on associations between behaviour and particular parts of the brain rather than on overall brain size. For primates, visual components of the brain are of particular interest (Barton, 2006).

Additional support for the MEH emerges when the contributions of gestation period and BMR are combined (Martin, 1998). When brain size residuals were examined in relation to summed residuals for basal metabolic rate and gestation period, there was a marked improvement in the correlation coefficient compared to the values found with residuals for basal metabolic rate or gestation period in isolation ($r = 0.38$ for BMR alone; $r = 0.38$ for gestation period alone; $r = 0.55$ for BMR and gestation combined). This suggests that BMR and gestation period together account for $\approx 30\%$ of variation in relative brain size between species. It should be noted that the MEH actually predicts that maternal BMR and gestation period would primarily influence neonatal brain size and that other factors (e.g. maternal investment through lactation) can intervene in the interval between birth and attainment of adult brain size. Various other lines of evidence support the inference that maternal resources are of particular importance for the evolution of the mam-

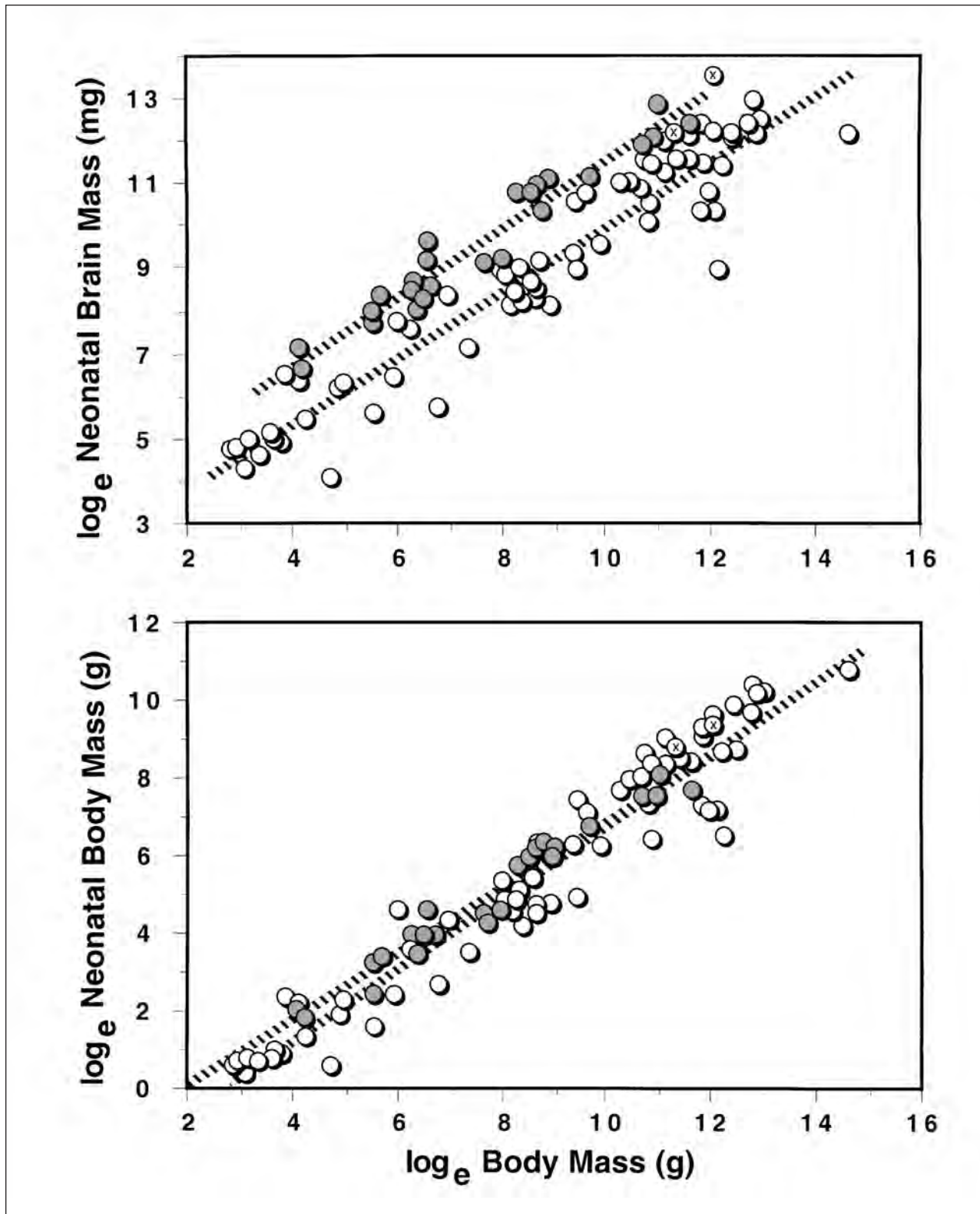


Figure 6 Plots of neonatal brain mass (g) and neonatal body mass (g) against adult body mass (g) for a sample of 92 placental mammal species. Primates (shaded symbols) show an upward grade shift relative to other mammals (unshaded symbols) for neonatal brain mass, as indicated by the separate least-squares regression lines (provided for visual orientation only). By contrast, for neonatal body mass least-squares regression lines indicate no difference between primates and other mammals.

malian brain. Experimental work on genomic imprinting, for example, has shown that maternally expressed genes specifically favour brain development (Keverne et al., 1996a). Furthermore, these maternally expressed genes favour higher centres of the brain (the “executive brain”: neocortex + striatum), while paternally expressed genes promote more basal brain regions (the “emotional brain”: hypothalamus + septum) instead (Keverne et al., 1996b).

CHALLENGES TO THE MATERNAL ENERGY HYPOTHESIS

Although several lines of evidence can hence be cited in support of the MEH, it has been subject to various challenges. One such challenge came from a test conducted by McNab & Eisenberg (1989) to investigate the proposed connection between brain size and BMR. These authors correctly noted that the MEH explicitly predicts that there should be a positive correlation between the residual values for brain size and BMR, both calculated relative to body size. They reported that analysis of data for 174 mammal species (including monotremes and marsupials) indicated that the relationship between relative brain size and relative BMR was not statistically significant ($p = 0.08$), although the trend was indeed positive as predicted. As noted by Martin (1998), however, the analysis conducted by McNab & Eisenberg (1989) was flawed because a parametric test was used to determine statistical significance. Such a test requires normality of distribution in the values compared, but it was applied after normally distributed logarithmic residual values had been converted to quotients with a strongly skewed distribution. A non-parametric test (Spearman rank correlation) applied to the derived quotient values revealed that the relationship is, in fact, statistically significant ($r_s = 0.17$; $p = 0.025$). As an alternative approach, a parametric test (Pearson correlation) was applied to the logarithmic residual values, also yielding a statistically significant result ($r = 0.16$; $p = 0.040$). Hence, the residual values for BMR and brain size reported by McNab & Eisenberg (1989) are actually significantly correlated. Despite this significance, however, the correlation is surprisingly weak in view of the other findings reported above. In fact, Martin (1998) reported a much stronger positive correlation from an analysis of 51 placental mammal species ($r = 0.38$; $p = 0.005$). The reason for this discrepancy has now emerged with the discovery that the dataset used by McNab and Eisenberg (1989) was itself seriously flawed. Data for brain sizes in rodents, taken from Mace et al. (1981), were systematically distorted because of the inadvertent addition of 0.59 g to the brain mass of every species (Isler and van Schaik, 2006b). Because rodents contributed disproportionately to the sample analysed by McNab and Eisenberg ($\approx 45\%$ of species included), the inaccurate values dramatically affected the results reported. Following correction of that error, a significant

correlation between relative BMR and relative brain size was in fact found (Isler and van Schaik, 2006b). This amendment is particularly noteworthy because Aiello & Wheeler, (1995) specifically cited the doubly flawed paper by McNab and Eisenberg (1989) in their original presentation of the ETH. They stated (p. 211) that their “conclusions are derived from the general observation that there is no significant correlation between relative basal metabolic rate and relative brain size in humans and other encephalized mammals.” That statement has now been invalidated.

A quite different challenge to the MEH arises from the claim that the results may have been biased by phylogenetic inertia (Pagel & Harvey 1990; Barton, 1999). From initial studies that attempted to offset effects of phylogenetic relatedness by conducting data analysis at the family level, it was reported that there was no significant relationship between BMR and adult brain size for mammals generally (Pagel and Harvey, 1988a), although a significant relationship between gestation period and neonatal brain size did remain (Pagel and Harvey, 1988b). Subsequently, Harvey and Pagel (1991) indicated that the exponent value for scaling of brain mass to body mass in placental mammals is reduced from 0.75 to 0.69 following contrasts analysis. Using a maximum likelihood approach, Pagel (1999) later reported exponent values of 0.59 for mammals and 0.48 for primates. Moreover, Barton (1999) reported that for primates no significant correlation between adult brain size and BMR or gestation period remains after application of the independent contrasts method (see also Barton, 2006). Yet Martin (1998) had reported in the meantime that an analysis of data for 51 placental mammal species had revealed that a highly significant correlation between adult brain size and BMR is found even after calculation of residual values determined from independent contrasts relative to body mass contrasts ($r = 0.465$; $p = 0.001$). However, the correlation between residuals for brain size and gestation period, although remaining positive, was found to be non-significant ($r = 0.203$; $p = 0.116$). Curiously, these conclusions are the opposite of those reported by Pagel and Harvey from analyses at the family level. Those authors found a significant correlation between relative brain size and gestation (Pagel and Harvey, 1988b) but not between relative brain size and BMR (Pagel and Harvey, 1988a). It has already been noted that there is a major pitfall in calculation of independent contrasts arising from magnification of the effects of error terms (Ricklefs and Starck, 1996; Martin et al., 2005). Because of this, assurance of data quality in a representative dataset is absolutely crucial. A recent analysis of a large, carefully monitored dataset for 347 mammal species has now demonstrated that there is in fact a significant correlation between BMR and adult brain mass after controlling for the effects of both body size and phylogenetic inertia (Isler and van Schaik, 2006b). The same finding has since been confirmed for primates taken in isolation (Isler et al., in press).

Table 1. Partial correlation coefficients (r) between adult brain mass and maternal energy investment per offspring ($MEI = (\text{gestation period} * \text{BMR})/\text{litter size}$), partialling out adult body mass and neonatal body

	All species (N=229)		Precocials (N=72)		Altricials (N=147)	
	r	p	r	p	r	p
Raw data	0.362	<0.0001	0.637	<0.0001	0.198	0.017
Independent contrasts	0.177	0.008	0.401	0.0007	0.108	0.205

A further challenge of the MEH was raised by Pagel and Harvey (1988b), who suggested that multiple litters should be taken into account in the attempt to allow for the maternal energy input that every single offspring receives. Isler and van Schaik (in review) have found that relatively large-brained mammalian mothers produce fewer, but individually heavier offspring than small-brained mothers. This is in accordance with the MEH, which would additionally predict that, for a given neonate mass, a large-brained mother should invest more energy in a single offspring than a small-brained mother.

In other words, it is predicted that, after partialling out body mass and neonate mass, adult brain mass should still be positively correlated with maternal energy investment per offspring. To test this, we defined maternal energy investment (MEI) per offspring as gestation length multiplied by BMR and divided by litter size. Independent contrasts were calculated with PDAP:PDTree (Garland et al., 1992) in Mesquite (Maddison & Maddison, 2007), using the supertree of Bininda-Emonds et al. (2007). Precocial and altricial mammals were analysed separately, excluding bats. Species were defined as precocial if the young open their eyes at birth or shortly thereafter.

Partial correlation coefficients from this analysis are given in Table 1. In analyses of raw logarithmic species means, MEI and brain mass are positively and significantly correlated in all three groups (all mammals, precocials and altricials), whereas the correlation in altricials is no longer significant if independent contrasts are analysed. This might be explained by the fact that in altricial mammals a large proportion of brain growth is accomplished after birth, up to the age at weaning. To test whether the MEH also applies to the weaning period, we would need better data on weaning mass than presently available. However, our analyses thus far fully support the MEH. We conclude that large-brained precocial mothers indeed invest more energy in every single offspring, and, apart from producing heavier neonates in the first place, also invest more energy per unit neonate mass than relatively small-brained mothers, because the larger brain is so costly to grow.

Yet another potential challenge to the MEH is posed by the recent claim that the value of the scaling exponent for the relationship between BMR and body mass in placental mammals is not 0.75 but 0.67 (White and Seymour, 2003). This finding is puzzling because application of contrasts analysis had in fact confirmed the

exponent value of 0.75 for scaling of BMR to body mass in placental mammals (Harvey and Pagel, 1991). In fact, White and Seymour (2003) reached their conclusion after excluding certain groups of mammals because of potential high energy turnover associated with digestion and after transforming the BMR data from the raw values that are usually used in analyses. As there are also problems with the published version of the dataset (confirmed by Michel Genoud, pers. comm.) further analyses are required to assess the validity of the results reported

FOSSIL EVIDENCE FOR MAMMALIAN BRAIN EVOLUTION

An empirical finding that has emerged for all mammalian taxa for which an adequate fossil record is available is that average relative brain size tends to increase over time. Marsh (1874) originally noted that Eocene mammals from Wyoming generally have small brains in comparison to their modern counterparts. Indeed, he noted that in some “the brain cavity was hardly more capacious than in the higher reptiles”. For example, in the primitive ungulate *Uintatherium* brain size was approximately one eighth of that in a modern rhinoceros of comparable body size. Progressive increase in the size of the brain was also reported in the evolution of horses. Subsequently, Edinger (1929, 1948) cast doubt on the existence of general trend towards increasing brain size, but she misinterpreted the fact that (other things being equal) a simple ratio of brain size to body size declines with increasing body size because of the negatively allometric scaling of brain size. Jerison (1970, 1973) subsequently demonstrated that, if relative brain size is calculated with due attention to allometric scaling, there is in fact a general trend towards increase in the average value over time. However, the spread of values also increases over time, with a few species showing little or no increase in relative brain size. Accordingly, some extant placental mammals (notably certain insectivores) have relative brain sizes that are little different from those of early placentals, but most have distinctly larger brains than any early fossil relatives. It is quite possible that brain size reduction has sometimes occurred in individual lineages, but this seems to be a relatively rare occurrence.

Average relative brain size clearly increased through the Tertiary as a general rule within primates (Martin, 1990). Relative brain size in Eocene primates is generally below that in extant prosimians, although there is some

overlap in values between omomyiforms (often interpreted as relatives of tarsiers) and certain strepsirrhines (lemurs + lorisiforms). However, relative brain size in omomyiforms is below that found in extant tarsiers. In the earliest higher primates for which brain size is documented (early Oligocene *Aegyptopithecus*, *Catopithecus* and *Parapithecus*), relative brain size is comparable to that in extant prosimians but below the range of values for extant monkeys and apes. It has also been shown that in the Miocene New World monkey *Chilecebus* relative brain size is smaller than in extant platyrrhines (Sears et al., 2008). A similar trend towards increase in relative brain size over time has also been clearly demonstrated through analysis of an impressive dataset for toothed cetaceans by Marino et al. (2004). Eocene archaeocetes have very small brains compared to more recent toothed cetaceans, and an overall trend through the Tertiary is seen, leading up to the notably large brains of modern dolphins and their relatives.

It is equally well established that relative brain size increased over time during the evolution of mammalian carnivores. Initial data provided by Jerison (1970, 1973) showed that early Tertiary carnivore relatives (creodonts) and archaic ungulates (condylarths) had relatively small brains compared to their modern counterparts. Randsky (1977, 1978) subsequently provided additional evidence showing that relative brain size was smaller in creodonts and the earliest known carnivores during the early Tertiary. In an analysis of encephalization quotients (EQ values) within the caniform suborder Caniformia, Finarelli and Flynn (2007) showed that taxa early in the evolutionary history of the group possessed significantly lower median values than extant taxa. A pronounced upward shift in median values was found at the Miocene-Pliocene transition. A gradual increase in variance around median relative brain size was also found. Reconstructions of ancestral EQ values revealed that increased encephalization took place in parallel across all major caniform clades, with the possible exception of skunks. A subsequent study focused specifically on brain size in Canidae in order to reveal underlying trends that might be masked in a more wide-ranging investigation (Finarelli, 2008). A shift towards higher encephalization in crown Caninae was found relative to a basal grade of encephalization in Hesperocyoninae, Borophaginae and *Leptocyon*. However, at this level of analysis no associated change in variance was found.

Widespread acknowledgment of a general trend towards increasing brain size during mammalian evolution was recently challenged in specific relation to bats by Safi et al. (2005). These authors concluded that brain size actually decreased over time in numerous bat lineages. However, their analysis was entirely based on analysis of relative brain size in extant bats, with no reference whatsoever to the fossil record. The results reported by Safi et al. are entirely dependent on their application of a statisti-

cal test that supposedly identifies directionality in the data (i.e. a trend towards increasing or decreasing brain size) in relation to a phylogenetic tree. The outcome of the test was that no statistically significant directionality was detectable. Once this inference has been made, it necessarily follows that increase in brain size in some lineages over time must be balanced by decrease in brain size in other lineages, such that the overall average remains unchanged over time (i.e. lacks directionality). It is hence only to be expected that a decrease in brain size was inferred in approximately half of bat species in the phylogenetic reconstruction presented by Safi et al. (2005). In fact, the test of directionality applied by Safi et al. (2005), using the software CONTINUOUS (Pagel, 1997, 1999; now included in Bayes-Traits) tests whether a directional change parameter should be included in the model of evolution of the trait under consideration. This parameter effectively measures the regression of trait values across species against total path length from the root of the tree to the tips. The CONTINUOUS manual states that it detects any general trends towards a dominant direction of evolutionary change (i.e. whether species have got bigger, smaller, faster, longer, etc.). The test can only be used with trees that have some variation in total path length from the root to tip species. In consequence, the test cannot be applied to the commonly used trees with branch lengths estimated as time elapsed on the basis of molecular data, because all extant taxa must exhibit the same distance from the root. Making matters worse, Safi et al. (2005) applied the test to a tree in which all branches between bifurcations are of equal length (=1). In their tree, therefore, species from species-rich taxa groups necessarily exhibit a longer pathway from root to tip than other species. Thus, they in fact tested whether speciose taxonomic groups differ in relative brain mass from taxonomic groups with fewer species, and did not find any indication of this. Any conclusions about directionality of brain size evolution drawn from this test are thus invalid.

In the absence of any attempt to verify their results by comparison with the fossil record, the findings reported by Safi et al. (2005) must in any case be treated with great scepticism. The potential dangers of reconstructing changes in size over time without reference to the fossil record are aptly illustrated by an analysis of body size of the mammalian order Carnivora by Finarelli and Flynn (2006). Among caniform carnivorans (Canidae, Ursidae, Pinnipedia and Musteloidea), many subgroups are now represented predominantly by large- or small-bodied species and the distribution of body sizes among extant species across the phylogeny in fact suggests a pattern of decreasing body size from an ancestral value of 10-50 kg. However, estimated body sizes for fossil representatives of a given caniform taxon often lie

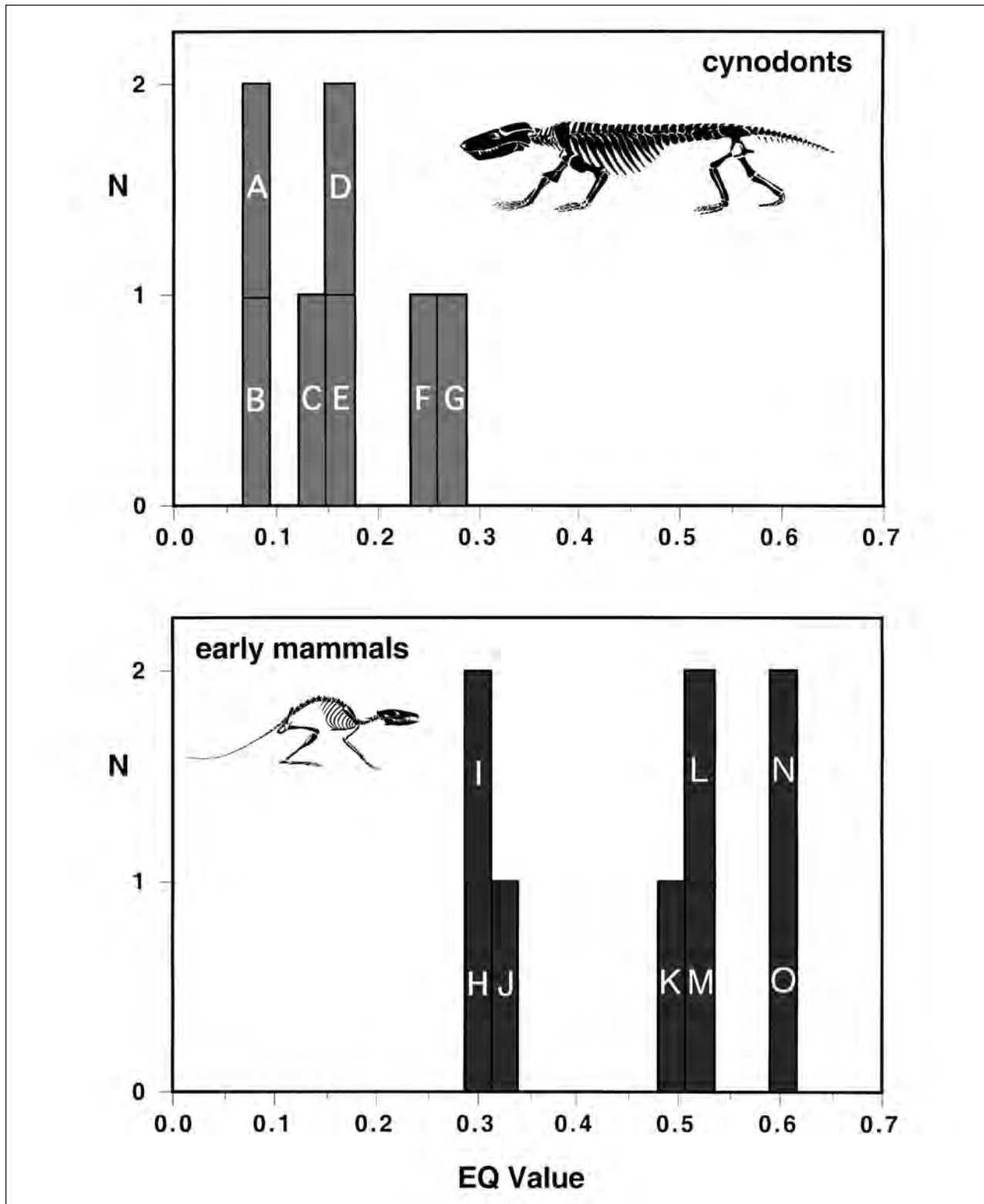


Figure 7 Histogram showing relative brain sizes in cynodont therapsids ($n = 7$) and early mammals ($n = 8$), as indicated by encephalization quotient (EQ) values. EQ values were calculated using the formula determined for 309 modern placentals by Martin (1981). An EQ value of 1 indicates the average condition for modern placentals. Data on brain and body size derived from Jerison (1973), Crompton and Jenkins (1978), Quiroga (1980, 1984), Kielan-Jaworowska (1983, 1984), Krause and Kielan-Jaworowska (1993), Kielan-Jaworowska and Lancaster (2004), Macrini et al. (2007). Key to cynodonts: A = Thrinaxodon; B = Exaeretodon; C = Probelesodon; D = Probainognathus; E = Diademodon; F = Therioherpeton; G = Massetognathus. Key to early mammals: H = Vincelestes (placental); I = Kennalestes (placental); J = Triconodon; K = Asioryctes (placental); L = Chulsanbaatar (multituberculata); M = Ptilodus (multituberculata); N = Zalambdalestes (placental); O = Kryptobaatar (multituberculata).

well outside the observed ranges for extant members, so the modern distribution of body sizes is not representative of the evolutionary history of the group. When 367 fossil taxa were included with 149 extant species for a combined analysis designed to reconstruct ancestral body sizes, a small-bodied ancestor (1-5 kg) was indicated both for Caniformia and for the monophyletic subclade Arctoidea (Ursidae, Pinnipedia and Musteloidae). As was aptly noted by Finarelli and Flynn (2006): “Evolutionary trends can reduce the accuracy of character state reconstructions, especially for methods assuming Brownian motion as the model for character change. This is because an estimated root value under such a model will always be some form of weighted average of observed values for terminal taxa (Schluter et al., 1997), and if a trend moves the range of observed character state values beyond the ancestral condition, it will be difficult, if not impossible, to accurately reconstruct the condition at the ancestral node (Garland et al., 1999; Oakley and Cunningham, 2000).”

There are therefore good reasons to question the findings reported by Safi et al. with respect to the evolution of relative brain size in bats. To test whether brain size evolution in bats was directional or not, the most obvious approach would be to seek data on brain size in fossil bats at different times in the Tertiary. However, the fossil record for bats is relatively poor, so it might prove very difficult to conduct an adequate test of the presence or absence of directionality in brain size evolution. Given the compelling evidence from diverse mammalian fossils for a general trend towards increasing brain size in mammalian evolution (Jerison, 1973), it seems highly unlikely that the conclusions drawn regarding bats will survive proper testing.

The existence of a general trend towards increase in relative brain size over the course of mammalian evolution is of particular interest in the context of the MEH. Given that resources provided by the mother throughout gestation and lactation seem to be of particular importance for the development of the brain, the emergence and subsequent refinement of pregnancy and suckling are presumably connected to evolutionary changes in brain size over time. It is, for example, to be expected that the origin of lactation in early mammals and its presence in the common ancestor of monotremes, marsupials and placentals some 200 million years (Ma) ago might have been accompanied by an increase in relative brain size. Most extant reptiles show no parental behaviour, so development of the offspring prior to independent feeding relies entirely on the resources provided in the egg when laid by the mother. Moreover, interspecific scaling of brain size to body size follows a different trajectory in reptiles compared to mammals. The size of the egg is related to the mother’s metabolic capacity, while the size of the brain in the hatchling is related to the egg’s metabolic capacity. The outcome is a lower exponent of ≈ 0.56 for brain:body scaling in reptiles (Martin, 1981), which imposes a handicap that increases with increas-

ing body size. In a further crucial development at a later stage of mammalian evolution, egg-laying was replaced by internal development of the offspring (vivipary) in the common ancestor of marsupials and placentals at least 135 Ma ago. Retention of the developing egg within the mother’s body at once permitted continuous provision of maternal resources to the developing offspring, as opposed to reliance on a one-off provision of resources in an externally deposited egg. Overall, these considerations lead to the expectation that relative brain size might have increased in the earliest mammals and would probably have increased even further with the origin of vivipary.

The earliest mammals arose from the cynodonts, advanced mammal-like reptiles (therapsids), close to the Triassic/Jurassic boundary about 200 Ma ago. Estimates of brain size and body size are now available for 7 cynodonts (*Diademodon*, *Exaeretodon*, *Massetognathus*, *Probainognathus*, *Probelesodon*, *Therioherpeton* and *Thrinaxodon*), providing an adequate basis for comparison with early mammals. Unfortunately, very little is known about relative brain size in Jurassic mammals, so comparison of cynodonts with the earliest known mammals is not yet possible. However, data are available for the Late Jurassic *Triconodon*, an Early Cretaceous placental (*Vincelestes*) 3 Late Cretaceous placentals (*Asioryctes*, *Kennalestes*, *Zalambdalestes*), 2 Late Cretaceous multituberculates (*Chulsanbaatar*, *Kryptobaatar*) and the Palaeocene multituberculate *Ptilodus*. As can be seen from Figure 7, the cynodonts uniformly have relatively smaller brains than the early mammals. The early mammals, in turn, have relative brain sizes that consistently lie below the average condition for modern mammals (indicated by an EQ value of 1). However, the values for the early mammals do overlap with the lower end of the range for modern mammals. This evidence confirms the expectation that relative brain size should be increased in early mammals relative to advanced mammal-like reptiles, but should lie below the average condition for extant mammals. Although no information on relative brain size is available as yet for the earliest mammals, there is an indirect indication that expansion of brain size relative to the reptilian level was probably under way quite early in mammalian evolution. It is generally accepted that the multituberculates diverged very early in mammalian evolution, and some authors have indeed linked them to monotremes rather than to the lineage leading to marsupials and placentals. Yet the values for multituberculates in Figure 7 are comparable to those for early placentals.

Following the origin of vivipary in the lineage leading to the ancestry of marsupials and placentals, refinements in intrauterine development would have permitted a further increase in provision of maternal resources. Placentation is generally poorly developed in marsupials and gestation periods are very short, although provision of maternal resources through suckling is enhanced by an extended pouch life. Marsupials generally have only

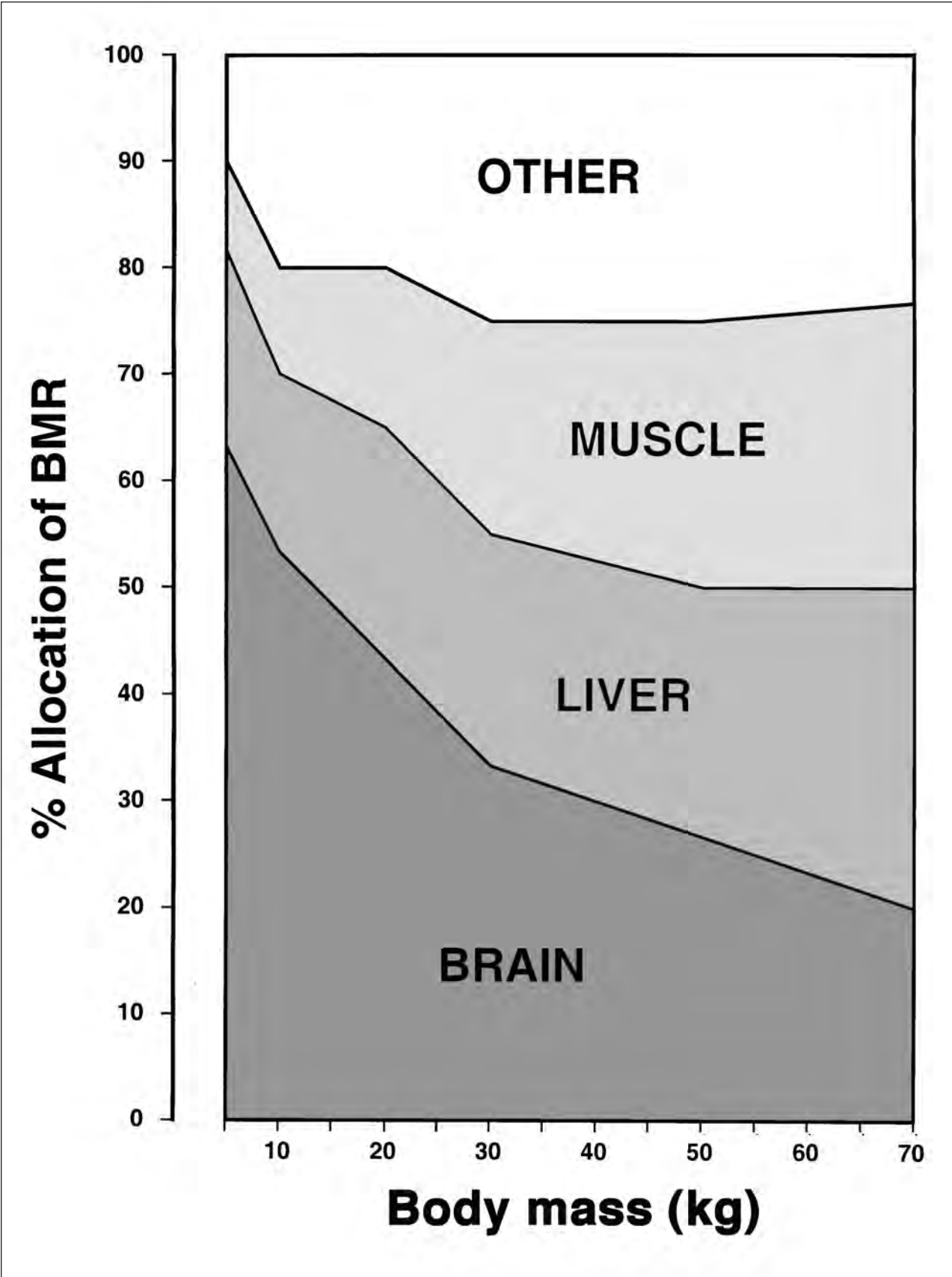


Figure 8 Proportional allocation of BMR to brain, liver, muscle and other tissues in humans at different body mass, ranging from birth to adulthood. (Data from Holliday, 1986.)

small to moderately developed brains, as would be expected from these constraints. Among placental mammals, however, many lineages have developed extended gestation periods, which are associated with precocial offspring (well developed and usually singletons). This contrasts with the condition in mammals that produce litters of poorly developed altricial offspring, which have markedly shorter gestation periods (Martin et al., 2005). Comparative evidence indicates that the altricial condition is primitive for placental mammals. Refinements in placentation doubtless occurred in parallel in many lineages during the course of evolution of placental mammals, and this would have provided a basis for increased provision of maternal resources. However, maternal resources are also provided during lactation, so this provides an additional avenue for maternal investment in the development of the offspring's brain.

A NOTE ON IMPLICATIONS FOR HOMINID BRAIN EVOLUTION

Because the modern human brain is the largest, relative to body size, among mammals generally, the problem posed by energy demands is particularly acute. Indeed, this problem is most marked early in postnatal life in comparison to adults. Data for allocation of BMR to different tissues in humans at different body sizes (Holliday, 1986) show that allocation of energy to the brain is predominant early in life (Fig. 8). Leonard et al. (2003, 2007) have shown that dietary quality (rather than BMR) may be a key factor in ensuring an adequate supply of energy to the brain in adult humans. In a plot of residuals for diet quality and brain size (both calculated relative to body mass), humans are clear outliers in having an unusually high dietary quality in comparison to other primates. As noted by Leonard et al. (2003, 2007), the relatively small gastrointestinal tract of humans is consistent with adaptation for a high-quality diet and may, in itself, have no direct connection with brain size. Mounting energetic requirements accompanying increasing brain size over the course of human evolution must clearly be considered as a fundamental issue (Martin, 1983). One thought-provoking attempt to take this into account has explored implications of carnivory for increased brain size in human evolution (Vasey and Walker, 2001).

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