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Brain Size, Cranial Morphology, Climate, and Time Machines[1]

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INCREASING CRANIAL CAPACITY has historically been associated with increasing complexity of society. The resultant tendency has been to think of humans with larger brains as mentally more capable. Gene-pool (racial affinity) and somatic (body-size) explanations have also been advanced to account for the braincase variation.

We offer an alternative hypothesis that suggests that hominid expansion into regions of cold climate produced change in head shape. Such change in shape contributed to the increased cranial volume. Bioclimatic effects directly upon body size (and indirectly upon brain size) in combination with cranial globularity appear to be a fairly powerful explanation of ethnic group differences. Within this hypothesis, the evolutionary trends of brachycephalization and encephalization are considered as functionally connected. This thermoregulatory model is taken not as exclusionary or competitive with other approaches but rather as an adjunct toward understanding the distribution of cranial morphology over time and space.

Anthropometric distributions are importantly affected by climatic adaptation. Examples of investigations, reviews, and discussion include Thomson (1913), Roberts (1953, 1978), Wiener (1954), Coon (1955, 1965), Newman (1953, 1961), Baker (1960), Schreider (1964), Hiernaux (1968), Wolpoff (1968), Steegman (1970, 1975), Beals (1972), Koertvelyessy (1972), and Crognier (1981). Traits with thermoregulatory associations include nose form (nasal index), weight, body build (ponderal index and surface area:mass ratio), head shape (cranial and cephalic indices), endocranial volume (cranial capacity), cranial morphology (size/shape composite), and relative brain size (cranial capacity:stature).

Previous work (Beals, Smith, and Dodd 1983) has demonstrated that thermoregulatory adaptation in head shape can be traced through a portion of the fossil record and that the trend of brachycephalization is partially explained by an increased occupation of cold environments. For the cranial index, climatic association over time has been quantified, so that multiple regression predicts the expected index for any given point of grid coordinates during the course of hominid evolution.

A similar procedure is under way with regard to cranial capacity. The ultimate purpose is to create a "time machine" that constructs clinal maps throughout the Pleistocene. The final portion of this paper attempts an experimental "respondent feedback" to the paleontological evidence.

PROJECTING THE VARIATION

Our mapping system (HOMPLOT)[2] originated from the desire to plot trait associations for instructional and research pur-

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[2] HOMPLOT is an outgrowth of software originally designed in 1978 to assist students in locating cultures. It uses Tektronix graphics hardware, although the output can be routed to any desired plotter. Basically, the operator selects type of data for display, data base, color scheme, and portion of the world to be projected. Clinal maps were drawn by a Tektronix 4662 interactive plotter, using a Miller geographical projection. The system is interactive, operating largely by prompts or a user menu at the top of the video screen. Details of the procedure have been described by Smith, Fuhrer, and McNaughton (1979) and by Fuhrer and Smith (1978).

Manual linear interpolation is used for producing clinal maps from the pattern of points as plotted at the center of mass of the ethnic group territory. This is ordinarily done by assigning different colors to class intervals but may also be accomplished by plots of actual observations. Programs have been devised which have the capability of

poses. Geographical outlines are computer-drawn by operator selection of any set of southwest/northeast coordinates. The program plots by matching coordinates with information intended for display. Points may be labeled by name (e.g., Hopi, Koobi Fora), arbitrary code (D-64), or associated datum (147 cm). Labels are limited to ten characters. Plotting accuracy is limited to nearest degree. Optional features include grid overlay and printing on high-gloss paper. Colors may be used to differentiate data sets. Isophenes (lines indicating class-interval boundaries) are currently hand-drawn from the plotted pattern of points. It is planned to develop a procedure to alter base maps by Pleistocene glacial and coastline oscillation. The technology exists to make projections three-dimensional or kinetic.

The goal is to combine the computerized mapping program with rates of evolutionary change, distance analysis,[3] and climatic correlation. Computer technology is being used as a kind of "time machine" to construct clinal maps for any point in time or geographical area, compare predictions with reference points (appendix), and calculate the probability of "correspondence" for a particular specimen to the empirical expectation (given multiple regression with time, sex, location, taxon, and climate).

Most of the necessary steps have been accomplished. A major remaining problem limiting completion is obtaining sufficient consensus on the reliability of the paleontological data. Files are as follows:

HOMDAT is a hominid data file containing 147 specimens with reported values of either cranial capacity or cranial index along with site, specimen number, estimated date, presumed sex, latitude and longitude, climate, taxonomic attributions, notes, and references. It is derived from 54 original and secondary sources.[4]

CRANDAT is a data base for cranial capacity reports among present-day ethnic groups. It contains 122 populations (noncomposite[5]), with observations on coordinates, endocranial volume among males and females, dimorphism by sex, sex-combined mean (0.5 [$\bar{x}$ males + $\bar{x}$ females]), heterographic area,[6] climatic zone, references, and method adjustments.

CLIMDAT is a composite file with 82 ethnic groups from which correlations between cranial morphology and specific climatic variables are calculated. Anthropometric traits which may currently be analyzed are cranial capacity, weight, stature, cranial capacity relative to weight, stature, and surface area, ponderal index, cephalic index, nasal index, coefficient of cranial morphology, and surface area:mass ratio. Surface area (Brown and Brengelmann 1965) is calculated by $m^2 = (0.202) \times (\mathrm{Wt})^{0.425} \times (\mathrm{St})^{0.725}$. All of the anthropometrics are sex-combined. Each of the populations has the following associated weather data:[7] solar radiation, total hours of sunshine, winter and summer vapor pressure, mean annual precipitation, winter and summer temperature, isothermic zone (Schwidetzky's classification), and climatic zone.

Since each data base has numerous references, interpretations from them are identified as hominid, cranial, or climatic files. Figure 1 plots coordinates for the 122 groups of the cranial file. Names of populations represented in the climatic files are overprinted in the vicinity of their locations. Copies of the data bases may be obtained from the authors. We are also able to merge the data bases with the much larger set of cultural distributions computerized by the Human Relations Area Files (HRAF), which contains information on up to 1,170 societies and 150 variables. Each merger is a kind of "quantum leap" in the number of questions that are answerable. For example, all of the anthropometric and climatic variations previously mentioned can be statistically compared with any of the cultural and environmental factors within HRAF. Figure 2 illustrates the application of the mapping program to cultural data. The present paper applies it to the evaluation of the bioclimatic model of cranial evolution.

NATURE OF THE EVIDENCE

Expansion of the braincase is probably the most widely discussed single trend of human evolution. There are now approximately 100 published reports of cranial capacity among adult Pleistocene specimens, and the reported range extends from 428 cm^3 (St-60) to 1,740 cm^3 (Amud).

Figure 3 depicts variation in the heterographic present. Microcephalic and hydrocephalic pathologies range from 350 to 2,900 cm^3. Normal individual variation extends from 900 to 2,100, while group means range from 1,085 to 1,518.

Because methods and interpretations have changed over time, any discussion of the trait must be done within a historical context. According to Todd (1923), the first attempt at measuring endocranial volume was made by Soemmering in 1785. The number of individual observations so far probably exceeds 20,000. By 1940, data collection on ethnic groups had virtually ceased (in part because of its association with racial prejudice). For modern populations, comparative data derive from museum specimens, private collections, and the by-products of historical archeology. Evidence from cadavers has been largely used for method comparison.

constructing isophenes by calculation. Among the oldest and most widely used is SYMAP (Sheehan 1979) It operates, however, in batch mode and is designed for line printer rather than graphics output. Algorithms for calculating isopleths have been described by Schmid and MacCannell (1955) and include nearest-neighbor indices, spatial autocorrelation, and various weighting techniques.

[3] The shortest distance between grid coordinates is calculated; observations of similarity are combined into class intervals and examined by trend analysis. The general expectation is that similarity declines as distance increases. Distance may be a possible factor in predicting data points in different geographical locations from known observations. It is unknown whether the reliability of the time-machine projections would be significantly enhanced by inclusion of a distance factor.

[4] References within files are coded by author and date. Complete citations for the hominid and cranial files can be obtained on request

[5] Noncomposite sets take coordinate difference as the unit of observation For example, the Gilyak of Sakhalin are counted independently from the Gilyak of the Amur region. Composite sets take ethnic group means as the unit of observation They are generally required to match reports on cranial capacity with additional anthropometrics We have used means of means rather than an average weighted by sample size The latter is not always available, for instance, body weights are sometimes national averages with a sample size given as "many." Furthermore, a weighted mean is not necessarily more representative of the type of climate to which groups may be exposed. Where, for example, a large sample is reported from southern China and a small sample from the north, a weighted "Chinese mean" would be less representative of the overall "Chinese climate."

[6] "Heterography" is an analogy to "ethnography" coined by Kelso (1966). It refers to the investigation of human biological variation through space and includes typological, populational, and clinal approaches. "Heterographic present" is an analogy to the "ethnographic present" but often differs from it in time. Much of the biological information on ethnic groups was collected after they were first known culturally. "Heterographic areas" (Beals and Kelso 1975) are major geographical areas having substantial barriers to gene flow.

[7] Weather variables were obtained by plotting the center of each ethnic group territory and assigning values from the nearest weather reporting stations to each such center. Monthly data were meaned at five-year intervals from 1955 on. Temperatures refer to warmest and coldest month maximum and minimum means. They nearly always occur in January or July, depending upon the hemisphere. Solar radiation is measured in langleys (ly = one gram calorie per cm^2 of earth surface) or kilocalories (kcal = energy to heat 1 kg of water 1° C). Atmospheric radiation includes both night and day conditions. Values within text are kcal per cm^2 earth surface Vapor pressure is expressed in millibars (mb = 10^3 dynes per cm^2) and measured as the mass of water (g) in a given volume of air (m^3). It is a reflection of absolute humidity, not to be confused with barometric pressure (1,013.2 mb at zero altitude) or relative humidity (ratio of vapor to amount at air saturation). Isothermic zones are Schwidetzky's (1952) scale and range from 1 (over 30°) to 6 (under 10°). Climatic zones are modified from Beals (1972) and based upon predominant types of thermal stress with annual precipitation.

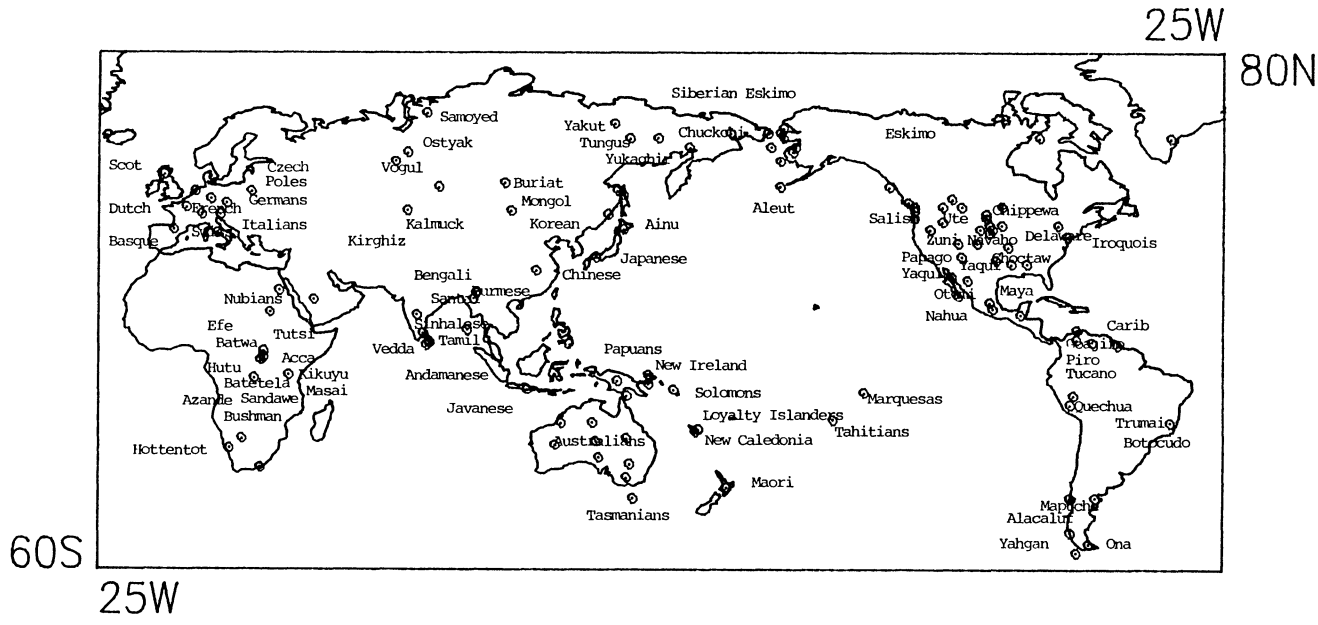

FIG. 1. Selected mapping program features and problems. Outline map is computer-drawn with boundary enclosure and location of 122 cranial capacity reports. Ethnic-group names from the cranial file are manually overprinted. Points are ordinarily labeled by name, numerical coordinate, or associated information. Labels were suppressed for the map above since they require excessive space when a large number of points are plotted. Overprinting and spacing problems are resolvable by using numbers rather than names and printing on a drum plotter rather than the table-top plotter used here.

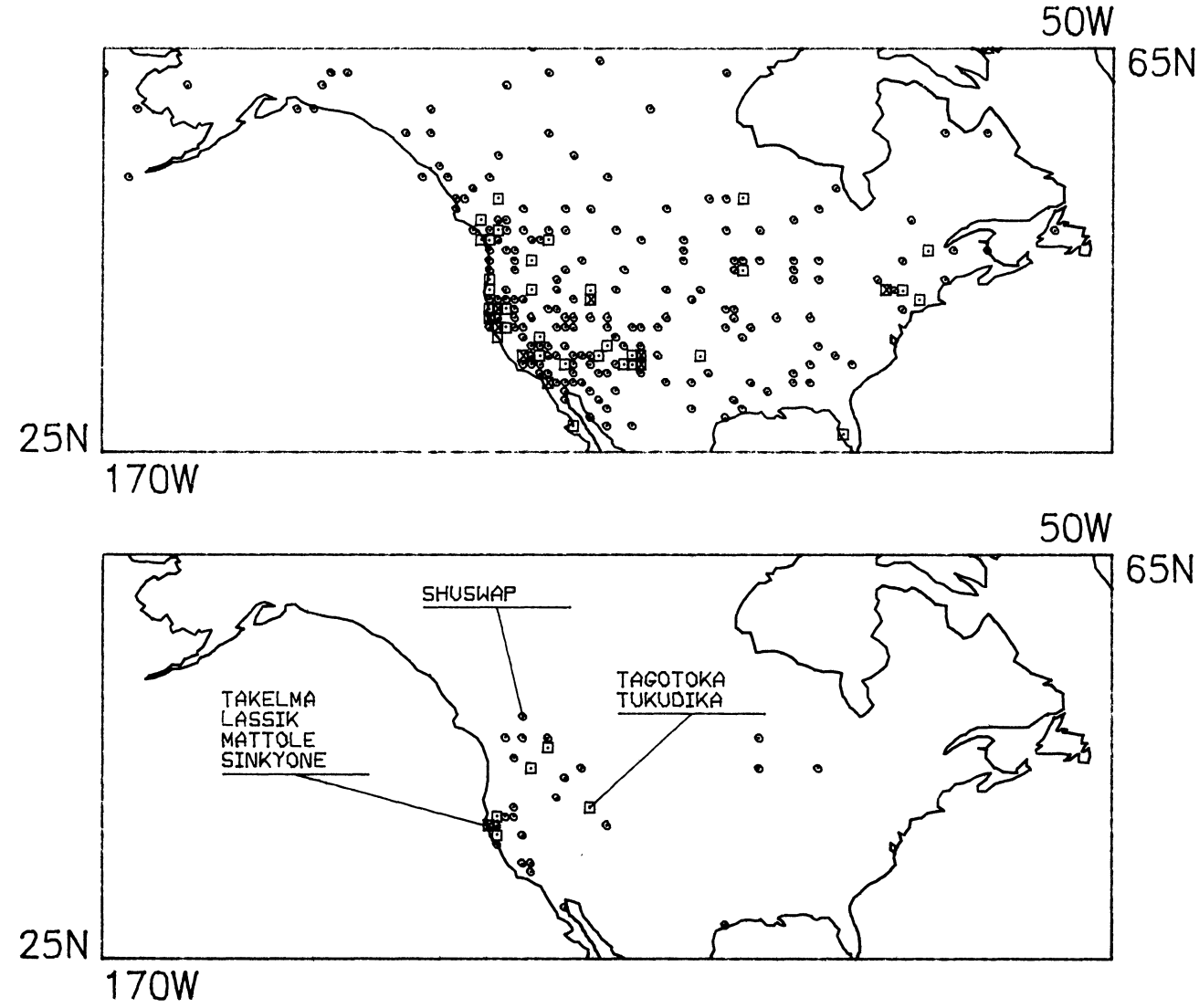

FIG. 2. Application of mapping program to ethnographic data. All *Ethnographic Atlas* cultures are included within the coordinates plotted. *Top,* location of groups at time of contact with European colonizers. The increased concentration of information toward the west is indication of more concern with acquisition of ethnographic data in conjunction with United States territorial expansion. *Bottom,* cultures depending upon fishing, hunting, and gathering in relatively equal proportions, a pattern concentrated among Plateau, Great Basin, and California coastal societies. Lower map illustrates label-datum lines. ⊙, single case; ⊡, two cases; ⊠, three or more cases.

Actual brain size may be measured by external dimensions, weight, or volume. Except for endocasts, evolutionary evidence is limited to measurement of the container. Works on methodology include Broca (1873), Welcker (1885), Todd (1923), Todd and Kuenzel (1925), Pickering (1930), Sankas (1930), Stewart (1934), Tildesley and Datta-Majumder (1944), Hambly (1947), Hrdlička (1952), Jørgensen and Quaade (1956), and Jørgensen, Paridon, and Quaade (1961).

Methods are divided into direct and indirect procedures. One indirect method is Pearson's formula for males of various racial groups,

$$cm^3 = (0.000365) \times (L \times B \times H) - 359.34,$$

in which L is length, B is breadth, and H is auricular height. Data derived by formula estimation are excluded. A few populations for which data are otherwise sparse are, however, estimated by cranial module. Module is a common measure of head size based upon the mean of the three diameters; $CM = \frac{1}{3}(L+B+H)$, where H is basobregmatic height. The relation between module and capacity was first noted by Hrdlička (1925) in connection with his practice of recording module at two decimal places (e.g., 15.20 for a male Solomon Islander). Dropping the decimal sometimes revealed surprising similarity to the volume as actually measured.

The association of module and capacity has been investigated by Sankas (1930). Unity occurs at a volume of approximately 1,540 cm^3, and percentiles (known as the capacity:module relation) vary by sex and shape (from around 70 to 110%, almost always less than unity and usually less in females and in linear head shapes). Conversion of cranial module (CM) to capacity (CC) requires matching by both sex and ethnic group. Given the lesser reproducibility of direct methods, it is unknown whether module conversions are more or less reliable than direct measurement.

It should be noted that, because endocranial volume is a cubic measure, cranial size and cranial capacity are not directly comparable. A small increase in external dimension produces a disproportionate increase in volume. To illustrate, Australian males have a reported module of 15.15, a cranial index of 69.9, and an endocranial volume of 1,309. Respective values for Buriat males are 15.33, 82.5, and 1,538. The comparative ratio of the module is 0.99, while the ratios for the cranial index and capacity are 0.85. In short, modules are almost identical while difference in capacity is substantial. Globularity of the container is the principal factor. Cranial thickness may also have a differential effect.

Most of the data were obtained by Hrdlička's direct method of mechanical packing with mustard seed. Broca's method of filling the cranium with shot is obsolete; however, it is a primary source of evidence in the historical context of brain size interpretation and is the only source of evidence for some populations. The procedure yields results which are greater than those of seed/water techniques and must be reduced for valid comparison. A standard 6% reduction is used for reports obtained with shot.

NATURE OF THE EXPLANATIONS

Alternative interpretations are mentioned during evaluation of the data. No single cause satisfactorily explains all the evidence. Each model has its successes; each has its failures. Four general paradigms have been proposed, which we label as phyletic, cognitive, somatic, and bioclimatic.

The underlying proximate explanation of the trait's variation through time and space is phyletic (similarity by descent). Encephalization among hominids is a particular segment of a general paleontological trend most pronounced among mammals and includes increases over time both in average brain size and in its diversity (Jerison 1970). Likewise, the proximate answer for any given ethnic group is its immediate ancestry.

Among ethnic groups, the explanation has historically been framed within a racial context. Reflecting the prevailing opinion of his time, Topinard (1878:229–30) wrote, for example, that "the inferior races have a less capacity than the superior" and that "cranial capacity seems to vary according to intellectual endowment."

The phyletic model (whether in terms of races or higher taxa) does not, of course, provide an effective answer, that is, specify the particular set of ecological relations which caused the evolutionary trend to occur. As in the above quotation from To-

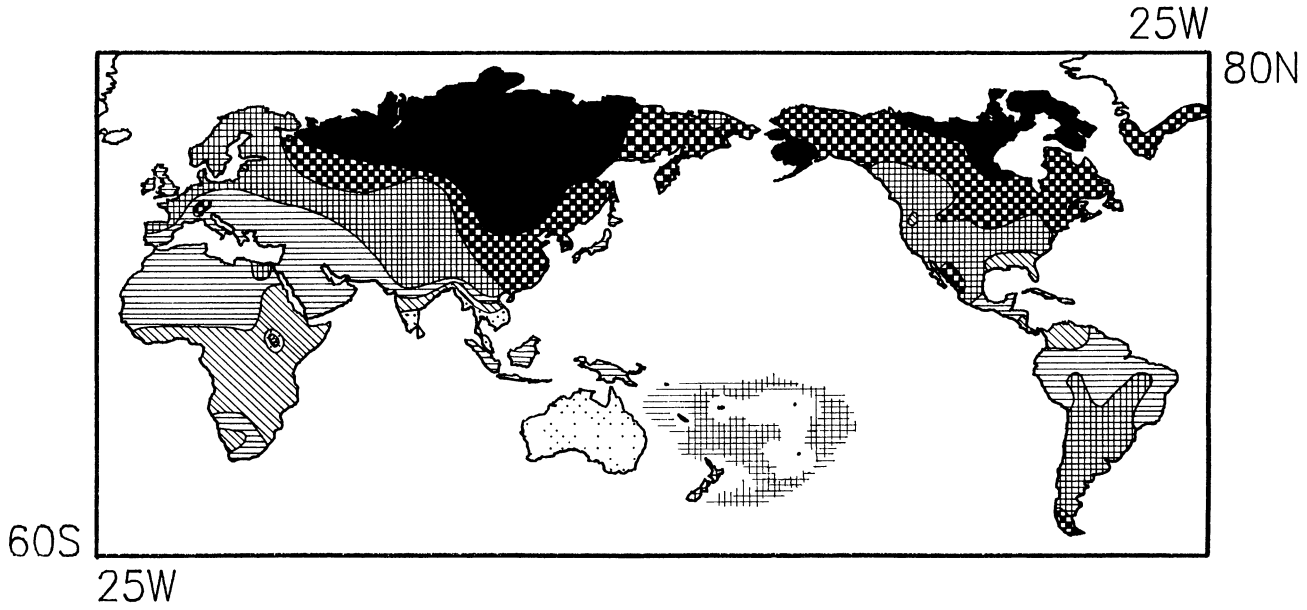

FIG. 3. Application of program for clinal depiction of cranial capacity (cm^3) at heterographic present. Outline map and data plots are computer-drawn for sex-combined means. Map assumes that report on Akka is valid and that West Africa is a continuation of surrounding pattern (see distribution of samples in fig. 1). *Black,* 1,450 and over; *checkerboard,* 1,400–49; *crosshatching,* 1,350–99; *horizontal striping,* 1,300–49; *diagonal striping,* 1,250–99; *dots,* 1,200–49; *circles,* under 1,200.

pinard, it is usually followed by a presumed effective cause (a cognitive difference for the case cited).

Cognitive models explain brain size in terms of mental function and associated behavior. Each species and individual has a cognitive map that affects modes of receiving, interpreting, and acting upon information. Application of the model requires that brain size be at least partially a function of behavior that influences reproductive success. Examples of such relations for mammals, as suggested by MacLean (1982), are nursing in conjunction with maternal care, audiovocal communication for maintaining mother-offspring contact, and playful behavior. Commonly assumed relations among hominids include effects of tool use and language.

The lowest endocranial volume ever reported among heterographic populations is 1,085 cm^3 among the diminutive Akka[8]—with a corresponding body surface area of 1.19 m^2. This exceeds the value for Lower Pleistocene hominids by at least 400 cm^3, even though body sizes are reasonably comparable. The evidence of Pilbeam and Gould (1974) also indicates that hominid brain size has increased more rapidly than any prediction based on compensations for body size would allow. It is, in short, difficult to explain the paleontological trend without assuming at least some degree of cognitive influence.

Yet if this assumption is made, one would expect to find supporting evidence among present-day groups. The search has historically focused upon IQ scores or levels of cultural potential, but no convincing case for such associations has ever been presented.

A third potential class of explanation is somatic—effect of body size upon brain size (other than that portion of body size attributable to climate). Sexual dimorphism, nutrition, and a host of other nonclimatic variables may have some effect, for example, ease of movement through underbrush or physical strength in predator defense, combat, or weapon use.

A general principle of mammalian phylogeny is that brain size increases as body size increases. There is, however, a disproportionate relationship. Jerison (1973) obtained a brain:body-weight ratio of 2:3. This is comparable to the increase in ratio of surface area to body weight and suggests that muscle and sensory innervation is the principal factor. Gould (1977:182–83) suggests "brain weight is not regulated by body weight, but primarily by the body surfaces that serve as end points for so many innervations." Recently, however, Martin (1981) has indicated a ratio of 3:4, implying that the determining factor is metabolic rate rather than surface area. In our climatic data, body weight statistically explains 39%, surface area 38%, and stature 6% of the variance in ethnic-group cranial capacity.

It is clear that factors in addition to body size are needed to explain the variation in cranial capacity. Populations with very large cranial capacity are not at corresponding extremes of weight, stature, or surface area. Furthermore, large differences in capacity can be observed when body size is virtually identical. For example, sex-combined surface areas for the Choctaw and Aleut are 1.60 and 1.59 m^2 respectively, while corresponding endocranial volumes are 1,292 and 1,518. Finally, braincase volume is more highly correlated with climate than any of the summative measures of body size. This suggests that cranial morphology may be more influenced by the thermodynamic environment than is the body as a whole.

A geometric factor needs to be added to the explanations previously discussed: volume of the brain container is affected by shape as well as size. Maximum volume occurs with a sphere ($V = 4/3\ [\pi\ r^3]$). Thomson (1903) demonstrated the connection between encephalization and brachycephalization experimentally by removing the calvarium and replacing the brain with a rubber bladder into which air could be pumped. Endocranial volume, then, is the result not simply of body size but also of cranial shape.

To our knowledge, the first suggestion that such morphology is a reflection of thermoregulation was given by Coon (1955:296): "It is easier to keep a small head cool than a large one. Witness the extreme dolicocephaly of hot-country peoples. In regions of great cold a large head is at an advantage from this point of view, as is a round one." From a geophysical perspective, the energy available to flora and fauna basically depends upon the earth's inclination to the sun. As high-energy photons of solar radiation decrease, the body and cranium must become more energy-conserving. Innovations such as specialized tools and controlled use of fire permitted occupation of areas of lower solar radiation and thereby set in motion a series of physiological and anatomical changes. Such trends of ecotypic differentiation should be observable in the fossil record—at least since the first significant exposure to winter frost (approximately a half-million years ago).

The selective mechanism capable of producing the required differential reproduction is a thermodynamic life crisis. It is not a matter of day-to-day comfort. The most obvious causes of death are hypothermia ("exposure") and heat stroke. These have probably always been relatively infrequent as a percentage of the total death rate. Thermoregulation, however, plays a contributory role within a spectrum of crisis situations such as shock, drowning, and traumatic injury. The same inventions (e.g., reindeer herding) that allowed occupation of regions other than the tropical savannah of origin may also have increased the probability of death in which thermoregulation plays a part (Steegman 1975).

This brief summary of explanatory models cannot convey more than a general outline. Critiques of the use of brain size in typology have been offered by Gould (1978, 1981). Tobias (1971) has reviewed the evolutionary evidence. Brengelmann and Brown (1965) have summarized physiological aspects of thermoregulation. General treatments of human bioclimatology occur in Coon (1965) and Flach (1981).

Our focus is the bioclimatic model, and the investigation suggests that approximately 30–40% of the variance in population means can be attributed to thermoregulation. The obvious question is, what explains the remainder? Part of the complexity is that all of the explanatory approaches (including our own) involve elements that produce nonsystematic variance and therefore complicate any general interpretation. Among them are statistical "noise" from measurement and sampling error, local circumstance (i.e., a famine that affects body size), stochastic genetic events affecting geographical distribution, and inventions that alter relative death rates.

CRANIAL CAPACITY AND CLIMATE

A summary of data on endocranial volume is given in table 1. The distribution forms a normal curve that is mesokurtic and slightly negatively skewed. Our averages for volume are somewhat less than the 1,400 cm^3 frequently cited as typical of modern humans. The latter figure historically derives from not adjusting the shot method and often considering Europeans or males as the model. We mention this because the magnitude of the difference is sufficient to affect interpretations of the rate of change over time.

As in physiology, it is convenient to have a standard of an "average" person. The physiologists' standard human is a reflection of their most common research subject—an adult male of European descent, with a weight of 70 kg and surface area of 1.73 m^2—who generates energy at the approximate rate of 85 kcal/hour when sitting. This is an output similar to that of

[8] The Akka pygmy report is questionably low. We are reluctant, however, to exclude original observations on the basis of statistical suspicion. Reports were excluded if based upon an individual, a nonstandard measurement technique, known distortion, or identification too vague to be useful, e.g., "164 Americans other than Mexicans."

TABLE 1

MEAN CRANIAL CAPACITIES (cm^3) FOR 122 ETHNIC GROUPS

SAMPLE	$\bar{X}$	RANGE	σ	$\sigma\bar{X}$	β	SKEW (−3)
Males	1,427	1,100–1,651	81.6	7.3	1.3	−0.5
Females	1,272	1,070–1,427	82.9	7.5	−0.7	−0.4
Combined	1,349	1,085–1,581	77.5	7.0	0.1	−0.5
Dimorphism	155	20–276	54.0	4.9	0.2	0.0

SOURCES. Biasutti (1958), Genovés (1970), Hrdlička (1924–42, 1925, 1942, 1952), Oetteking (1930), Martin and Saller (1959), Schlaginhaufen (1940), Sergi (1911), Stewart and Newman (1950), Todd (1923).

a hundred-watt light bulb (kcal = 1.16 watt). Normal daily heat loss is 16 kwh. Of this, only 4 kwh is replaced by food metabolism, and the remainder must be met by some combination of insulation (clothing) and atmospheric energy. The amount of atmospheric radiation available in combination with worldwide temperature and humidity is largely a function of latitude and varies from 557 cal per cm^2 per min between 0 and 10° N to 310 cal per cm^2 per min between 60 and 90° N (Flach 1981).

Our heterographic (in contrast to physiological) standard "human" represents the sex-combined world average under all types of climate, with each climatic zone given equal weight.[9] He/she weighs 54.1 kg and has a stature of 157 cm and a surface area of 1.525 m^2. This corresponds to a mass:area ratio of 35 kg per m^2, with an endocranial volume of 885 cm^3 per m^2 of surface area, 24.9 cm^3 per kg of weight, 8.6 cm^3 per cm of stature, 17.3 cm^3 per unit of cephalic index, and 32.4 cm^3 per unit of ponderal index. The typical human has for each cubic centimeter of brain mass 11.46 cm^3 of total body radiation/conduction/convection surface. (Dural contribution is approximately 50 cm^3 but is closely matched by shrinkage of the dried cranium.)

Table 2 tabulates heterographic data in traditional fashion—by continental area. If one merely lists such means by geographical region or race, causes of similarity by genogroup and ecotype[10] are hopelessly confounded. To illustrate, the percentage (TC/N) is given of samples within each continental area which also happen to be exposed to significant winter frost (temperate, wet cold, and dry cold areas). For example, 73% of the samples from Asia are native to areas of winter frost, compared with 100% of those from Europe. The correlation is 0.91 ± 0.08. This simple factor alone statistically explains 83% of the variance in capacity between major geographical regions. For the last column of table 2, we have used the resulting regression to predict the continental means. Comparisons are close; the average difference from actual observations is only 17 cm^3.

The implication is that any effort to attribute racial or cognitive significance to brain size is probably meaningless unless the effect of climate is controlled. For example, the endocranial volumes of Europeans and Africans differ little from what one would expect given the difference in their respective winters.

RELATION OF CRANIAL CAPACITY TO ITS COMPONENTS

The volume of the brain container is obviously a function of its dimensions and geometry. Increasing vault height and breadth relative to length thus increases capacity. Empirical relations between external dimensions and container volume relate to the time-machine project, since, if partial data are available, more reference points through time may be determined by prediction. The climatic file was used to correlate data with composite means of length, breadth, height, and module. A discriminant function indicated that the greatest contribution to the volume derives from breadth, followed by length and height. Intercorrelations are shown in table 3. The matrix illustrates the differing geometries of cranial size (module) and brain size (endocranial volume). The latter is primarily determined by breadth. To simplify, the proximate reason some groups have larger brains is that their heads are broader. While some of the increase in volume is due to a larger head (which in turn is due to a larger body—which in turn is partially due to thermoregulation), another portion derives from increased globularity of the container, again partially attributable to thermoregulation, with breadth playing the primary role.

In one sense, a larger brain can be explained geometrically. One might speak of brain size as being biophysical, while brain function is biocultural. In a larger perspective, there is no single cause of hominid encephalization, but rather an interplay of total ecology involving the magnitude of solar radiation, the principles of thermodynamics, and cultural innovations which led to adaptation within new econiches.

A multiple regression was calculated between volume and external measurement,

$$cm^3 = -403.9 + (80.6\ B) + (42.8\ L) - (9.3\ H),$$

which has a multiple R of 0.82 and applies to sex-combined

TABLE 2

SEX-COMBINED MEAN CRANIAL CAPACITIES (cm^3) FOR CONTINENTAL AREAS COMPARED WITH PREDICTED VALUES BASED ON CLIMATIC ZONE[a]

REGION	N	$\bar{X}$	σ	TC/N[b]	PREDICTED
North America	43	1,380	57	0.77	1,366
Asia	26	1,380	83	0.73	1,361
Europe	10	1,362	35	1.00	1,394
South America	12	1,350	42	0.50	1,333
Oceania	21	1,277	68	0.14	1,289
Africa	10	1,276	84	0.10	1,284

[a] Cases from temperate, wet cold, and dry cold climatic zones divided by total cases (N)

[b] Predicted $CC = 1{,}272 + 121.8\ (TC/N)$.

TABLE 3

CORRELATIONS BETWEEN COMPOSITE MEANS OF CRANIAL LENGTH, BREADTH, HEIGHT, MODULE, AND CAPACITY

TRAIT	LENGTH	BREADTH	HEIGHT	MODULE
BREADTH	0.13	...	...	...
HEIGHT	0.63	−0.11	...	...
MODULE	0.67	0.57	0.61	...
CAPACITY	0.36	0.78	0.06	0.53

[9] Crude averages, such as means of data tables, are usually disproportionately representative of particular regions or groups. For instance, the cranial file disproportionately represents North America because of the exhaustive catalogs of Hrdlička. In order to have a consistent and objective standard of comparison, we calculate sex-combined means for each climatic zone and then give equal weight to each zone. The result is an average morphology under all conditions of climate.

[10] Ecotypes are statistical aggregates associated with particular environmental conditions, such as climate. Genogroups are populations classified by common genetic heritage. The distinction is similar to that between analogous and homologous variation.

contemporary ethnic groups. Interestingly, when climatic zone was incorporated into the analysis, it made a greater contribution to the variance than either length or height.

For the time machine, more reference points may be obtained by satisfactorily predicting the cranial capacity of fragmentary specimens (if breadth is known) by including the climate from which the specimen originates. Beyond this, the extent of geometric influence upon volume leads us to reconsider the generally presumed taxonomic significance of brain-size difference between contemporary hominids, such as *H. habilis* and *Australopithecus*. The question is whether this difference is a variation that has behavioral significance (which in turn may or may not have reproductive-isolation meaning) or a slight variation in cranial geometry. Among present-day groups, large differences in the capacity of the container are known to have no reproductive-isolation consequence. They result instead from small differences in absolute dimensions.

Correlations were calculated among all the climatic and anthropometric variables; a summary of linear relations between capacity and other traits is shown in table 4. Overall patterns between the size (volume) and shape (cephalic index) are virtually identical; they increase together, increase with weight and surface area, decrease with nasal index, and are only weakly associated with stature.

Cranial Capacity and Climatic Zone

The basic test of bioclimatic theory is comparison of population means in regions exposed to winter frost (temperate, wet cold, and dry cold regions) with those from regions of dry or wet heat. Table 5 contains the summary from the cranial file. The global mean for populations in temperate and cold climates is 1,386 ± 6.7, while that for hot-climate populations is 1,297 ± 10.5. The absolute difference of 89 cm^3 is highly significant ($t = 7.5$, $p = <0.0001$). The lower variance of temperate/cold groups is also significant ($F = 1.69$). The same pattern of the means occurs within each continental area; there are exceptions to the rule with individual groups, but the means are invariably higher for temperate/cold cases within each geographical division. Figure 4 shows climatic zones as based upon generalized, predominant types of thermal stress. Figure 5 illustrates the trends which result from plotting the means for each climatic zone separately. Table 6 summarizes correlations of climatic zone with 11 morphological traits. Head morphology in size, shape, and nasal form is more closely related to climate than is the body as a whole.

Cranial Capacity and Latitude

Grid coordinates in the hominid file are supplied for each site. By taking selected segments of time, it is then possible to evaluate spatial trends which may be helpful in predicting the required data points for the clinal maps. This allows spatial comparisons between the past and the present. A general feature of hominid evolution has been occupation of the globe beyond the tropical savannah of origin. The bioclimatic model predicts that cranial capacity will increase with distance from the equator—latitude being correlated with a decrease in solar radiation. Latitude is actually intercorrelated with a number of climatic conditions, relationships of which produce a high

TABLE 4

CORRELATIONS BETWEEN COMPOSITE MEANS OF CRANIAL CAPACITY, WEIGHT, STATURE, SURFACE AREA, CRANIAL INDEX, AND NASAL INDEX[a]

	CRANIAL CAPACITY	WEIGHT	SURFACE AREA	CRANIAL INDEX	NASAL INDEX
WEIGHT	0.63	...	...	...	...
	(0.001)				
SURFACE AREA	0.61	0.96	..	.	..
	(0.001)	(0.001)			
CRANIAL INDEX	0.37	0.36	0.26	...	..
	(0.001)	(0.004)	(0.032)		
NASAL INDEX	−0.46	−0.55	−0.55	−0.40	...
	(0.001)	(0.001)	(0.001)	(0.001)	
STATURE	0.24	0.71	0.87	−0.04	−0.29
	(0.024)	(0.001)	(0.001)	(0.362)	(0.004)

[a] Figures in parentheses are significance levels.

TABLE 5

DISTRIBUTION OF SEX-COMBINED MEAN CRANIAL CAPACITIES (CM^3) FOR ETHNIC GROUPS BY CONTINENTAL AREA IN RELATION TO PRESENCE OR ABSENCE OF WINTER FROST

	CLIMATIC ZONE							
	Wet or Dry Heat				Temperate or Cold			
REGION	N	$\bar{X}$	σ	$\sigma\bar{X}$	N	$\bar{X}$	σ	$\sigma\bar{X}$
Old World								
Europe	...	...	...	...	10	1,362	35	11
Africa	9	1,268	85	28	1	1,344	...	...
Asia	7	1,284	81	31	19	1,415	51	12
Oceania	18	1,275	67	16	3	1,288	91	52
Total	34	1,275	73	12	33	1,385	63	11
New World								
North America	10	1,352	56	18	33	1,389	55	10
South America	6	1,333	43	18	6	1,366	37	15
Total	16	1,345	51	13	39	1,386	53	9
Grand Total	50	1,297	74	10	72	1,386	57	7

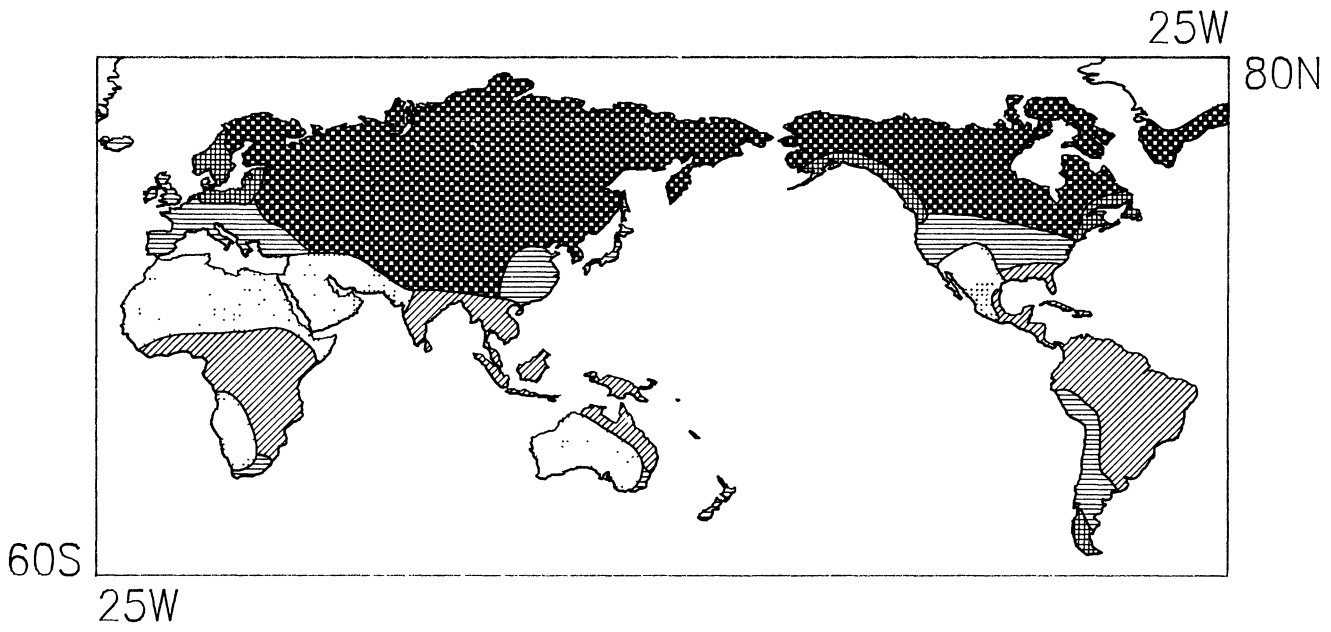

FIG. 4. Zones of predominant types of climatic stress. *Checkerboard,* dry cold; *crosshatching,* wet cold; *horizontal striping,* temperate, *diagonal striping,* wet heat; *dots,* dry heat.

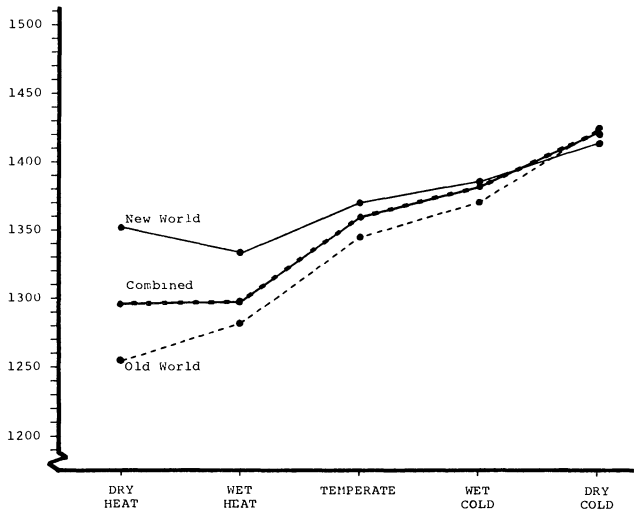

FIG. 5. Mean cranial capacity (cm^3) by climatic zone.

TABLE 6

CORRELATIONS OF CRANIAL MORPHOLOGY AND TOTAL BODY VARIABLES WITH CLIMATIC ZONE[a]

TRAIT	*r*	*N*	*p*
Cranial capacity:stature (cm^3 per cm)	0.68	67	0.001
Cranial capacity	0.65	67	0.001
Nasal index	−0.49	82	0.001
Suface area:mass (m^2 per kg)	−0.47	52	0.001
Cephalic index	0.46	82	0.001
Ponderal index	−0.46	52	0.001
Weight (kg)	0.38	52	0.003
Surface area (m^2)	0.27	52	0.024
Cranial capacity:surface area (cm^3 per m^2)	0.25	37	0.068
Cranial capacity:weight (cm^3 per kg)	−0.17	37	0.153
Stature (cm)	−0.05	82	0.335

[a] Climatic zone is coded from 1 to 5 for dry heat through dry cold

correlation with capacity ($r = 0.62$, $p = 0.00001$). On a global scale, each degree of equatorial distance adds 2.5 cm³ to the volume. Volume as a function of latitude is shown in figure 6. This scattergram also indicates one of the reasons the validity of the record low report among the Akka is statistically questionable.

Since Oceania, the New World, and the Old World have had different occupation patterns over time, latitude associations within them were examined. Some of the comparative data are shown in table 7. As anticipated, rates in different parts of the world vary according to their culture histories. The highest slope of 3.1 cm³ per degree of distance from the equator is found within the African-Eurasian landmass, which has long been occupied by hominids. As also expected, the association is random within Oceania, where occupation is recent and there is little cold stress.

The Americas provide a unique test of the theory, since there is a known point of origin (the Bering Strait), a known period of adaptation, and a known direction of dispersion (toward the equator and through a funnel of tropical forest in Central America). These circumstances predict that the mean of the trait will be higher in America, the point of regression origin from the equator higher, and the slope of the regression lower. All three of these are empirically observable.

American data also indicate that braincase volume can change rapidly in response to climatic conditions. The slope from the equator to a distance equivalent to the Bering Strait (65°) amounts to an average difference of almost 100 cm³. Assuming an initial entry of 35,000 B.P. and a 5,000-year period for occupation of the various ecozones, then the systematic adaptive pattern observed in the clinal maps is a reflection of only 30,000 years' development. This implies a rate of change greater than 3,000 cm³ per million years.

Cranial Morphology and Climate

During the general course of hominid evolution, the cranium tends simultaneously toward both larger size and rounder shape. Even if size remains the same, volume increases as the ratio of length to breadth decreases. The two trends together can be considered a trend toward globularity. Reduction of the browridges may also be a part of the process—large ridges increase surface area. The overall effect produces a simpler and more regular cranial topology, along with a more pedomorphic appearance. Perhaps the morphological complex sometimes attributed to neotenous mutation may be more a question of biophysics.

At any rate, cephalic index and cranial capacity are expected to have interactive effects. If so, the correlation of both with climate should be higher than with each separately. Their multiple regression is

$$CZ = -16.4 + 0.0088\,(CC) + 0.091\,(CI),$$

and there is a significant additive effect, with a multiple R of 0.69.

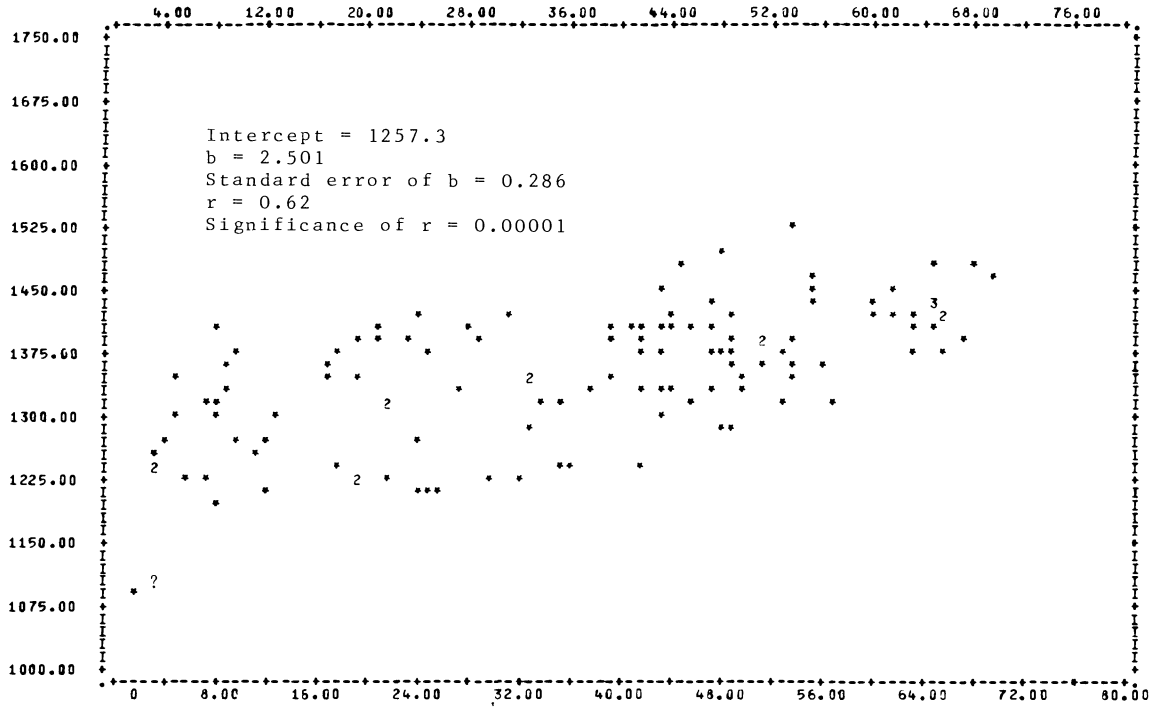

FIG. 6. Distribution of sex-combined mean cranial capacity among 122 populations as a function of distance from the equator. Axes are cranial capacity (cm³) and absolute degrees north or south latitude. Question mark refers to Akka report. Numbers on scattergram are multiple cases.

TABLE 7

CRANIAL CAPACITY (CM³) AND LATITUDE WITHIN MAJOR WORLD REGIONS

REGION	*N*	*O*	*b*	*r*	*p*
New World	55	1,313.8	1.452	0.44	0.0004
Oceania	21	1,296.2	−0.982	−0.17	0.2329
Old World	46	1,232.8	3.069	0.76	0.0001
Old World + Oceania	67	1,235.1	2.844	0.68	0.0001

NOTE: *N*, number of means; *O*, origin at equator; *b*, slope from equator; *r*, coefficient of correlation; *p*, significance level.

While multiple regression allows for interaction between size and shape, it is desirable to plot a composite value which at least crudely corresponds to one's visual perception of a specimen. We are, however, limited to the cephalic index and volume as imperfect measures of the actual morphology. As a point of reference, we return to our heterographic standard human. With each climatic zone having the same weight, the global mean cephalic index is 78.0. The cranial and cephalic indices are not, however, identical, again primarily because of geometry. Since the head is oval rather than spherical, removal of approximately equal tissue from the circumference lowers the length:breadth ratio (Krantz 1980*a*). On the average, the cranial index is about 1.5 units lower. Subtracting this magnitude leaves 76.5 as the standard for comparison with the fossil record. The analogous reference point for volume is 1,353 cm^3.

Visual appearance is a matter of cognition. For simplicity we give size and shape equal weight and calculate a coefficient of cranial morphology:

$$CCM = \tfrac{1}{2}\,[(\text{obs.}CC/1{,}353) + (\text{obs.}C^rI/76.5)] - 1.$$

When length:breadth ratio is combined with volume, their individual contributions to the visually perceived morphology are lost; individual components are therefore included in the data files. The coefficient is standardized to a mean of zero, and differences from the mean are percentage values from a typical modern human under all types of climate. Positive values should be associated with cold environments, negative values with hot ones. The coefficient can also be used as simple description without any climatic implications. For instance, a baseball has a coefficient of −0.27, a slow-pitch softball 0.01, a volleyball 1.45. More to the point, the lowest coefficient from a Pleistocene adult for which we have information is Sterkfontein 5 (−0.38) and the highest Grotte des Enfants 4 (0.13). This merely indicates a range for purposes of comparison; any climatic implication requires matching with reasonably corresponding time.

In the paleontological record as a whole, more relative change has occurred with volume than with shape. The lowest cranial index for an adult known to us is Sangiran 4 (62.8). It has a ratio to the heterographic standard human of 1.22, whereas the corresponding ratio for cranial capacity (Sterkfontein 60, 428 cm^3/1,353 cm^3) is 3.16. For some reason, however, there is a reversal of these relationships in the comparison between the Upper Paleolithic and the heterographic standard human, in which volume decreases while roundness increases dramatically. For modern populations, the coefficient should vary by ecological adaptation. The range is from the Vedda (−0.10) to the Buriat (0.11). Figure 7 illustrates the distribution.

Brain Size and Climatic Variables

Highs and lows (normal) and means of the seven climatic variables for the 82 populations in the climatic file are shown in table 8. Kikuyu data are selected as representative of a current tropical savannah. Tropical savannahs are relatively uniform, with more of a wet/dry seasonal difference than a summer/winter one. They represent the climatic ecology of the ancestral hominid homeland. Most present-day populations are exposed to lower winter temperature and lower vapor pressure, and these latter two factors might be anticipated to have the highest correlations with contemporary anthropometric means. The correlation matrix is given in table 9.

Climatic influence on relative brain size is likely to be more interesting than that on the absolute value. Table 10 summarizes the available data on the distribution of braincase volume relative to weight, stature, and surface area. Groups with large volumes per unit of mass include San (33.4 cm^3 per kg), Andamanese (27.6), and Bengali (27.8). Groups with small volumes per unit of mass include Choctaw (20.8), French (22.0), Mapuchi (22.1), and Maori (22.1). An overall relation between cranial capacity and body mass is clear from these examples. Brain size in relation to weight follows the mammalian pattern. As previously mentioned, the greater the body weight, the smaller the relative volume of the cranium.[11] The linear correlation of weight with cranial capacity is 0.63 ± 0.10; the correlation of cranial capacity with cranial capacity:weight ratio is −0.16 ± 0.16. Incidentally, greatest mass is not an arctic phenomenon. The empirical model for extreme cold is moderate weight, moderate stature, moderate nasal index, moderate brain size per unit of weight, but large absolute cranial capacity, large cranial capacity per unit of stature, round cra-

[11] Conventional interpretation of brain weight (E) to body weight (P) is the allometric relation $E = K \times P^{0.67}$. However, Martin's (1981) work indicates taxonomically variable slopes. For placental mammals, his regression is $(\log_{10} E_m) = 0.76\,(\log_{10} P) + 1.77$, with E_m in milligrams and P in grams

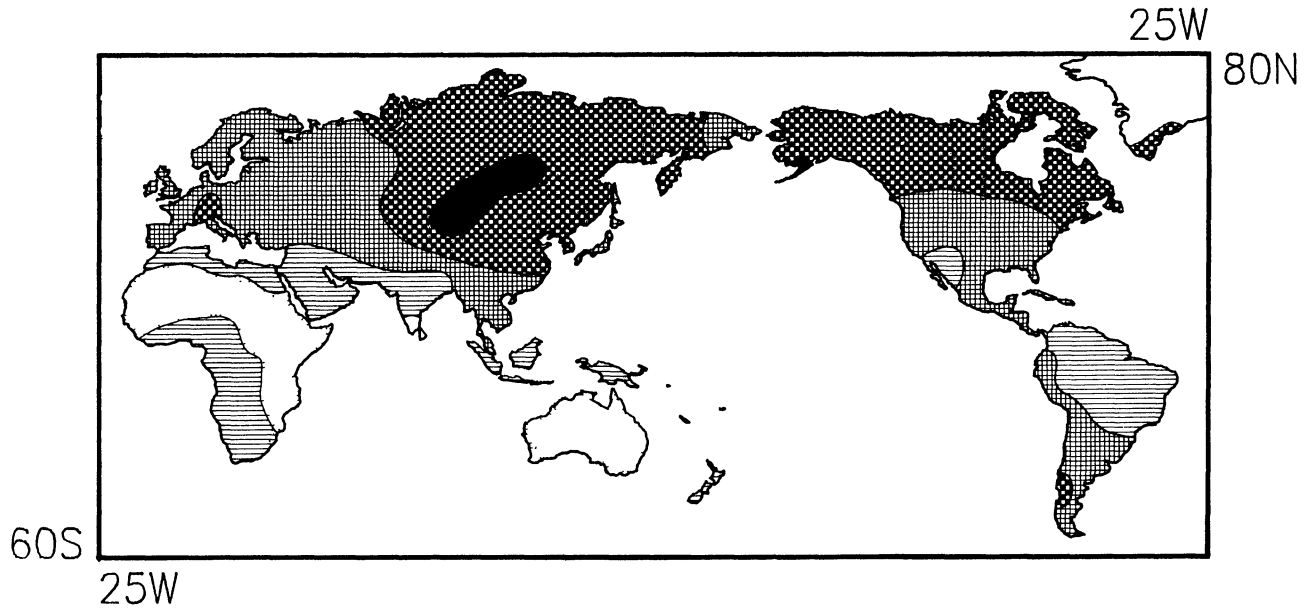

FIG. 7. Coefficient of cranial morphology at heterographic present. Class intervals are percentage of difference from world mean set at zero. *Black,* 10–14%; *checkerboard,* 5–9%; *crosshatching,* 0–4%; *horizontal striping,* 0–(−4)%; *dots,* −5–(−9)%; *white,* −10–(−14)%.

TABLE 8

VALUES OF CLIMATIC VARIABLES FOR POPULATIONS IN THE CLIMATIC FILE

VARIABLE	NORMAL MAXIMUM[a]	GROUP COMPOSITE[b]	MEAN FOR TROPICAL SAVANNAH[c]	NORMAL MINIMUM[a]
Solar radiation (kcal per cm²)	220 (Nubians)	132	150	70 (Yahgan)
Sunshine (annual hours)	4,200 (Nubians)	2,264	2,000	1,500 (Mapuche)
Winter vapor pressure (mb)	32 (Vedda)	15	25	1 (Eskimo)
Summer vapor pressure (mb)	33 (Maya)	14	23	1 (Chukchi)
Annual precipitation (cm)	450 (Andamanese)	118	100	5 (Nubians)
Winter temperature (°C)	29 (Tucano)	8	15	−38 (Yakut)
Summer temperature (°C)	35 (Papago)	22	26	6 (Siberian Yuit)

[a] Highs and lows are extremes for normal (not record) weather patterns

[b] Mean for all 82 groups.

[c] Data associated with Kikuyu (1°S 137°E), taken as reasonably typical of Lower Pleistocene environment within Africa

TABLE 9

CORRELATIONS BETWEEN INDICATORS OF CRANIAL MORPHOLOGY AND INDIVIDUAL CLIMATIC VARIABLES

	N	CZ	SR	HRS	WVP	SVP	PRE	WTM	STM	ISZ
CC	67	0.645	−0.573	−0.335	−0.510	−0.497	−0.327	−0.637	−0.482	0.598
		(0.001)	(0.001)	(0.002)	(0.001)	(0.001)	(0.003)	(0.001)	(0.001)	(0.001)
CC:St	67	0.683	−0.551	−0.407	−0.404	−0.421	−0.215	−0.641	−0.471	0.536
		(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.041)	(0.001)	(0.001)	(0.001)
CC:Wt	37	−0.173	0.410	0.389	0.299	0.024	0.025	0.112	0.146	−0.295
		(0.153)	(0.006)	(0.009)	(0.041)	(0.443)	(0.442)	(0.254)	(0.194)	(0.038)
CC:SA	37	0.249	0.060	0.129	0.071	−0.138	0.030	−0.215	−0.096	0.014
		(0.068)	(0.363)	(0.223)	(0.338)	(0.208)	(0.431)	(0.101)	(0.286)	(0.468)
CCM	66	0.689	−0.610	−0.393	−0.485	−0.452	−0.182	−0.623	−0.426	0.633
		(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.072)	(0.001)	(0.001)	(0.001)
CI	82	0.456	−0 338	−0.221	−0.287	−0.224	0.029	−0.390	0.141	0.455
		(0.001)	(0.001)	(0.023)	(0.005)	(0.021)	(0.399)	(0.001)	(0.104)	(0.001)

NOTE: Figures in parentheses are significance levels *CZ*, climatic zone, *SR*, solar radiation; *HRS*, annual hours of sunshine, *WVP*, winter vapor pressure; *SVP*, summer vapor pressure, *PRE*, annual precipitation, *WTM*, coldest-month mean low temperature; *STM*, warmest-month mean high temperature, *ISZ*, isothermic zone; *CC*, cranial capacity, *St*, stature; *Wt*, weight, *SA*, surface area, *CCM*, coefficient of cranial morphology; *CI*, cephalic index.

nium, and low surface area:mass ratio. Brain size relative to stature[12] has significant associations with all of the climatic variables. It also has the highest correlation with winter temperature ($r = -0.64 \pm 0.07$) of any of the six cranial variables. Groups with high ratios include Aleut (9.8 cm³ per cm), Eskimo (9.8), Yakut (9.6), and Yukaghir (9.6). Groups with low ratios include Australians (7.7), Nubians (7.4), and Sinhalese (7.8). The ratio is a good indicator of climatic conditions, and we assume that a large endocranial volume in combination with moderate to short stature would be particularly indicative of cold adaptation during the Pleistocene—as is indeed observed among Glacial Neandertals. Figure 8 depicts geographical variation for the heterographic present. The Old World has a striking southwest-northeast cline, while New World variation is more regular with distance from the equator. Extremely low values around the East African Horn are consistent with the world's greatest physiological heat stress.

Climate is a multivariate phenomenon, and questions arise with regard to the relative importance of its components. In the general summary of table 9, volume (CC) has higher correlations than shape (CI), but there is sufficient interaction to produce the highest associations known in the coefficient of cranial morphology. Generalized classifications (climatic zone and isothermic zone) tend to have higher correlations with the morphology than do individual climatic variables. Climatic zone produces the highest correlations with the traits and is also the most applicable to the fossil record. With respect to both temperature and vapor pressure, winter conditions are more important than those of the summer. We assume that annual precipitation has no morphological effect in itself and that the occasional significant correlations with the anthropometrics are attributable to synergistic relationships between precipitation, temperature, and vapor pressure. There is little difference in the associations between vapor pressure of the summer and winter. As one would anticipate from the dispersion pattern of hominids, major types of adaptations are to

[12] "Relative" brain size normally refers to brain:body-weight ratio. "Relative" as used here includes a greater number of comparisons, i.e., cranial capacity relative to surface area, weight, and stature—each of which is individually identified to avoid confusion. All reference to surface area comes from calculation dependent upon weight and stature. It is possible (but impractical) to estimate surface area directly by the "mummy wrap" method occasionally attempted in physiology. Ethnic group data for directly measured surface area are virtually nonexistent. Topics of brain:body relations that we consider beyond our present scope include lean body mass, differential body composition, brain-weight:endocranial-volume correlation, and functional significance of the neurology. Discussion of surface area calculation, metabolic rate, and lean body mass is given by Brown and Brengelmann (1965).

TABLE 10

CRANIAL CAPACITY (CC) RELATIVE TO WEIGHT, STATURE, AND SURFACE AREA[a]

RELATION	*N*	$\bar{X}$	RANGE	σ	*CV*[b]
CC:Weight	37	24.75	20.8–33.8	2.5	10.3
CC:Stature	67	8.60	7.4–9.8	0.5	6.4
CC:Surface area	37	875.59	769.0–1,000.0	54.0	6.2

[a] Data based on population means.

[b] Coefficient of variation

reduced energy from the sun, lower absolute humidity, and the rigors of a cold winter.

SUMMARY

1. Variation in endocranial volume among ethnic groups is partially explicable by thermoregulation. It is significantly associated with every climatic variable examined and has the highest correlations of any single morphological trait considered. Furthermore, the mechanism of thermodynamic life crisis relates the biophysics to differential reproduction, which in part explains not only the present variation but also the trend of encephalization.

2. Average cranial capacity is not as great as is generally assumed. There are historical reasons for this; the larger figures of the past result primarily from not adjusting for the overestimation of Broca's measurement procedure. The world mean depends on how one chooses to weight reports. We suggest 1,353 cm^3 as an appropriate estimate. This reflects sex-combined ethnic groups under all conditions of climate.

3. From a structural perspective, the greatest contribution to volume is from breadth. Different populations have different cranial geometries. Most simply stated, some groups have larger brains than others because their heads are rounder. Arctic peoples obtain large capacities not so much from large heads as from a more globular shape. The high correlation between breadth, climate, and absolute volume leads us to believe that if breadth can be obtained from fragmentary fossil specimens, cranial capacity can be reasonably estimated.

4. As anticipated from conditions of solar energy, the brain container volume and latitude are highly correlated. The world average slope is 2.5 cm^3 per degree of latitude, but the slope is substantially sharper in the Old World. Latitude associations are supported by the culture history of each continental area.

5. The evidence suggests that thermoregulation has more effect upon the cranium than upon the body as a whole. The highest correlations occur with the coefficient of cranial morphology, absolute volume, and capacity relative to stature. Lower correlations are observed with surface area:mass ratio, cephalic index, nasal index, and ponderal index. Lower yet (but still significant) are the correlations with weight and body surface area. Stature and cranial capacity relative to weight and surface area appear to have but negligible associations with climate.

6. Generalized climatic classifications usually have higher associations with anthropometrics than specific variables. The strongest individual effects occur with solar radiation, winter temperature, and vapor pressure. Winter conditions are more important than those of the summer. The overall pattern fits with hominid dispersion from a tropical savannah.

7. We find little support for the use of brain size in taxonomic assessment (other than with paleontological extremes over time). Racial taxonomies which include cranial capacity, head shape, or any other trait influenced by climate confound ecotypic and phyletic causes. For Pleistocene hominids, we doubt that the volume of the braincase is any more taxonomically "valuable" than any other trait. Ecotypic differentiation (fig. 9) appears sometimes greater than average taxonomic difference. A slight increase in head size combined with a rounder cranium has a disproportionate effect upon volume. Even with absolute capacity difference, a connection to reproductive isolation is questionable given the lack of such connection among modern peoples.

8. The bioclimatic model provides a fairly powerful explanation of several morphological traits. It likewise accounts for a portion of the trends toward brachycephalization and encephalization. We suspect that it may play a role in browridge reduction as well as, certainly, in the evolution of body size. It is not, however, a full explanation of the paleontological trends. In the first place, adaptation to cold is limited to approximately the last half-million years. Second, crania become more capacious and rounder even among fossil ecotypes not exposed to winter frost (table 11, fig. 9). Climatic adaptation is apparently superimposed upon other causal mechanisms. It is possible that cognitive and somatic factors could account for a portion of the unexplained variance. If so, it is likely that the weight of climatic, somatic, and cognitive effects varies over time. We conjecture that prior to around 200,000 B.P., encephalization was primarily the result of a combination of selective advantage in mental/linguistic capacity and larger body size with associated energy efficiency. We further conjecture that within our own species (including Neandertals) climatic factors have become the principal source of the variation.

9. The explanation of human brain size difference has historically been colored by a search for "the cause." This tradi-

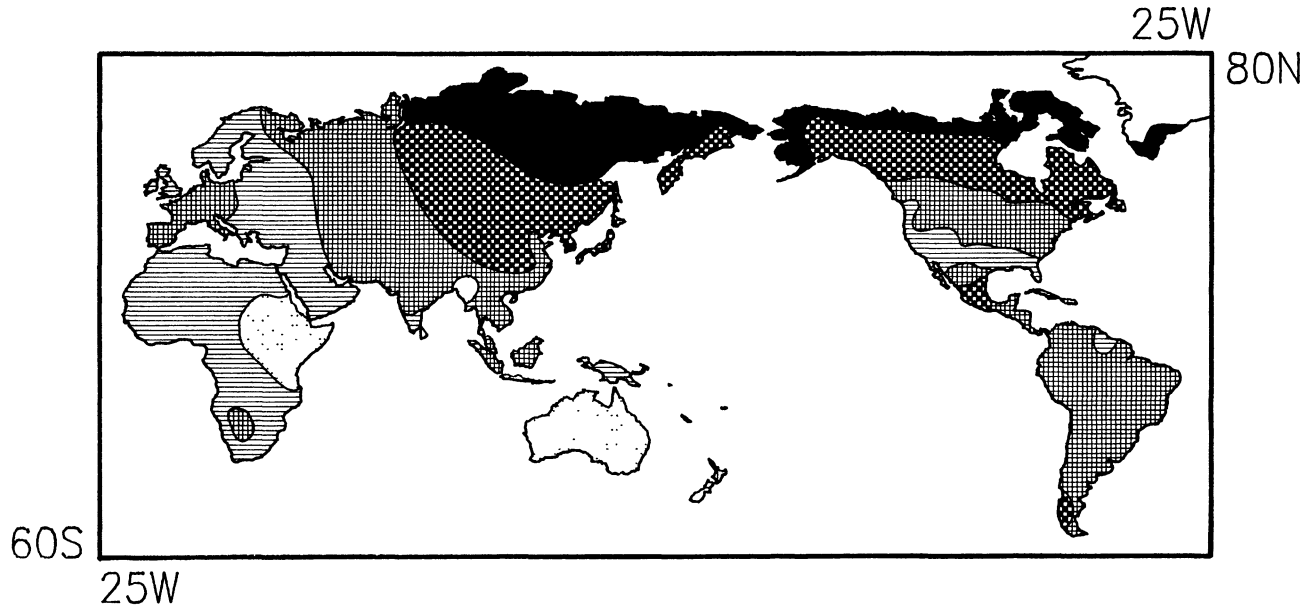

FIG. 8. Distribution of cranial capacity relative to stature (cm^3 per cm). *Black,* 9.5–9.9; *checkerboard,* 9.0–9.4; *crosshatching,* 8.5–8.9; *horizontal striping,* 8.0–8.4; *dots,* 7.5–7.9.

tionally focused upon difference in mental ability or race. Neither has been shown to have any significant direct effect. The distribution indicates that racial means are actually reflections of secondary correlation with climate. For example, Native Americans have a common ancestry but almost the entire range of variation in cranial capacity. The cognitive model requires that mental function change not only the internal organization of the brain, but also its absolute size. It is not supported by any preponderance of direct evidence from either psychology or ethnology.

Interpretations have more recently turned to body size, but no measure of this explains more than 40% of the variance. Metabolic rate as "the cause" cannot be directly evaluated for lack of ethnic group data. Yet given the association between capacity and shape, the need for a multiple-factor interpretation remains evident. Heterographic evidence supports Thomson's (1903) almost ignored experimental work.

With an ever broader perspective, cognition is part of the answer in an indirect manner—through cultural inventions which led to occupation of the world's diversity of ecological zones. "The cause," in short, does not exist. Explaining the variation in human brain size requires a synthetic theory, portions of which best apply to given particulars of time and space.

APPLICATION TO THE TIME MACHINE: HYPOTHESES AND INTERACTIONS

To investigate the paleontological evidence, the combination of data processing technology and the unique format of CURRENT ANTHROPOLOGY permit an interactive feedback with respondents. Within this section we attempt an experiment in which the respondent is invited to select a problem, data set, and type of analysis. Within limits of response space, we will apply files to the requested description, analysis, hypothesis, or map—including whatever additions or corrections to the

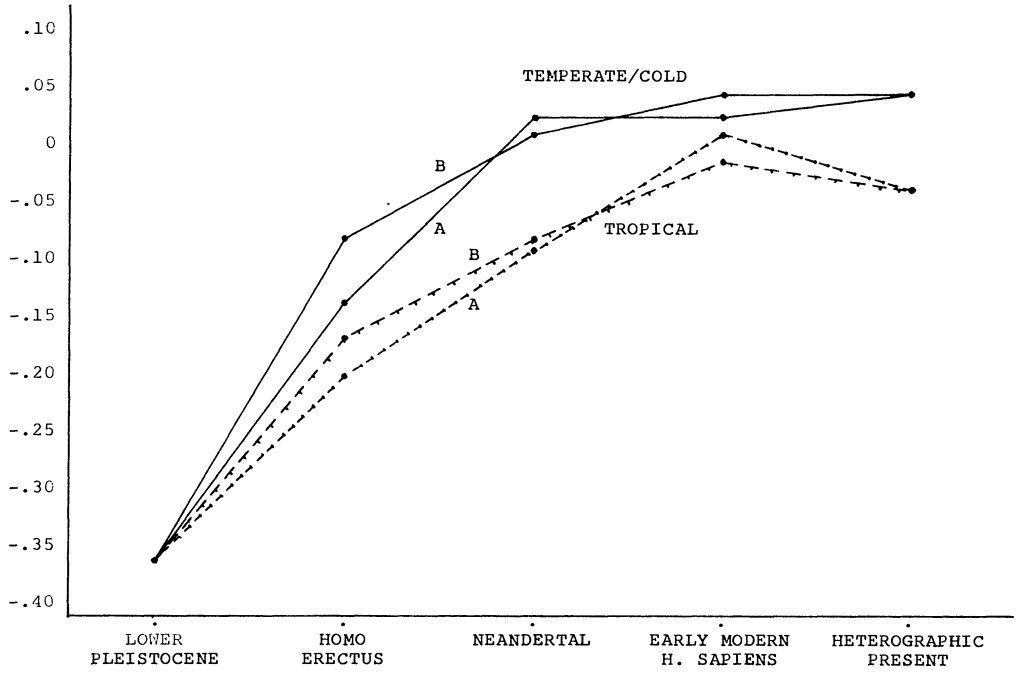

FIG. 9. Postulated approximate effect of occupation of temperate and cold regions on coefficient of cranial morphology. Data are plotted from table 11 and give equal weight to ecotypic means. Letters *A* and *B* refer to gradualist and alternative attributions as listed in appendix. Other weighting systems generally produce less differentiation. The bioclimatic model produces ambiguous interpretations for *H. erectus* and early modern *H. sapiens*. Increase through time occurs within the tropics as well as in temperate and cold regions and indicates that nonclimatic factors are also required to explain the evolutionary trend.

TABLE 11

CRANIAL MORPHOLOGY BY TAXON AND ECOTYPE IN EARLY *Homo*

	"GRADUALIST" MODEL			ALTERNATIVE MODEL		
	CI	CC	CCM	CI	CC	CCM
H. erectus						
Tropical.....	70.0	918	−0.20	71.4	997	−0.17
Temperate.....	73.5	1,014	−0.14	73.5	993	−0.15
Glacial.....	...	...	...	80.0	1,273	−0.01
Neandertal						
Tropical.....	70.0	1,200	−0.09	71.7	1,213	−0.08
Temperate.....	73.9	1,493	0.03	75.6	1,359	0.00
Glacial.....	77.1	1,400	0.02	76.9	1,412	0.02
Early modern *H. sapiens*						
Tropical.....	71.1	1,471	0.01	70.0	1,451	−0.01
Temperate.....	72.7	1,374	−0.01	72.7	1,478	0.02
Glacial.....	75.0	1,506	0.05	75.0	1,506	0.05

appendix might be obtained from feedback. We have misgivings concerning limitations of funds, time, response length, and state of project development. Nonetheless, we consider it as a practical and interesting possibility to be explored.

There are severe limits on the nature of the evidence. Heterographic interpretations can be based upon thousands of specimens within an approximate 100-year span of time. Paleontological interpretations must be made upon scarcely 100 cases spread over more than two million years. In addition, there are complications of reliability which result from reconstruction, estimation of adult capacity from subadults, postmortem deformation, dating error, and sexing error. Reliability is, however, a matter of degree and sometimes subjective judgment.[13] As a practical matter, the summaries and illustrations that follow are "total body of reported evidence." All the cases in the appendix are included, since any particular inclusion/exclusion set may be specified. Some of the major questions of reliability are briefly noted in the appendix.

Any particular taxonomic rearrangement may be chosen. In table 11, morphology is tabulated by taxon and ecotype as a basis for comparison. There are two models. The first is "gradualistic" in the sense that the chronological sequence correlates more closely with taxon. The second model is derived from the most common alternative attribution among disputed specimens. Major differences occur with a broad or narrow concept of Neandertals, the antiquity of *H. sapiens,* and *H. habilis* as a taxon separate from *Australopithecus* and *H. erectus.*

The hominid data generally support the conclusions drawn from the study of ethnic groups. In table 11, a pattern of larger, rounder crania in colder climates is observable for both taxonomic models. The evidence is strongest among Neandertals, more ambiguous among *H. erectus* and early modern *H. sapiens.* In figure 9 the coefficient of cranial morphology is plotted for Tropical compared with Temperate/Glacial forms. Data are not adjusted for sex proportion or collective difference in time; however, this may be statistically corrected if desired.

Figures 10 and 11 scatter cranial index and capacity by time without regard to taxon. For consistency, each is graphed on the same logarithmic scale of time in thousands of years B.P. The resulting regression data are included in the illustrations. Lines of regression are omitted since they are not necessarily the best fit for selected periods of time—within which rates of evolution vary. The time machine uses selected time segments rather than overall rates. In figure 12, the mapping program is used to illustrate limits due to lack of data, unoccupied regions, and glaciation.

Maps or associations may be taken from any of the files mentioned (cranial, climatic, hominid, or HRAF). A variable list not within the files may be added but requires a convenient tabulation from the respondent. Funds are not available for analyses beyond programs to which we have access. Resources are presently lacking to provide analyses or maps beyond those associated with the present paper.

[13] All investigations of cranial capacity including this one have reliability problems, e.g., sampling and measurement error. Generally, cranial capacity value is more reliable than brain weight (Brues 1977). There are time and location differences between the skeletal observations and the anthropometrics. All reports of cranial capacity can be regarded as population estimates only. To our knowledge, these factors do not produce a systematic effect upon the overall statistical conclusions. A major factor limiting the reliability of paleontological conclusions is smallness of sample size relative to total population. For example, Westing's (1981) estimates imply that the entire hominid file in the appendix represents only one individual per 50 million born up to 10,000 years ago. For the feedback experiment, any statistical weighting system can be specified.

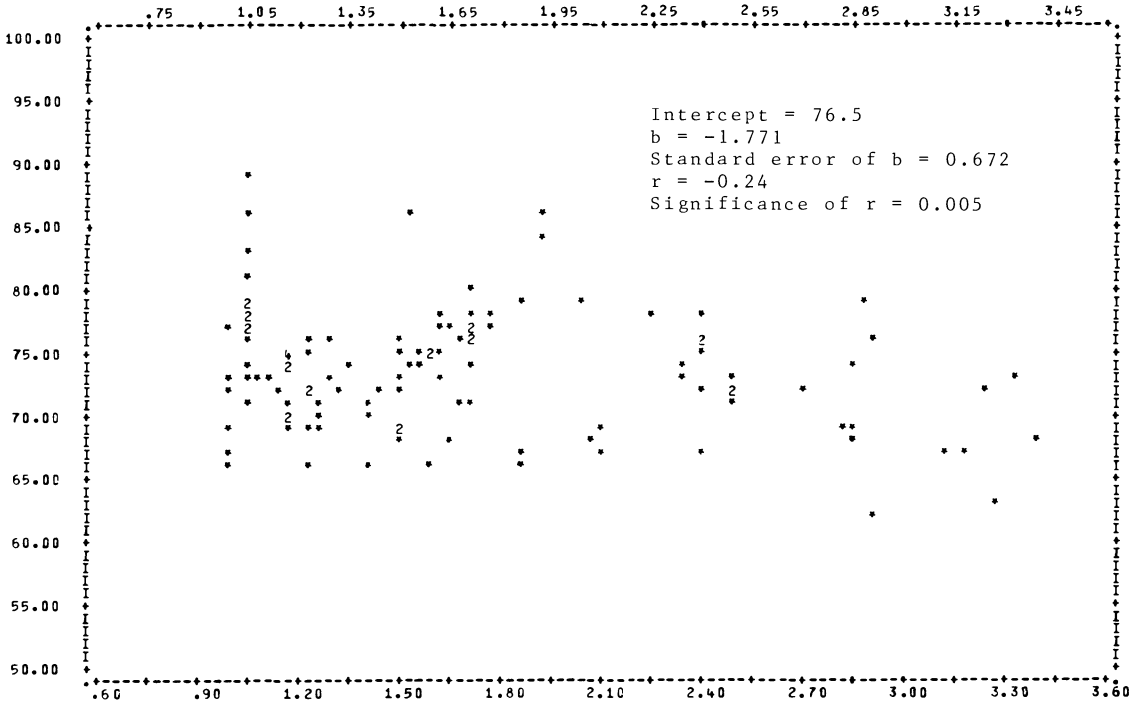

FIG. 10. Evolution of cranial index. The overall trend is geometric, with a high rate of increase during the Holocene. The heterographic composite is 76.5. Among contemporary groups, the index has a lower association with climate than does cranial capacity. The converse may be true with fossil forms (table 11). With regard to climatic influence, the data for *H. erectus* follow the expected direction (lower indices in the tropics), but means are not significantly different. We assume that little climatic differentiation with morphology had occurred at such an early date. The model has no applicability to Lower Pleistocene forms, confined to the tropics. The greatest difference is observed between Glacial and Tropical Neandertals, in which the index—adjusted by appropriate regression for time—is approximately 7 units higher. The evidence indicates a decrease in the index between the Middle and the Upper Paleolithic, and we have been unable to explain this without a gene-flow model in regard to the "Neandertal Problem." As with cranial capacity, climatic adaptation is fairly successful in explaining variation among contemporary humans but less so in explaining the phyletic trend.

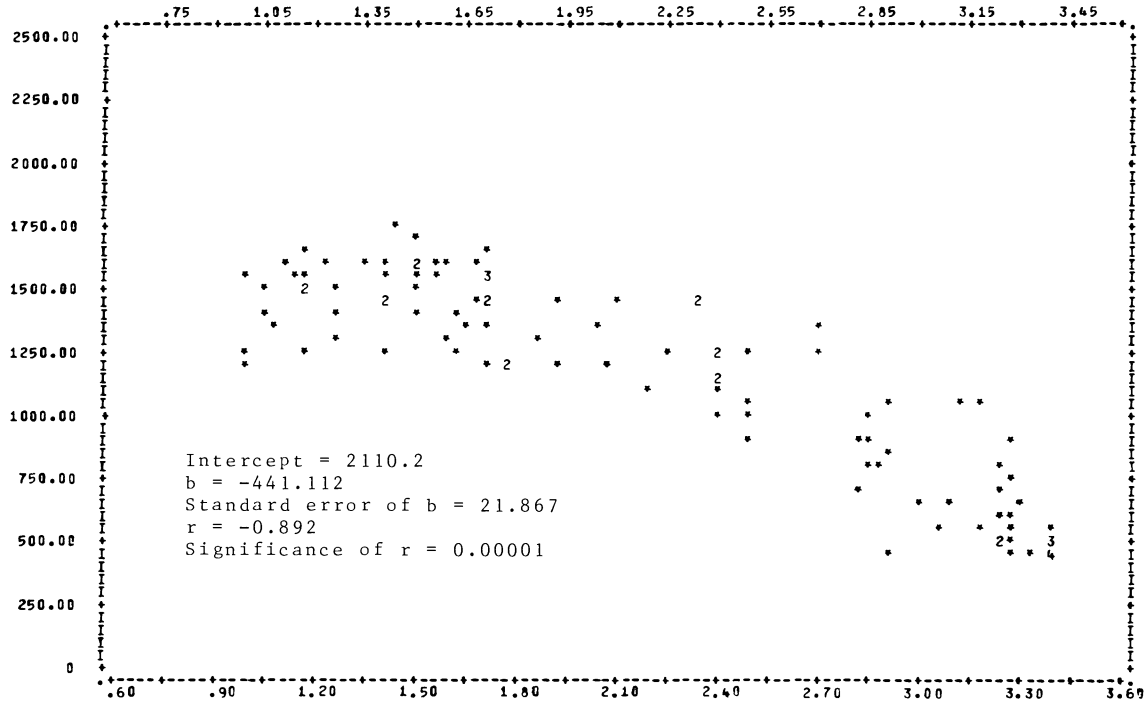

FIG. 11. Evolution of cranial capacity. The heterographic composite is 1,353 cm^3. Volumes are greater among most specimens younger than 100,000 years B.P. The extremely high figures typically reported for early modern *H. sapiens* are structurally obtained more from large absolute head size than from the geometric contribution of brachycephalization (cranial capacities are greater than in current Arctic peoples but with a narrowness more similar to that found in groups under conditions of dry heat). We consider "de-encephalization" through the last 100,000 years as confirmed We speculate that cognitive factors may have been significant among *Australopithecus, H. habilis,* and *H. erectus* but ceased to operate after the origin of *H. sapiens*—in which climate is apparently the principal cause of variation. Part of the reason for de-encephalization from the Upper Pleistocene may be a decrease in body size due to increased occupation of tropical rain forest.

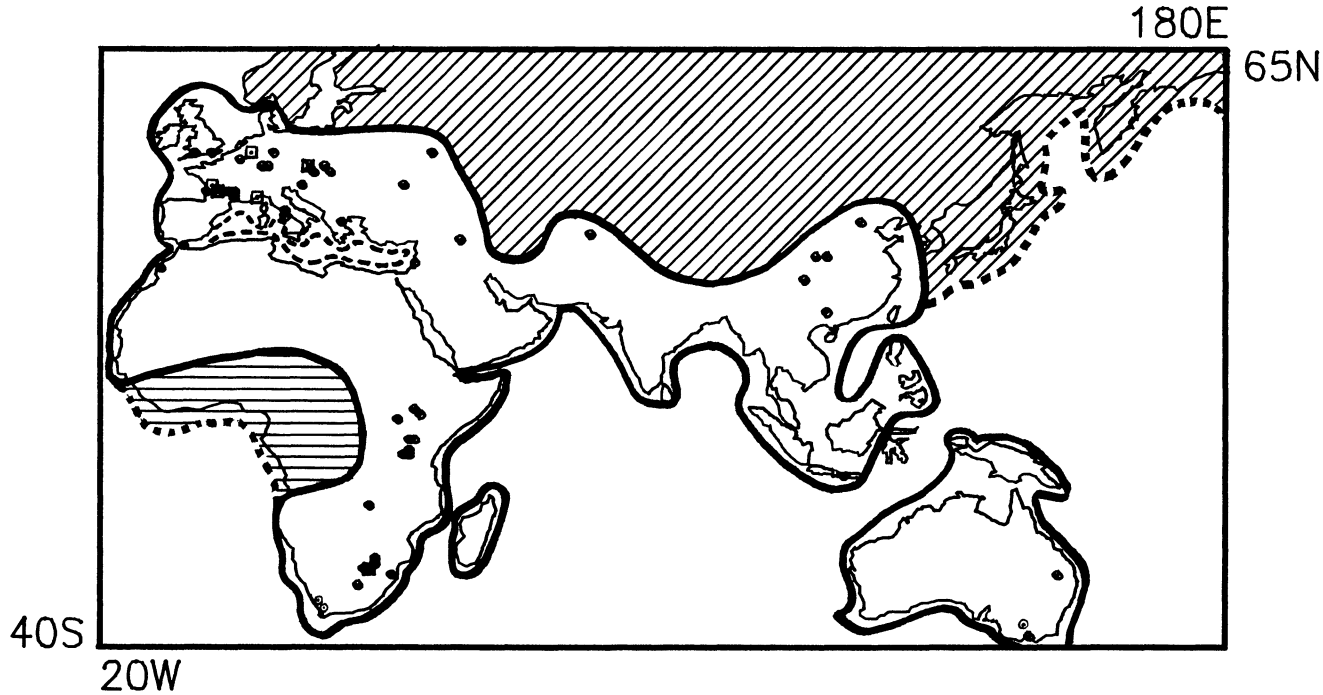

FIG. 12. Limits of "time-machine" data. Sites from the hominid file are plotted with grid overlay and label lines suppressed. Heavy solid line follows coastline at maximum glaciation. Heavy dotted line continues landmass around areas with inadequate data for clinal maps during the Pleistocene.

APPENDIX: HOMDAT

The following is a list of hominid specimens, in chronological order, for which values are available for either cranial index (*CI*) or cranial capacity (*CC*). Estimated dates are in thousands of years. Presumed sex (*S*) is indicated where possible. Climatic zone is coded as tropical (*TR*), temperate (*TM*), or glacial (*GL*). Taxonomic codes are *AA, Australopithecus africanus; AR, A. robustus; HH, Homo habilis; HE, H. erectus; N,* Neandertal, Neandertaloid, archaic *H. sapiens; MM,* early modern *H. sapiens*. Sources are coded as follows: *A73,* Aigner and Laughlin 1973; *A76,* Alexeyev 1976; *B35,* Von Bonin 1935; *B50,* Briggs 1950; *B70,* Brain 1970; *B79,* Brace, Nelson, Korn, and Brace 1979; *B80,* Billy 1980; *D62,* Dart 1962; *D65,* Day 1965; *D80,* Day, Leakey, and Magori 1980; *F78,* Frayer 1978; *H51,* Howell 1951; *H72,* Holloway 1972; *H73,* Holloway 1973; *H78,* Holloway 1978; *H80,* Holloway 1980; *H80B,* Holloway 1980*b*; *H81,* Holloway 1981; *J66,* Jacob 1966; *J73,* Jacob 1973; *K70,* Kelso 1970; *L70,* Leakey 1970; *L72,* Leakey, Mungai, and Walker 1972; *L73,* Leakey 1973; *L74,* Leakey 1974; *L75,* Lestrel 1975; *M62,* McKern and Kozlik 1962; *M74,* Mann and Trinkaus 1974; *NND,* Neumann n.d.; *N79,* Newell 1979; *O52,* Oakley 1952; *O67,* Oakley and Campbell 1967; *O71,* Oakley, Campbell, and Molleson 1971; *O75,* Oakley, Campbell, and Molleson 1975; *P72,* Phenice and Saur 1972; *P73,* Parenti 1973; *P74,* Protsch 1974; *P75,* Protsch 1975; *R74,* Rightmire 1974; *S54,* Singer 1954; *S77,* Sigmon 1977; *S80,* Smith 1980; *T71,* Tobias 1971; *T81,* Thorne and Wolpoff 1981; *V49,* Vallois 1949; *V75,* Vallois and Vandermeersch 1975; *W39,* Weidenreich 1939; *W45,* Weidenreich 1945; *W45B,* Weidenreich 1945*b*; *W58,* Woo 1958; *W71,* Wolpoff 1971; *W80,* Wolpoff 1980; *W80B,* Wolpoff 1980B. Full references are available upon request.

We will be grateful for readers' attention to errors or omissions.

SPECIMEN	CI	CC	DATE	S	LOCATION	CZ	TAX	NOTES AND SOURCES
KOOBI FORA-732		500	2500	F	004N037E	TR	AR	ER 732(H72-73)(L72)(H78)
STERKFONTEIN-1		435	2500		026S027E	TR	AA	(P73)(K80)
STERKFONTEIN-5	67.5	485	2500	F	026S027E	TR	AA	"P.TRANSVAALENSIS"(O67)(P72)(P73)(B79)
STERKFONTEIN-7		500	2500		026S027E	TR	AA	(P73)(K80)
STERKFONTEIN-8		530	2500		026S027E	TR	AA	(P73)(K80)
STERKFONTEIN-19		436	2500		026S027E	TR	AA	COMPOSITE OF 19/58(H72-73)(H78)
STERKFONTEIN-60		428	2500		026S027E	TR	AA	(H72-73)(H78)
STERKFONTEIN-71		428	2500		026S027E	TR	AA	(H72-73)(H78)
OMO-L338Y-6		448	2100	M	005N036E	TR	AA	JUVENILE, CC +5%
SWARTKRANS-46	73.0		2100	M	026S028E	TR	AR	(O67)(W80)(B79)
KROMDRAAI-B		650	2000		026S028E	TR	AR	(O67)(P72)
SANGIRAN-4	62.8	908	1900	M	007S111E	TR	HE	DJETIS, HOLLOWAY REVISION (B79)(D65)(O75)
KOOBI FORA-1470		752	1800		004N037E	TR	AA-HH	ER 1470 (H78)(L73)(B79)
MAKAPANSGAT-37		435	1800		024S029E	TR	AA	COMPOSITE OF 37/38 (O67)(H72-73)
OLDUVAI-24		590	1800		003S035E	TR	AA-HH	(P73)(H78)(H7(-73)(H78)
SWARTKRANS-54		500	1800		026S028E	TR	AR	(O67)(B70)
SWARTKRANS-1585		530	1800		026S028E	TR	AR	(O67)(H72)(H78)
KOOBI FORA-406		510	1700	M	004N037E	TR	AR	ER 406(H72-73)(B79)(H78)
KOOBI FORA-1805		582	1700		004N037E	TR	AA-HH	ER 1805 (L74)(B79)(H78)
KOOBI FORA-1813		509	1700		004N037E	TR	AA-HH	ER 1813 (L74)(B79)(H78)
OLDUVAI-7		687	1700		003S035E	TR	AA-HH	(H80)(P73)(H72-73)(B79)
KOOBI FORA-3733	72.3	800	1700		004N037E	TR	HE	ER 3733(B79)
SAMBUNGMACHAN-1		1034	1500	M	007S111E	TR	HE	DATE UNCERTAIN, (W80(O75)
OLDUVAI-5	67.0	530	1500	M	003S035E	TR	AR	"ZINJANTHROPUS"(O67)(H72-73)(B79)
OLDUVAI-9	67.4	1067	1300	M	003S035E	TR	HE	"CHELLEAN MAN"(B79)(H78)
OLDUVAI-16		640	1250		003S035E	TR	AA-HH	(P73)(H72-73)(B79)
CHESOWANJA-1		550	1150		003N033E	TR	AR	(P72)(S77)
OLDUVAI-13		650	1000	F	003S035E	TR	HE-HH	CINDERELLA, (P73)(H72-73)(B79)
SANGIRAN-12		1059	830	M	007S111E	TR	HE	(W80(O75)
SANGIRAN-10	75.5	855	830	F	007S111E	TR	HE	HOLLOWAY REVISION (W80)(J73)(O75)
TAUNG-1	62.4	440	800		026S028E	TR	AA-AR	ADULT ESTIMATE OF CC (H78)(O67)(B79)
LANTIAN-2	78.8	780	775	F	034N109E	TM	HE	(W80)(A73)(H80)(P72)(O75)
SANGIRAN-2	74.2	813	710	F	007S111E	TR	HE	HOLLOWAY REVISION (D65)(O75)
SANGIRAN-3	68.8	900	710		007S111E	TR	HE	JUVENILE, CC FOR ADULT (K80)(D65)(O75)
SANGIRAN-17	67.9	1004	710	M	007S111E	TR	HE	(W80)(J73)(T81)(D65)(O75)
OLDUVAI-12		720	650	F	003S035E	TR	HE	FRAGMENTARY, (W80)(H78)
TRINIL-2	68.8	900	650	F	007S112E	TR	HE	(K80)(O75)
VERTESZZÖLLÖS		1325	500		048N018E	GL	HE	(P72)(W71)
SALDANHA	72.0	1225	500	M	033S018E	TR	HE-N	REVISED DATING (B79)(O67))(P72)(S54)
CHOUKOUTIEN-3	72.3	915	300		040N115E	TM	HE	ADOLESCENT CC +2% (W80)(D65)(O75)
CHOUKOUTIEN-10	71.4	1225	300	M	040N115E	TM	HE	(W80)(D65)(O75)
CHOUKOUTIEN-11	72.4	1015	300	F	040N115E	TM	HE	(W80)(D65)(O75)
CHOUKOUTIEN-12	72.6	1030	300	M	040N115E	TM	HE	(W80)(D65)(O75)
NGANDONG-1	75.5	1172	250	F	007S112E	TR	N-HE	HOLLOWAY REVISION, SOLO-1 (K80)(P72)(B79)(O75)
NGANDONG-6	66.8	1251	250	M	007S112E	TR	N-HE	HOLLOWAY REVISION, SOLO-5 (K80)(P72)(B79)(O75)
NGANDONG-7	76.0	1013	250	F	007S112E	TR	N-HE	HOLLOWAY REVISION, SOLO-6 (K80)(P72)(B79)(O75)
NGANDONG-10	74.6	1135	250	F	007S112E	TR	N-HE	SOLO-9 (K80)(P72)(B74)(O75)
NGANDONG-11	78.3	1231	250	F	007S112E	TR	N-HE	HOLLOWAY REVISION, SOLO-10 (K80)(P72)(B79)(O75)

NGANDONG-12	72.0	1090	250	M	007S112E	TR	N-HE	HOLLOWAY REVISION, SOLO-11 (K80)(P72)(B79)(O75)
STEINHEIM	72.6	1460	225	F	049N009E	TM	N	DISTORTED (P72)(B79)(H51)(W80B)
EHRINGSDORF-H	74.0	1450	220		051N011E	TM	N	DATING REVISED (W80)(B79)(H51)(O71)
SWANSCOMBE	78.0	1250	175	F	051N000E	TM	N	ESTIMATED CI (W80)(P72)(B79)(O52)(D65)
TA-LI		1120	150	M	034N107E	TM	HE-N	(W80)
OMO-1	68.6		130		005N036E	TR	N-MM	KIBISH, UNCERTAIN DATE (K80)(R74)
OMO-2	67.4	1435	130		005N036E	TR	N-MM	KIBISH, UNCERTAIN DATE (K80)(R74)
LAETOLI-18	68.3	1200	120		004S034E	TR	N	(D80)
FONTECHEVADE	78.9	1350	110	F	046N000E	GL	N	SPECIMEN NUMBER UNCERTAIN (K80)(W80)(B79)
KRAPINA-C	83.7	1200	85	F	046N016E	GL	N	CI QUESTIONED (W80)(B79)(S80)
KRAPINA-D	85.5	1450	85	M	046N016E	GL	N	CI QUESTIONED (W80)(B79)
GANOVCE	78.9	1320	70		049N020E	GL	N	(W80)(O71)
KANJERA-1	66.1		70	F	001S035E	TR	N-MM	RECONSTRUCTED, REDATED (L70)(W80)(P75)
KANJERA-3	67.3		70		001S035E	TR	N-MM	SEE ABOVE (L80)(W80)(P75)
GIBRALTAR-1	76.8	1200	60	F	036N005W	GL	N	(B79)(H51)(S80)
SACCOPASTORE-1	78.4	1200	60	F	042N013E	GL	N	(W80)(B79)(H51)(S80)
LA FERRASSIE-1	75.5	1641	52	M	045N001E	GL	N	(B79)(S80)
LE MOUSTIER	76.5	1352	52	M	045N001E	GL	N	SEX DOUBTFUL (B79)(H51)
MONTE CIRCEO	76.0	1552	52	M	041N013E	GL	N	(B79)H51)(S80)
NEANDERTAL	73.6	1452	52	M	051N007E	GL	N	(B79)(H51)(S80)
SPY-1	71.3	1525	52	M	050N005E	GL	N	(B79)(H51)
SPY-2	76.5	1425	52	F	050N005E	GL	N	(B79)(H51)
PETRALONA	80.0	1220	50	M	040N023E	GL	N-HE	(W80)(B79)(W80B)
TESHIK-TASH	78.4	1565	50		038N067E	GL	N	ADOLESCENT, CC +5% (H51)(W45)
INGWAVUMA-1	70.5	1450	47		027S032E	TR	MM	BORDER CAVE, DATE REVISED (O67)(P72)(P75)
SHANIDAR-1	76.2	1600	47	M	037N044E	TM	N	(W80)(K70)(B79)(O75)
LA QUINA-H5	67.6	1345	45	M	046N000E	GL	N	SEX DOUBTFUL,ADULT (B79)(H51)
LA QUINA-H18	77.0		45		046N000E	GL	N	CHILD (B79)(H51)
D.IRHOUND-1	73.2	1420	42		032N009W	TM	N-MM	(O67)(W80)(P72)(B79)
D.IRHOUND-2	75.1		42		032N009W	TM	N-MM	(O67)(W80)(P72)(B79)
SUBALYUK	78.2		42		048N021E	GL	N	CHILD(7-9 YEARS)(A76)
TABUN-1	77.0	1271	41	F	033N035E	TM	N	(W80)(B79)(M74)(H51)
BROKEN HILL-1	65.9	1280	40	M	014S028E	TR	N-MM	"RHODESIAN MAN" (O67)(P72)(B74)
LA CHAPELLE	75.0	1600	40	M	045N002E	GL	N	(B79)(H51)(S80)
FLORISBAD-1	75.0		38		029S026E	TR	MM-N	(O67)(P72)(B79)(P75)
QUAFZEH-6	73.7	1568	37	M	033N035E	TM	N-MM	JEBEL KAFZEH (W80)(V75)
FISH HOEK-1	75.0	1600	36		034S019E	TR	MM	(O67)(P72)(P75)
CHATELPERRON	85.5		34		044N004E	GL	MM	(P72)
EYASI-1	74.3		34	F	004S035E	TR	N-MM	SEX DOUBTFUL (O67)
G.DES ENFANTS-4	76.3	1715	32	M	044N008E	GL	MM	GRIMALDI (F78)(NND)
G.DES ENFANTS-5	68.6	1375	32	F	044N008E	GL	MM	(F78)(NND)
G.DES ENFANTS-6	69.3	1580	32	M	044N008E	GL	MM	(F78)(NND)
SKHŪL-4	71.8	1554	32	M	033N035E	TM	N-MM	(B79)(P72)(H51)(M74)(O75)
SKHŪL-5	74.5	1520	32	M	033N035E	TM	N-MM	(H51)(B79)(P72)(M74)(O75)
SKHŪL-9	68.1	1590	32	M	033N035E	TM	N-MM	(M74)(P72)(H51)(B79)(O75)
MLADEC-5	73.1		31	M	049N017E	GL	MM	LAUTSCH,(W80)(B79)(O71)
AMUD-1	72.1	1740	28	M	033N036E	TM	N-MM	RECORD CRANIAL VOLUME,(W80)(B70)(O75)
PREDMOST-3	71.3	1580	26	M	049N017E	GL	MM	(B79)(NND)
PREDMOST-4	70.2	1250	26		049N017E	GL	MM	(B79)(NND)
PREDMOST-9		1555	26		049N017E	GL	MM	(NND)
PREDMOST-10		1452	26		049N017E	GL	MM	(NND)
COMBE CAPELLE	65.7	1440	25	M	045N003E	GL	MM	(P72)(B79)
CRO-MAGNON	73.8	1590	22	M	045N001E	GL	MM	(P72)(B79)(D65)
MARKINA GORA	71.5		21		051N039E	GL	MM	KOSTENKI (A76)(O71)
CAP BLANC	76.3		20	F	045N001E	GL	MM	MAGDALENIAN, ABSOLUTE DATE UNCERTAIN (V45)(O71)
STAROSELYE	73.1		20		046N034E	GL	MM	CHILD, CI ESTIMATED FOR ADULT (A76)
CHOUKOUTIEN-101	70.2	1500	18	M	040N115E	TM	MM	UPPER CAVE (W38)(W80)(B79)
CHOUKOUTIEN-102	69.3	1380	18	F	040N115E	TM	MM	UPPER CAVE (W80)(B79)(W38)(O75)
CHOUKOUTIEN-103	71.3	1300	18	F	040N115E	TM	MM	UPPER CAVE (W80)(B79)(W38)(O75)
BARMA GRANDE	71.6		17	F	044N008E	GL	MM	GRIMALDI, DATE UNCERTAIN (NND)
BARMA GRANDE	76.3		17	M	044N008E	GL	MM	GRIMALDI, POSTHUMOUS DEFORMATION (K80)(NND)
BARMA GRANDE	72.2		17	M	044N008E	GL	MM	GRIMALDI, MENTONE (K80)(NND)
BRNO-1	69.0	1600	17	F	049N017E	GL	MM	(W80)(P72)(B79)
LE FIGUER	74.7		17		045N004E	GL	MM	CHILD(B80)
OLDUVAI-1	66.0		17		003S035E	TR	MM	LOW CI DUE TO POSTMORTUM DISTORTION (P74)(O67)
WADJAK-2		1650	15	F	008S112E	TR	MM	(W80)(D65)
CAPE FLATS	69.0	1230	15		035S018E	TR	MM	(O67)(P72)
CHEDDAR	70.4		15	M	051N003W	GL	MM	(F78)(NND)
GAMBLE'S CAVE-4	70.8		15	M	001S036E	TR	MM	(O67)(L70)
GAMBLE'S CAVE-5	73.7		15		001S036E	TR	MM	IMMATURE, MALE? (O67)(L70)
LAUGERIE	74.9		15	F	045N001W	GL	MM	L. BASSE, SEX UNCERTAIN (F78)(NND)
LAUGERIE	74.9		15	M	045N001W	GL	MM	L. BASSE (F78)(NND)
LIU KWANG-1	75.1	1480	15	M	024N109E	TM	MM	LIUKIANG (O75)(P72)
OBERCASSEL	74.6	1500	15	M	051N007E	GL	MM	(F78)(NND)(B79)
OBERCASSEL	70.0		15	F	051N007E	GL	MM	(F78)(NND)(B79)
SPRINGBOK-1	73.8	1540	15		025S029E	TR	MM	MAY BE LATER BURIAL (O67)(P72)
CHANCELADE	72.0	1530	14		045N001E	GL	MM	(P72)
KEILOR-1	72.6	1593	13	M	038S145E	TR	MM	(W45B)(O75)

TALGAI-1	73.4	1370	12	M	027S150E	TR MM	ADOLESCENT, CC +5% (W45B)
OFNET "2.1"	80.5		11	M	049N010E	GL MM	OFNET REDATED FROM MESOLITHIC-NEWELL-79 (N79)(NND)
OFNET "2.11"	77.7		11	F	049N010E	GL MM	ID NUMBERS FROM NEUMANN CATALOGUE (N79)(NND)
OFNET "3.1"	88.9		11	F	049N010E	GL MM	(N79)(NND)
OFNET "4.1"	86.2		11	F	049N010E	GL MM	(N79)(NND)
OFNET "5.11"	77.0		11	F	049N010E	GL MM	(N79)(NND)
OFNET "8.1"	83.3		11	F	049N010E	GL MM	(N79)(NND)
OFNET "11.1"	78.7		11	M	049N010E	GL MM	(N79)(NND)
OFNET "13.1"	75.7		11	F	049N010E	GL MM	(N79)(NND)
OFNET "14.1"	72.7		11	F	049N010E	GL MM	(N79)(NND)
OFNET "15.1"	76.8		11	F	049N010E	GL MM	(N79)(NND)
OFNET "18.1"	78.9		11	F	049N010E	GL MM	(N79)(NND)
OFNET "21.1"	70.5	1500	11	M	049N010E	GL MM	(N79)(NND)
OFNET "24.1"	73.7	1420	11	M	049N010E	GL MM	(N79)(NND)
OFNET "25.1"	78.2		11	F	049N010E	GL MM	(N79)(NND)
COHUNA	65.8	1260	10	M	036S144E	TR MM	(P72)(O75)
KOW SWAMP-1	67.0		10	M	036S144E	TR MM	(T81)(O75)
KOW SWAMP-5	72.4		10	M	036S144E	TR MM	(T81)(O75)
KOW SWAMP-14	68.6		10	M	036S144E	TR MM	(T81)(O75)
TZE YANG-1	77.4	1210	10	F	030N105E	TM MM	(P72)(W58)(O75)
WADJAK-1	72.5	1550	10	F	008S112E	TR MM	(P72)(B79)(W45B)(D65)(O75)

Comments

by J. Lawrence Angel
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As a student in the mid-1930s at Harvard I learnt how Bergmann's law of surface-mass relation applies to human populations, with exceptions for recent migrants from another climate and for culturally protected groups in the last few millennia. We were also taught that cranial capacity was greater in cold climates and cranial and cephalic indices lower and nasal index higher in tropical ones, apparently from natural selection. I taught these things in turn with pleasure because they explain modern brain-size differences in terms of climatic determination of mass-surface relations rather than intelligence. No one except Nazis or White supremacists could then see biological differences in intelligence between any surviving groups. By now it seems likely that there has been no meaningful increase in brain size since the *Homo erectus* phase fully ended (cf. Howells 1973) about 100,000 B.C. Coon reemphasized much of this in books from 1939 to 1965 (e.g., Coon 1962).

I thank Beals, Smith, and Dodd for their painstaking gathering and analyzing by computer of all the rather patchy data on endocranial volume, body size, body surface area, and head form. It is vastly more useful than in the form of the earlier maps (e.g., those of Biasutti) or clines. The authors have had to assume correct and unbiased measurements and have made proper adjustment for the overestimation of cranial capacity when lead shot is used rather than mustard seed. They also assume genetic determination of the variables with minimal disturbing ontogenetic effects of nutrition, often considerable, or of artificial head deformation.

The reason the authors find the culture—intelligence—brain-"size" feedback less effective than climate in explaining brain increase in human evolution is that increasing intelligence relates to silent or redundant cortical surface (with its subcortical links) as well as increasing sensorimotor cerebral and cerebellar cortical surface for better-controlled actual and imagined action, achieved in the pongid-to-*Homo sapiens* contrast by more and deeper surface folding without a proportional increase in mass. As Hebb (1949) points out, there is an upper size limit for efficient brain function in terms of cell numbers, interaction, arrangement, and blood supply—size of female pelvis related to newborn head is irrelevant as a limiter. Human beings reached this upper limit of efficiency about 100,000 years ago. Hence to say that "one would expect to find supporting evidence among present-day groups" creates an absurd straw man: 4,000 generations is time enough for selection to iron out kinks and to equalize intelligence (and approximate neuronal surfaces—not exact mass) in all surviving groups.

Minor criticisms: (1) "Encephalization" means putting something inside the head (brain, or fluid or blood) without implying brain-size increase. (2) The New World is not a foolproof test of climatic selection over 30,000 years, since the latest arrivals, the Inuit, came after the Pleistocene from ancestors adapted to Siberian cold with large Arctic endocranial volume. (3) Neoteny is not a mutation, but a phenotypic result of the slowing of some, but by no means all, relative growth rates (usually by selection for a number of rate genes, rarely by environmental malnutrition). (4) Figures 10 and 11 may confuse some readers, since they reverse the usual left-to-right reading usage in Western culture.

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Beals, Smith, and Dodd's bioclimatic model suggests that, among modern human populations, increased cranial capacity reflects increased brain size and that the latter is the result of selection pressures working to increase brachycephaly, itself a thermoregulatory adaptation. An increase in brain size is thus seen as a side effect of thermoregulation. While I concur that the variables of brain size and thermoregulation are associated, I do not think that they are causally related in the manner suggested. My hesitation is as follows. The brain is a metabolically very expensive organ (Armstrong 1983, 1984). Although the human brain represents about 2% of the total body mass, the brain continuously uses about 20% of the body's total supply of energy (Sokoloff 1981). This large use of energy normally undergoes no significant alterations or cycles such as during normal sleep-wake cycles or during increased mental activities (Sokoloff et al. 1955, Sokoloff 1981, Mangold et al. 1955). The assignment of a high percentage of energy to the brain distinguishes us from other known animals (Armstrong 1983, 1984). It is hard to think that such a metabolically expensive organ would enlarge passively from selection for brachycephaly.

While the differences in cranial capacities between the winter-frost and dry/wet-heat ethnic groups are statistically significant, they are also small, 89 cm^3. The small differences means that the data on which the interpretations are based must be very clean, particularly with regard to the populations' nutritional and disease states. While overall brain growth is somewhat protected from malnutrition (compared with that of other

tissues, such as muscles and skin), the brain also has diminished capacities for recuperation (e.g., Dobbing and Sands 1973) unless a protein-*enhanced* diet becomes available (Angulo-Colmenares, Vaughn, and Hinds 1979). Pre- and postnatal malnutrition produces lowered brain weights in both human and laboratory animals (e.g., Dodge, Prensky, and Feigin 1975). Changes in brain weights have also been noted for populations. Miller and Corsellis (1977) observed an increase in the mean adult brain weight (52 g for men and 23 g for women) of people dying in the London Hospital from 1907 to 1977. It is thought that most of this increase is the result of changed nutrition. How much of the difference between ethnic populations may represent differences in nutritional standards? Perinatal diseases can also influence brain size directly or indirectly by retarding overall fetal growth (e.g., Myers et al. 1971), a condition which produces children with smaller cranial capacities (Leutenegger 1982). Again it is not clear how much catch-up growth is possible (Roche 1981). Perhaps in the future skeletal markers can be used to estimate disease and nutritional status of the populations used in studies of cranial capacities.

The high and provocative associations between climate and cranial capacities should also be examined for non-neural associations. Cranial capacities include the brain plus the meninges and cerebrospinal fluid. Changes in cranial capacities may be associated with increases in the latter two features, particularly the meninges. The meninges are connective tissue and are thus not as metabolically expensive as nervous tissue. While the suggestion that meningeal thickness and volume vary among ethnic groups is speculative, it is testable. With the advent of worldwide use of computerized tomography scanning it should also be possible to determine whether the ventricles (the brain's internal containers of cerebrospinal fluid) vary in size among different ethnic groups.

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This is an innovative and broadly conceived study. Aspects of it that rest upon a solid methodological and analytical foundation include (*a*) the cline maps, (*b*) the revised estimate for present-day worldwide mean endocranial volume, (*c*) the description of the overall heterographic human (present-day), (*d*) the empirical description of the "average" model for different climate zones, (*e*) the presentation of variate change over time (figs. 10 and 11), in which regression lines describing illusory central trends are omitted, and (*f*) the statistical correlations reported in table 5 and figures 5 and 6. This body of material is provocative and thought-provoking.

A number of questions are raised, however, by the analytical protocols and the conceptual framework within which the statistics and cline maps are interpreted. Why were the spatial autocorrelation algorithms of Sokal (Matula and Sokal 1980; Sokal and Menozzi 1982; Sokal and Oden 1978*a*,*b*) ignored in favor of an "in-house methodology" whose theoretical foundation is obscure and that does not provide discrimination statistics? As the authors point out, considerable measurement error exists in many of their parameters. Why were nonparametric statistical methods neither considered nor used?

The taxonomic assignments that underlie table 12 and figures 10 and 11 need considerable discussion. Issues that are under serious debate in the geochronological literature include the dating of the Djetis, Trinil, Vértesszőllős, Saldanha, Choukoutien, and Ngandong hominid material (Beaumont, de Villiers, and Vogel 1978, Jacob 1972, Ninkovich and Burckle 1978, Pope 1982). Furthermore, whether or not any European hominid specimens can be taken to represent *H. erectus* is a problem under intense scrutiny (Cook et al. 1982, Howells 1980, Stringer 1981). If *H. erectus* never occupied Europe, the hypothesis cannot be investigated for this taxon. Taxonomic schemes must be decided upon and adopted as a methodological device to provide an appropriate context within which to investigate certain evolutionary questions. However, such choices and their associated calibration must be explained and referenced. A lack of such discussion assumes consensus where none exists.

The data base for figures 10 and 11 is dominated by late Middle Pleistocene and Upper Pleistocene hominids. A regression analysis will therefore be biased towards illustrating late Quaternary *H. sapiens* population variability and against highlighting the evolutionary trend(s) that characterize (?) the last 2 million years. Artificially low r values will also result from this approach. It might be better to select a data set in which individual points are as evenly spaced over time as possible in order to maximize perception of the long-term trend in endocranial-volume evolution rather than uncritically submit to a discovery bias towards the late Quaternary. Furthermore, on the basis of statistical criteria it is impossible to choose between several bivariate models, both linear and nonlinear, that describe long-term trends in hominid endocranial-volume evolution (Blumenberg 1978, n.d.*a*; Godfrey and Jacobs 1981). Is the very complex question of evolution over time best left for a separate thorough presentation?

Likewise, interpretations of the scaling coefficient in allometric relationships might best be considered beyond the scope of the paper. It is not at all clear whether a particular body size and metabolic rate entrain a specific brain size or vice versa (Armstrong 1983, Blumenberg n.d.*a*).

Cognition is suggested as a critical variable for *Australopithecus, H. habilis,* and *H. erectus* (endocranial volume?) but not for the encephalization of later hominids, in which climate assumes the status of priority selection pressure. I disagree in the sense that behavior *follows* from a particular type of brain and cannot de novo create a new type of nervous system, although it can certainly foster biases in potentials actually realized (Blumenberg 1983). Yet, once a critical threshold (? *H. habilis*) is crossed, gene-culture coevolution might well be responsible for augmenting early *Homo* brain size. The Lumsden (1983)/Lumsden and Wilson (1981, 1983) model deserves comment here.

Throughout the text, an increase in cranial size is seriously considered as an important influence upon increasing endocranial volume—surely the cart before the horse! The brain is the active functioning organ that generates (adaptive) behavior; the cranium is but its protective housing. Might not a hypothesis about the coevolution of brain and cranium be more appropriate? Might not cranial morphology be mandated to a large extent by changes in brain anatomy and endocranial volume? Many shapes can contain identical volumes; indeed, cranial morphology reflects important proportional (allometric) relationships among brain parts (Baron 1979, Passingham 1973, Stephan and Andy 1974). Several early crania (ER 1470, ER 1805, ER 1813) are considered globular when compared with contemporaries (Howell 1978). An evolutionary trend towards the domed cranium *reflects* a progressive enlargement of the neocortex.

Modality of evolutionary change is confused with phylogenesis. Why is an evolutionary model gradualistic because chronological sequence correlates with a particular view of systematics? Such a correlation in the evolution of a nonbranching lineage does not comment upon rate of change. As I have said elsewhere, I disagree that endocranial volume and taxonomy bear little relation to one another (Blumenberg 1983). Overall distribution characteristics show statistically significant differences, and all but one taxon are characterized by a distinctive coefficient of variation for endocranial volume (Blumenberg n.d.*b*). *Within* a single species (taxon), variation in

endocranial volume may be due to both bioclimatic parameters and the range characteristic of stochastic genetic processes. A relationship between endocranial volume and reproductive isolation would be very difficult to demonstrate and likely does not exist. On the other hand, such a hypothesis may be entertained for between-species comparisons, wherein the object of study is not simply population-level variation. It is important not to confound the legitimately different levels of the evolutionary hierarchy (Arnold and Fristrup 1982). Furthermore, endocranial volume may be a valuable window that allows critical parameters of brain reorganization to be examined and interpreted (Blumenberg 1983; Jerison 1973, 1977; Hofman 1983, Passingham 1975).

As the authors observe, the majority of the variance in cranial morphology is not explained by their model. Statistical noise is certainly present, but I do not believe that all attempts to explain this unexplained portion of the variance are, of necessity, futile. There is an important contribution to be made from the realm of evolutionary genetics.

The cranium is not a tabula rasa subject only to environmental influence. Many components of the cranium have significant heritability coefficients with values that approach 0.5 (Bernhard et al. 1980, Cheverud 1982, Susanne 1977, Torgersen 1951). The large variance unaccounted for by the model is likely genetic variance. The University of Michigan group that has been studying Amerindian genetic architecture for over 20 years has established that tribal village gene pools may be considered demes as defined by classic population genetics and are quite distinct from one another. Furthermore, their mode of evolutionary change is dominated by drift, stochastic events, a punctuational modality, frequent departures from Hardy-Weinberg equilibrium, and a fission-fusion pattern of demic spread (Neel 1978, Smouse, Neel, and Liu 1983). The unexplained variance in this study may well reflect the present-day distinctiveness of gene pools whose evolutionary histories are very different and dominated by such processes. The general model for the hominid cranium is likely adaptive to all ecozones. I suspect that the unexplained variance reflects not differences in cranial morphology that are specific adaptations but the range inherent in this suite of stochastic genetic processes. Because of their molecular-level genetic mechanisms, such processes do not respond to selection pressures except fortuitously; they are random in design and effect and do not result in obvious directionality and adaptive significance (Barigozzi 1982, Dover and Flavell 1982, Milkman 1982). Nonetheless, in this particular case, I wonder if sexual selection (mate choice) might be an important directional selection pressure with specific cultural boundaries that modifies the stochasticity inherent in the genetic realm I have focused upon.

As with all ground-breaking endeavors, this study raises more questions than it answers, and several potentially valuable avenues within which to widen the model and conduct future research are suggested. The authors are to be congratulated for introducing cline maps and historical biogeography into this discussion and for broadening the conceptual frameworks within which endocranial-volume and cranial evolution may be investigated. They are also to be highly commended for offering their computer services to other workers investigating similar problems.

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The ecological fallacy results from accepting mere associations as causative relationships. Even if we accept the data as reasonably representative of the groups included and the groups included as representative of the variety of the world's populations, we are still left with the question of whether the thermoregulation hypothesis explains a large part of the distribution. Although a thermoregulatory mechanism that involves the skull does appear to exist, it is not clear that cranial capacity per se is affected by the evolution of these mechanisms. Recent studies on other mammals suggest that brain temperature is controlled by regulating the venous return from the brain. Some mammals have a "carotid rete" in which the small arterioles course through the venous sinuses of the brain, allowing for countercurrent heat exchange between arterial and venous blood as well as heat exchange between the blood and cerebrospinal fluid. In humans and other mammals the cerebral rete is absent. Nevertheless, in humans the internal carotid artery courses through the cavernous sinus. This sinus is connected to both the internal jugular venous return, via the petrosal sinuses, and the external jugular venous return of the face via the ophthalmic vein and its anastomoses. Changes in the ambient temperatures of the face produce changes in the tonus of the smooth muscles in the venous drainage of the face and, hence, the drainage direction of the venous blood in the cranium. This, in turn, affects heat exchange among the fluid spaces of the cranium (see Winquist and Bevan 1980). There are a number of other areas in which the internal and external jugular drainage systems anastomose. Most notable is the nasal cavity, where there is a complex system of arterial and venous plexi for temperature and humidity exchange (see Negus 1958). The evolution of this mechanism may indeed effect changes in cranial shape by its effect on the cranial base. Conroy (1980) has discussed the relationship of cerebral venous patterns on the size and shape of the cranial base foramina. This is important because there is ample evidence that the size and shape of the cranial base determine the configuration of the cranial vault and of the face (Taylor and DiBennardo 1982, Bjork 1950). Thus, although the authors assume that the measurements of the cranial vault have some functional significance, studies on the growth and development of the skull indicate that the size and the shape of the cranial vault may be the result of the way in which various factors are resolved at the cranial base. Since the indirect methods for the estimation of cranial capacity are all based upon measures of the cranial vault, it is possible that such methods are telling us more about the growth dynamics of the skull than about its volume. The authors frequently appear to equate cranial capacity with brain size, which gives the impression that cranial capacity reflects the number of neurons within the skull. Given the thermoregulatory mechanism cited above, the size of the fluid spaces in the cranium may be of greater importance, and if there is any increase in cranial capacity due to climatic adaptation, it may be the result of increasing the size of these spaces. In addition, the metabolic role of the neuroglia is still unclear, and it is also not clear whether a real increase of brain size occurs primarily by increasing the number of neurons (see Holloway 1968). Thus, the authors may have found an actual indicator of brain thermoregulation, but it may be independent of brain size.

What do we do with the additional argument that the colder climes were not inhabited until proper artificial protection was acquired? Hats, or their equivalents, certainly must have replaced a great deal of whatever other thermoregulatory mechanism previously existed; shouldn't this have buffered variation somewhat?

The above comments notwithstanding, we believe that the authors have presented a very important paper. The use of the computer for mapping and analyzing worldwide trends in biocultural relationships will eventually lead to important insights. The various difficulties in method will certainly not prove long-lasting. We applaud their efforts.

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This paper dresses up old-fashioned physical anthropology with new-fashioned computer techniques. One would expect the

strength of this approach to be more accurate and rapid analysis of metrical traits and their distribution, while weaknesses would lie in the lack of sound biological theory that has frequently characterized such "trait-plotting" methods of anthropological analysis.

For instance, the authors assume that statistical correlation implies causation via natural selection. Causal analysis, however, requires in-depth study not only of potential selective agents, but also of developmental and clinical data, all of which are ignored. These additional data suggest that brachycephalization, rather than being a metabolically adaptive event which permits increased brain size, is a developmental by-product of many interacting variables, some of which may themselves be correlated with climate. Supporting evidence for this interpretation comes from data indicating that, developmentally, the skull is a highly plastic entity. Cultural practices influence final head shape, as do a variety of functional matrices which exert their influence during the maturational period, e.g., the brain, the oral-masticatory apparatus, and the respiratory tract (Moss 1968). The concept that the brain expands to fill its container, the skull, is untenable on developmental grounds. Rather, brain growth creates tension on cranial suture lines. This tension initiates bone deposition and growth of the skull. The causal relationship of brain size and shape with respect to skull form is obvious from the anomalies of the skull that result from hydrocephalus and inherited microcephaly as well as from the craniofacial asymmetries which reflect normal brain lateralization (LeMay 1977).

Nor does the postulate that brain size increased to conserve body energy make sense. The average human brain consumes 20% of the body's metabolic energy. Much more metabolically effective ways of conserving heat would be the evolution of insulating layers of hair, fat, or clothing. In fact, the brain uses so much energy that extensive brain enlargement would be incompatible with survival in food-scarce environments unless it provided cognitive skills enabling increased foraging efficiency and/or increased cultural adaptation to harsh circumstances. The fact that a correlation between cognition and brain size has not been convincingly demonstrated does not mean it has been disproven. Most literature on this subject is either anecdotal or based on questionable brain-size and intelligence data. To answer this question in a scientifically valid fashion will require the development of accurate, culturally unbiased methods of determining both intelligence and brain size in healthy young adults. For now, the most logical explanation of brain expansion remains that the brain expanded because neural functions were selectively advantageous.

Further, ample evidence exists that factors other than brain growth also modify skull form. One of these is cradle-boarding, which occurs primarily in cold climates (Whiting 1981). Another is masticatory function. Tooth size, masticatory muscle strength, and angle of muscle pull have all been found to correlate with head shape in clinical dental practice (Sassouni and Forest 1971). Increased trends toward brachycephalization have also been demonstrated to occur in the archaeological record in conjunction with changes in both tooth size and muscularity and in the absence of pronounced brain-size or climatic changes (Carlson 1976). Moreover, thorough dental-anthropological analyses have explained Eskimo skull form on the basis of masticatory stress (Hylander 1977). Finally, altered respiratory patterns dramatically affect the form of the face and skull. For instance, children who habitually breathe through their mouths because of adenoid enlargement develop long heads and long faces. Removal of the adenoids reverses this growth trend (McNamara and Ribbens 1979). It is probable that patterns of both respiration and mastication vary with climate. The masticatory stresses experienced by the Eskimo, for instance, would impinge upon any preindustrial Arctic population. Consequently, prior to concluding that brachycephalization is a metabolic adaptation, an investigation of climatic variations in the cultural and biological factors impinging upon skull development should be initiated.

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The authors are profoundly right in raising the problem of the determinants of human cranial capacity. The problem has been for so long a matter of prejudice, speculation, and "intuitively satisfying" explanations based upon the simplistic conjunction "larger head—better thought" (though sometimes veiled by highly sophisticated mathematical theorizing) that it deserves a calm, reasonable treatment. The traditional approach to the problem of brain size (not exactly identical with cranial capacity because of the many accompanying tissues, vessels, and fluids) was based on viewing the brain as a "higher," exceptional organ directing the body. However, the brain is at the same time an ordinary organ demanding proper maintenance from the rest of the body.

There is ever more evidence accumulating, with the paper of Beals and colleagues being an important contribution, against a direct relationship between cranial capacity and intellectual capacity. First, within-group correlations between intelligence test scores of individuals and their head sizes are at best weak, on the order of 0.1–0.2 (e.g., Pearson 1906–7, Wrzosek 1931, Schreider 1968, Susanne and Sporcq 1973), and probably due to differences from family to family in the conditions for individual development. Second, head size diminishes with time over the last 20,000–30,000 years—a period of the most rapid cultural/intellectual progress (e.g., Tobias 1971, Olivier 1973, Henneberg 1984*a*). Hitherto offered explanations of this fact based on a close link between cranial capacity and intellectual ability (e.g., Tobias 1971) or on autodomestication (Thoma 1969) are unconvincing. Third, the tremendous increase in cranial capacity during hominid evolution seems to be fully explained by increase in body size (Guidotti 1980, Henneberg 1984*a*) when the dimensionality of measures of the two variables is equal. After the scales along which body size and cranial capacity are measured are properly adjusted for dimensionality (e.g., when stature is taken as a measure of body size, cranial capacity must be expressed as the cube root—$^1/_3$ power—of its directly measured size), a simple linear relationship is clearly visible in the data. Body-size increase is encountered in the evolutionary lines of many taxons of mammals, being the expression of a trend towards optimization of energy expenditure and resistance against environmental stresses. Hence hominid cranial capacity evolution seems to be nothing exceptional or unique. It is not the brain structure that evolves in a particular way, but the pattern of its functions. The change may be not anatomical but biochemical and related to a different structure of sensory input under new environmental and social conditions.

There are some minor faults in the paper, of which I will comment upon only a few. Correlation coefficients are indicative only of coincidences, not of actual causal relationships, and must be interpreted with due care. For instance, the correlation of head shape with climatic zone may result from different susceptibility of brachy- and dolichocephalics to infectious diseases and different distribution of pathogenic factors in climatic zones. Another problem is the possible curvilinearity of some relationships. Discrepancy in scaling may be the cause of the higher correlation between cranial capacity and body weight and surface area than between cranial capacity and stature. By the way, the dimensionality of human body weight seems to be less than 3, though certainly more than 1 and most possibly not exactly 2, since the human body is a geometric form very different from a sphere. To my knowledge nobody has measured its exact value, but some differences between the

scaling parameters obtained by various authors on various samples of mammals may reflect differences due to body shape in the dimensionality of its mass, treated as a measure of body size. Different tissues contribute in varying proportions to body weight in different species and populations (e.g., fat accumulation), while head size is primarily dependent upon the size and robusticity of bones. In this context one possible explanation for the decline in braincase size during the last 20,000 years is its relation to a process of structural reduction of the human skeleton (gracilization) occurring as a result of the relaxation of selection acting upon mechanical robusticity of the body coupled with the Probable Mutation Effect and periodic local selection favouring smaller bodies due to scarcity of resources resulting from overpopulation, natural disasters, etc. I am referring here not to changes in external dimensions due to simple thinning of the cranium's walls but to a true change in its internal dimensions (Henneberg 1984*a*,*b*).

Head-shape changes, being somewhat dependent upon climatic differences, occurred very rapidly, at least throughout the temperate zone, in the form of a recent microevolutionary trend. For instance, in Central Europe during the last 1,000 years alone, and without any important climatic change or historically known mass migration, the cranial index has increased from about 75 in the Early Middle Ages to almost 85 in modern times (about a 10-unit increase in the mean of a distribution with about 3 units s.d. over 30–40 generations). This rapid change is certainly not due to climatic change; rather, it is a result of strong selection favouring brachycephalics in response to cultural change transforming the human environment (dwellings, food production, diseases, social relations, etc.; see, e.g., Bielicki and Welon 1964, Henneberg 1976). This example warns against the acceptance of theories establishing simple relationships between human biological properties and general climatic or eco- zones. Human culture adapts to ecological conditions; the human body adapts to conditions created by both environment and culture. This is the case with the brachycephalization just described, gracilization, and possibly the reduction of jaws and resultant structural changes in cranial architecture (see Krantz 1980*b* and my comments upon it). Perhaps hominids living in various climatic zones had different conditions for cultural evolution and thus different rates and directions of biological evolution?

I propose using the computer files (1) to determine the correlation of anthropometric variables with cultural conditions or, still better, with ecozone + culture, using either nonlinear procedures or simply analysis of variance in its basic form instead of the product-moment procedure, and (2) to introduce, where possible, body-size estimates into HOMDAT and determine the correlation of body size and cranial capacity.

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The authors deserve to be congratulated for the realization of their impressive data-processing infrastructure and—as a first global-scale application of it—a study that has led to a model of brain(case) morphology as related to climate. Their courage in tackling so delicate and wide-ranging a problem must be warmly welcomed: generalizations like this bioclimatic model are urgently needed, but they imply a high risk of criticism on minor or major details which may be in contradiction with the (over-) simplified vision (Paul Valéry: "Tout ce qui est compliqué est inutilisable, et tout ce qui est simple est faux"). Their model as such—as a parallel to Bergmann's law—is of real interest; many explanations are innovative and merit wide discussion but also verification. However, it remains difficult to apprehend the validity of the model: there are important factors (such as duration of undisturbed occupation as well as the complete biological history of a population in a given area) which are totally out of control in this approach. Further, the considerable differences from one area to another in the extent of cranial variation (e.g., cranial index and stature in Europe) mean that sampling could have an unexpectedly strong influence on the strength of the correlations. The argumentation is straightforward and seems quite convincing at first. The morphometrics—and this is a rare example in which their simplicity is not a disadvantage—are quite suitable for this approach, which is basically geometric. It must be borne in mind, however, that there is much redundance among them and therefore some of the figures presented in the results may be misleading (the increase in cranial capacity of 2.5 cm^3 per degree of latitude should be corrected for body weight). The authors propose a functional linkage between encephalization and brachycephalization. In the discussion of "cognitive influence" and brain morphology they restrict their considerations to simple brain *size*. It would have been profitable to include brain *surface* as a parameter expressing cortical surface. Indeed, if reduction of relative head surface as a consequence of brachycephalization can be considered an adaptive trait with respect to cold, the increase of brain size observed in connection with spherization could be regarded as another adaptive mechanism, counteracting the reduction of cortical surface that would occur if the volume remained constant.

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In their very interesting and original paper, Beals, Smith, and Dodd state, on the basis of a large number of materials, that the strongest effects on changes and variation in individual cranial capacity occur with solar radiation, winter temperature, and vapor pressure and that the increase in capacity is 2.5 cm^3 per degree of distance from the equator. If the average cranial capacity on a global scale is taken as 1,353 cm^3 as they suggest, the increase in endocranial volume in a racial movement from the equator to 80° N. can be estimated at 200 cm^3, 14.8% of the average capacity. This increase would be too large to disregard. Concerning the progressive increase of endocranial volume in the human evolutionary process, however, it must be kept in mind that a basic difference between Neandertal and *H. sapiens* lies in the surface ratio of the different cerebral lobes. I agree with the authors that cranial breadth is the most important structural determinant of cranial capacity, for the shift of the maximum breadth to an area high above the cranial base apparently strengthened the tendency of the human skull to assume a globular form in the course of the evolutionary process. Here I would like to know whether the globularity in human skull form due to a northern, cold environment could more or less be explained by Allen's and Bergmann's rules. In recent centuries, brachycranic skulls show a considerable increase in frequency in Eurasian populations, including the Japanese, that live in warm climates. It is debatable whether climatic factors have become the principal source of cranial variation.

by ROBERT R. SOKAL
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28 XI 83

The authors are to be congratulated upon this very comprehensive analysis of an important anthropometric variable. An approach that would complement and corroborate these findings would be through spatial autocorrelation of the cranial as well as the climatic variables. If well-developed clines could be demonstrated through spatial correlograms for both the an-

thropometric and the putative climatic variables, then a study of the regression residuals of cranial capacity or cranial module on climate might be of interest. Continued clinal structure of these regression residuals with climatic factors kept constant would describe the remaining phyletic component of the phenomenon. Lack of further spatial structure of regression residuals would indicate a largely environmentally caused determination of cranial capacity. Another question that should be looked at in conjunction with the hypothesis put forward by the authors is whether currently observed differences in cranial capacity could have arisen under reasonable population genetic models given the amounts of time available. An especially crucial test case would be the differentiation among the Amerindian populations. A final caveat: the statistical significance of the correlations and regressions observed is probably not at the conventional level as given in table 7 and elsewhere in the paper. There are two complicating factors: spatial autocorrelation among the variables invalidates the ordinary distribution assumptions of bivariate analysis, and the spatial distribution of the points at which samples are obtained biases the computation of the correlation coefficient. This problem has been pointed out by several authors (e.g., Mather 1976 and King 1979).

by ERIK TRINKAUS
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The authors have argued, on the basis of a selection model for cerebral thermal stability and correlations across modern human populations, that variations in neurocranial size and shape among *H. sapiens* can be explained as a product of climatic adaptation. Even though they do not provide a proximate mechanism, other than general adaptive considerations, they are convincing that at least *part* of modern human neurocranial variation is due to climate. However, their statement that "within our own species (including Neandertals) climatic factors have become the principal source of the variation" cannot be substantiated.

During most of our species's evolution there has been a continuation of the encephalization that characterized the genus *Homo*. Middle Pleistocene specimens usually included within *H. sapiens* and providing reliable cranial-capacity estimates have a mean of 1,231 cm³ ($N = 4$), in between the means of earlier Middle Pleistocene *H. erectus* (1,101 cm³, $N = 11$) and Upper Pleistocene archaic *H. sapiens* (1,459 cm³, $N = 17$). It is only with Neandertals and fossils of a similar grade and with anatomically modern humans that encephalization is no longer a consideration; do *they* exhibit the postulated climatic patterning with respect to size and shape?

When the available cranial-capacity estimates are tabulated with archaic *H. sapiens* in the archaic sample and early anatomically modern humans in their sample (correcting some of the values given in the appendix, omitting questionable estimates, and adding specimens), the supposed climatic patterning largely disappears. There is little difference among archaic *H. sapiens* between "glacial" (1,482.4 ± 173.4 cm³, 1,200–1,681 cm³, $N = 8$) and "temperate" (1,438.9 ± 176.5 cm³, 1,200–1,740 cm³, $N = 8$) samples. The one "tropical" specimen in this group (Omo-Kibish 2: 1,435 cm³) falls in the middle of this range. Among early anatomically modern humans, the "temperate" and "tropical" samples are indistinguishable (TM: 1,487.2 ± 91.1 cm³, 1,300–1,587 cm³, $N = 9$; TR: 1,496.0 ± 166.1 cm³, 1,230–1,650 cm³, $N = 5$), even though the "glacial" sample is higher (1,570.4 ± 129.1 cm³, 1,375–1,880 cm³, $N = 13$); only the early modern "glacial" sample supports the supposed pattern. Could the lack of patterning be due to body-size differences? This is possible but unlikely, since cranial-capacity/stature indices (cm³/cm) for Neandertals (GL: 9.04, 8.0–9.7, $N = 5$; TM: 8.97, 8.0–9.7, $N = 3$) and early moderns (GL: 8.89, 8.3–10.3, $N = 9$; TM: 8.50, 8.2–8.8, $N = 3$) show only slightly lower values for the "temperate" samples than for the "glacial" ones.

A similar pattern is evident in cranial indices if the samples are rearranged as above. "Glacial" and "temperate" archaic *H. sapiens* samples are indistinguishable (GL: 74.3 ± 2.7, 67.8–76.1, $N = 9$; TM: 75.3 ± 2.6, 71.6–78.9, $N = 8$), as are the three climatic samples of early anatomically modern humans (GL: 72.2 ± 3.1, 66.3–77.8, $N = 17$; TM: 72.1 ± 2.1, 69.3–75.1, $N = 8$; TR: 71.9 ± 2.5, 69.0–75.0, $N = 4$). The data are not available to compare "coefficients of cranial morphology" in the same manner as above, but the cranial indices and published assessments of Upper Pleistocene neurocranial morphology (e.g., Stringer 1978, Trinkaus 1983, Vandermeersch 1981) suggest that they are unlikely to show significant differences between climatic samples of Upper Pleistocene humans of the same grade.

One could argue that small sample sizes, possible sex biases, and decisions on sample composition have unduly influenced these results. If this is the case, the available data should not be used to test any hypothesis of climatic patterning in neurocranial morphology and size. Yet, if one uses the maximum data available, if the comparisons are between hominids of similar grades, and if specimens are assigned to samples on the basis of their total morphological patterns, the results should not vary markedly from those presented here.

Although it is worthwhile investigating Pleistocene human morphology from a thermoregulatory point of view (e.g., Trinkaus 1981), it appears unlikely that neurocranial size and proportions were primarily influenced by thermal stress. It is more probable that the variation in size is due to a combination of encephalization and the influence of body mass (not merely stature) (the "meat-hed" hypothesis [Holloway 1981]). Neurocranial shape is controlled by relative rates of cerebral and neurocranial growth (Trinkaus and LeMay 1982), which are influenced by a variety of environmental and genetic factors, possibly in conjunction with the apparent shortening of human gestation length in the Upper Pleistocene (Trinkaus 1984, n.d.). Regardless of the relative importances of these and other influences on brain shape and size, the observed patterns are likely to be the result of a complex combination of them, not merely one such as thermal stress.

Reply

by KENNETH L. BEALS, COURTLAND L. SMITH, and STEPHEN M. DODD
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Many hypotheses are suggested in the comments. For most, however, no data are available, nor are they presented with sufficient information to enable their evaluation. Our responses to the comments are mostly in alphabetical order, although similar comments are combined and the paleontological portion left for the end.

As Angel remarks, there is little new about the thesis of thermoregulatory effects upon cranial morphology. It derives primarily from original ideas of Thomson and Coon. The present paper does quantify and document the ecological associations involved. The data are more comprehensive than those of other surveys, and the variables are for the first time geographically mapped.

Conclusions concerning the adaptations within the Americas are not materially affected even if the Inuit are eliminated from the sample on the basis of recent movement from Siberia—still an arctic environment. All the distribution maps are conventionally depictions of group location at the ethnographic present.

In writing of neotenous mutations we were referring to a mechanism of the phenomenon rather than the phenotypic result. Redundant cortical surface may have some relationship to variation in human intelligence, but our conclusions are limited to the morphology of the brain's container.

We have no contribution to make toward understanding how the brain functions. It is true that 4,000 generations is theoretically sufficient time for selection to "iron out kinks and equalize intelligence." The point is that no matter how many generations are involved, no sufficient evidence has ever been presented that variation in population brain size, head size, head shape, or cranial capacity has a connection to intelligence in the first place.

We need to rephrase Armstrong's initial summary of the hypothesis presented. Shorn of qualification, it is that increased cranial capacity is a result of increased cranial size (not brain size) in combination with rounder cranial shape—both of which are partially the result of thermoregulation. We concur that the brain is metabolically expensive. In fact, the cranium as a whole is thus expensive, especially with its lack of vasoconstriction. It does not, however, follow that metabolic expense would prevent thermoregulatory adaptation from occurring. Cranial variables tend to be more closely associated with climate than the body as a whole despite the metabolic expense. Moreover, the size of the brain generally increases throughout the paleontological record, which clearly indicates that factors overriding its metabolic cost do exist.

A key phrase in Armstrong's comment is "enlarge passively." Is the cranium increasing in size because the organ it surrounds is expanding, or is the organ expanding to fill the size and shape of its container? Versions of this query may be also gathered from other comments (Blumenberg and Gibson). Our distributional data cannot answer it. The nature of the interactive biology between the brain and its housing can nonetheless be separated from evaluation of the end product (observed endocranial volume), and it is observable that that end product has thermoregulatory adaptations.

We do follow a passive-enlargement interpretation in regard to cognitive significance. We mentioned, for example, the virtual identity of mean cranial size in Choctaw and Aleut, whose endocranial volumes are reported to differ by 226 cm^3. This "surplus" results from the differential geometry and apparently produces no behavioral difference. The additional 226 cm^3 must indeed be metabolically active, but anything cognitively affected thereby remains obscure.

Armstrong notes that the difference between winter-frost and dry/wet-heat ethnic groups is fairly small (89 cm^3). This value, however, includes temperate-zone cases associated with little climatic stress. Differences increase in proportion to climatic severity and become great between ecotypic extremes.

Gibson writes that we assume that statistical correlation implies causation, and Girgis and Turkel and Henneberg share her view. We make no such assumption, and the correlations are given as measures of association. The causation involved derives from the application of principles of geometry and thermodynamics to surface area:mass configurations.

We are aware of the influence upon head shape of cradleboarding, mastication, respiratory patterns, and numerous other factors. Particularly in regard to brachycephalization, the cultural aspects of the problem have been considered by Beals (1972).

Gibson continues that "the brain uses so much energy that extensive brain enlargement would be incompatible with survival in food-scarce environments unless it provided cognitive skills enabling increased foraging efficiency and/or increased cultural adaptation to harsh circumstances." In actuality, a glance at the distribution map (fig. 3) indicates that large brains occur in very harsh environments, e.g., Siberia. The climatic regularities empirically exist regardless of how much metabolic energy a larger brain may require.

Gibson adds a subclass to the cognitive model with the hypothesis that a larger brain may relate to foraging efficiency. If it does have significant effect, then the distribution becomes incomprehensible. For example, arctic and forest pygmy peoples differ in average cranial capacity by 300 cm^3, but can one reasonably conclude from this that the arctic peoples are more efficient at foraging? We do not understand how the cognitive model is the "most logical explanation" when no evidence is known to exist for its basic premise—namely, that normal variations in human (or contemporary hominid) brain size have some type of behavioral consequence.

Girgis and Turkel write that we "appear to equate cranial capacity with brain size, which gives the impression that cranial capacity reflects the number of neurons within the skull." We did not intend to convey any such impression, but brain size and cranial capacity are appropriate synonyms in the context. As mentioned, shrinkage of the dried cranium compensates for the dural contribution. The relationship has been intensively investigated, with the conclusion that "it is the brain volume alone in the natural skull which corresponds with the cranial capacity in the dried skull" (Todd 1923: 183). It follows that there is no advantage in substituting actual organ measurements for cranial capacity in the present discussion. Furthermore, brain weight is less reliable, more subject to preparation difficulty, and applicable to a much smaller amount of the available evidence.

We are in agreement with most of the comments of Henneberg and are cognizant of the recent microevolutionary change in head shape in Europe. We concur that climatic adaptation does not explain that phenomenon. Other examples of the limitations of the bioclimatic model could be added, and several have been previously given by Beals (1972) and Beals, Smith, and Dodd (1983). We reiterate, with Henneberg, that cranial morphology is affected by multiple processes, of which climatic adaptation is only one.

Both Henneberg and Morimoto suggest correlating the files with cultural conditions. As yet, we have not noticed any new contributions to make by such correlations.

It is desirable to introduce body-size estimates into the hominid file. The work has not been done. The correlations between body size and cranial capacity are given for ethnic groups in table 4. We have since enlarged the files on body size to a sample of 185 populations. Within this larger sample, however, we are forced to predict stature and weight estimates for the remaining sex when values for only one sex are supplied in the literature. The distributions of cranial capacity and surface area may be directly compared in figures 3 and 13.

Menk recognizes the bioclimatic interpretation as a global generality. It is useful as such but severely limited as an explanatory model in local circumstances. With Blumenberg, he also raises questions of sampling—which apply to all distributional investigations. We have recently submitted a proposal which would evaluate various sampling techniques with both the cultural and biological data bases. They include the use of Murdock's (1981) cultural provinces, the probability sample of Lagace (1979), the Standard Cross-Cultural Sample of Murdock and White (1969), geographical techniques (e.g., taking one case from each 10° grid square), and weighting of grid squares according to population. We would like to compare results with the maximum data reasonably obtainable and with minimal rejection of reported observations on various grounds of reliability.

Menk suggests correcting for body weight in the scattergram of absolute endocranial volume by latitude. However, total body-size values include the variable contribution of the cranium. Figure 14 plots cranial capacity relative to body weight for direct comparison with figure 6. This relative value varies inversely with latitude, whereas the absolute volume varies directly.

Morimoto asks whether the globularity in skull form due to

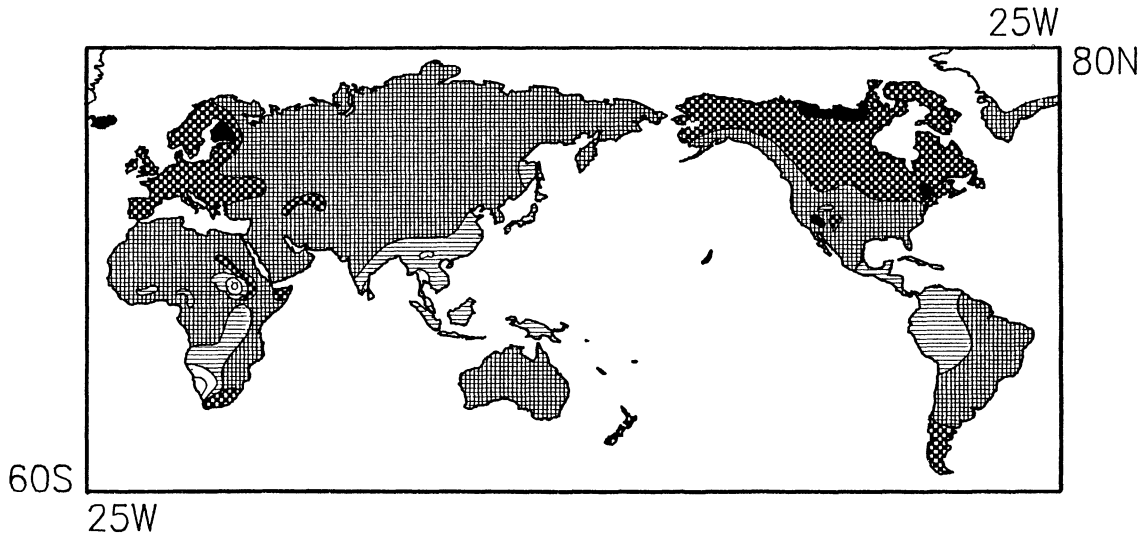

FIG. 13. Distribution of human body size (surface area) as calculated from sex-combined stature and weight means of 185 populations. Isophenes are 0.1 m^2 increments from *white* (1.2 and under) through *dots, horizontal striping, cross-hatching,* and *checkerboard* to *black* (1.7 and over).

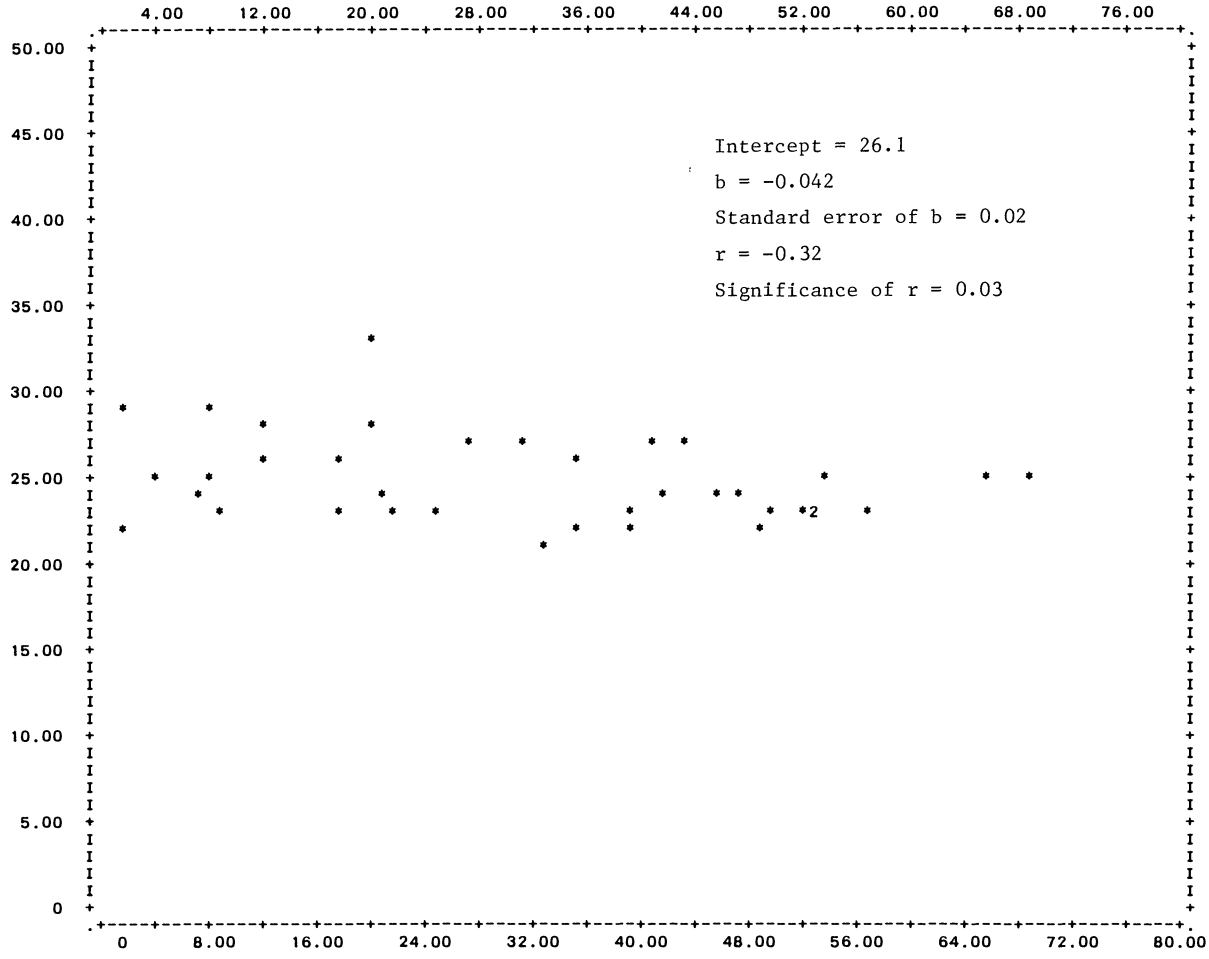

FIG. 14. Relative brain size as a function of latitude. *x*-axis, absolute degrees from the equator; *y*-axis, cranial capacity by weight (cm^3 per kg).

a cold northern environment could be explained by Allen's and Bergmann's rules. Since we consider size and shape of the cranium to be an instance of the two rules' operating together, our answer is yes—with the provision that these ecological rules apply to global variation and should not be taken as necessarily having explanatory value for local cases. We have, for instance, received the Japanese study to which Morimoto refers and are in accord with its conclusion that climate does not explain the distribution of head shape in Japan. Nor would one expect it to do so, given the relatively minor climatic variation within that small area and the temperate nature of the climate, with its associated small amount of thermoregulatory stress upon the population.

Both Morimoto and Trinkaus call attention to our statement that "climatic factors have become the principal source of [cranial] variation." In retrospect, we might better have written "*a* principal source" rather than "*the* principal source." However, the somatic, phyletic, and cognitive paradigms have no known functional and systematic components in regard to the worldwide variation of brain size, and from this perspective the bioclimatic model is clearly the principal source of the (systematic) component of the variation. An unknown but probably substantial portion of the nonsystematic variance lies in sampling and measurement error. Nonbioclimatic factors affecting the variance in some possible circumstance, in some possible location, at some possible time cannot be ruled out, but none of them appear to us to explain more of the variance than thermoregulation. None of them have been documented as explaining the distribution on a global scale.

In a similar vein, Blumenberg suggests that a portion of the unexplained variance in the bioclimatic model may be due to genetic factors. We agree. The particular role of any factor mentioned, however, remains obscure with either local or global patterns of braincase variation.

We have no disagreement with any of the comments of Sokal. As he remarks, the correlations and significance levels are in conventional form. Most of the analyses were performed by SPSS, one of the most widely used statistical packages available. Some preliminary work has been accomplished with his idea of examining residuals. The conclusions at this time suggest that proximity of peoples does explain some of the residual variances. We have not yet pursued the suggestions of Sokal and Blumenberg in regard to autocorrelation. The maps are drawn after finding associations with climatic variables. While there is a general connection between latitude and temperature, proximity to coastlines, microclimatic factors, and altitude mean that the clines do not exactly parallel latitudes. The angled pattern of Asia is an example, as is the interior of Africa.

In summary of the responses pertaining to the variation among contemporary groups, we find no evidence presented which materially alters our data, descriptions, or conclusions. Additional work can, of course, always be done, and the responses may provide guidance toward aspects of the problems involved.

One of the useful first steps toward evaluating a hypothesis is to examine a distribution map of the trait in question. One might thus scan figures 3, 7, and 8 and draw one's own conclusions in regard to the relative roles of the myriad factors that may be involved. Eliminating the thermoregulatory paradigm, a partial list drawn from the literature includes artificial deformation, fission-fusion patterns, neurocranium balance, drift, sampling error, measurement error, sexing error, nutrition, language, deviations from Hardy-Weinberg equilibrium, intelligence, adenoids, cradling, abandonment of cradling, nomadic incursions, tool use, racial affinity, cognitive style, underbrush movement, sexual selection, cultural complexity, physical strength, heterosis, pedomorphism, stature increase, mastication, respiration, parturition, and hats.

Turning to the paleontological experiment, Blumenberg supports particular portions of the presentation but raises a number of questions. Some of these questions have been considered in depth in very recent publications or in works not yet in print. For example, we have applied some nonparametric methods to the data (Beals, Smith, and Dodd 1983). In brief, the nonparametric statistics have slightly less power, reporting them requires more journal space, and their associations with the variables are slightly weaker, but the patterns are unchanged, and no conclusion is materially affected by the particular statistics selected for description.

The "in-house methodology" is not obscure. Production of distribution maps and their interpretation are different procedures. The maps are based upon the widely used Miller projection, and each plotted point is geographically correct to the nearest degree. In other words, distance and azimuth from any one point to any other point (as in figure 2) are valid. Either color sets or numerical plots can be used to designate the selected class-interval, and in the present paper all isophenes are drawn by linear interpolation—the most widely used method and also appropriate for the data. To illustrate, the reader might visualize the dots in figure 2 as being in different colors, around which lines are drawn. It is true that linear interpolation is only one of the procedures which can be used. There is a large body of technical literature on the relative merits of various isopleth construction methods. Each method has its own advantages and limitations.

The paleontological appendix lists all of the data we were able to obtain. Since more discoveries have been made in the Upper Pleistocene, it is, as Blumenberg notes, dominated by the later specimens. Plotting all of the cases is clearly the best approach for the feedback experiment. However, as we said, any data set could be specified. Figure 15 reduces all 91 cases less than 130,000 years B.P. to a single mean point. Any such rearrangement can be made by simple recoding. Data processing allows any selection desired for any particular purpose one has in mind. Our purpose with the time machine is not to debate the merits of anyone's rearrangement or selection of data, but rather to take that set and demonstrate its results. For example, if one used the regression in the condensed model (fig. 15) to predict the current observed mean cranial index, it would miss by 4.2 units. If one used the noncondensed model (fig. 10), it would miss by zero units, but this is also a function of the way we have selected the points.

Blumenberg's query in regard to the term "gradualistic" seems to be a question of semantics. As we explained, we used it to describe the major difference between the two lists of taxa—that in the alternative there is less correlation between taxa and chronological age. It is not meant as the antithesis of punctuated equilibrium. Neither gradualism in this latter sense nor punctuated equilibrium provides a better model of the trends than does the simple empirical observation that the rates vary in accordance with whatever the adaptive situation may be—sometimes increasing rapidly, sometimes increasing slowly, sometimes remaining unchanged, and sometimes decreasing.

Blumenberg argues for the utility of endocranial volume in taxonomic assessment. Usefulness is partially a matter of individual judgment, and if brain-size difference has a heuristic or empirical value, there is no reason not to use it. In our judgment, cranial capacity is no more taxonomically valuable than any other trait. By the same token, it is just as valuable.

The allusion to brain size and taxonomy in the text has to do with attempts to resolve the taxonomic controversy over certain specimens. Statistically significant differences in endocranial volume between taxonomic models can indeed be found. They are found in greater abundance between ethnic groups, but with no known taxonomic, reproductive, or behavioral consequence.

Blumenberg writes that the taxonomic assignments in the appendix require discussion. They are widely discussed in the sources cited. The assignments are not our own, but rather reflect attributions by multiple authorities. Our own assignments would not in any event resolve the controversies. More

generally, modern procedures of information processing reduce the need for taxonomic summary of a set, since the computing power can evaluate all of the cases in any customized taxonomy desired. With respect to the time machine, such attributions merely become variables whose inclusion in the equations may or may not improve the reconstructions.

Blumenberg states that we consider cognition "critical" for the encephalization of early hominids. In fact we "speculate that cognitive factors may have been significant." Unable to explain this early encephalization by either body size or climate, we fell back upon the cognitive model by default. This makes for a weak argument, and one of the commentators maintains that body size is sufficient.

Trinkaus agrees that at least part of modern human neurocranial variation is due to climate. We concur with him that the observed patterns in the fossil record are results of complex combinations of influences rather than thermal stress alone. As we stated, climatic adaptation is less successful in explaining phyletic trends, and the results are ambiguous for certain sample sets. The principal problem is smallness of sample size.

A proximate mechanism of adaptation is implicit. In the most abbreviated form, it is that the mass and surface area morphology of individuals is a survival factor in the probability of death associated with a thermodynamic life crisis. Such a proximate mechanism has never been disputed, although its relative role in explaining distribution patterns has been controversial.

Neither we nor our readers are in a position to evaluate the analysis by Trinkaus in which the "supposed climatic patterning largely disappears," for he has made unspecified corrections of, omissions from, and additions to the data set. It appears to us unlikely, however, that the patterning really does disappear. First, Trinkaus himself (1981) comes to affirmative conclusions in regard to climatic adaptation in postcranial remains. Given the higher correlations with climate of cranial features, one is hard-pressed to explain why effects upon the latter disappear while the former remain. Secondly, it is difficult to imagine what circumstance could reasonably exist that would produce climatic adaptation in modern forms but not in any of their ancestors, given the fact that many of those ancestors were exposed to extreme cold stress. Thirdly, we ourselves have made corrections to the appendix (see Beals, Smith, and Dodd 1983), and our results confirm the general conclusions drawn from the lists given in table 11. Finally, the systematic patterning which exists among ethnic groups can only be reasonably explained as an adaptation through time as well as space.

If Trinkaus had specified his emendations to the appendix, we could have used them to improve reconstructions such as the one in figure 16. Such reconstructions are dependent upon the sharing of paleontological evidence. To illustrate the use of the time machine to manipulate theoretical models, we selected a trait (the cranial index), a portion of the globe (the Mediterranean area), a time for the map to correspond to (20,000 B.P.), and a segment of the evolutionary rate of change for the

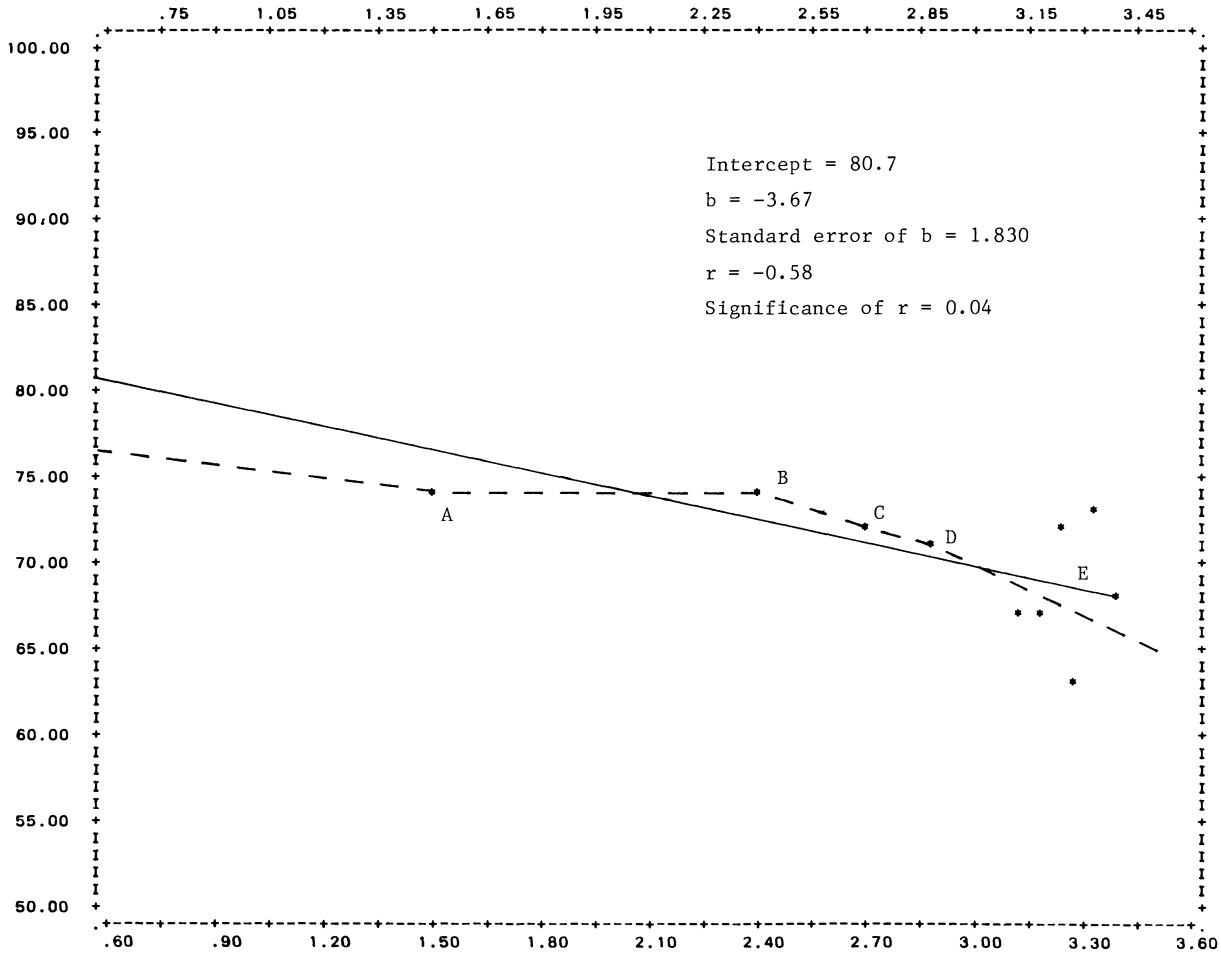

FIG. 15. A condensed model of hominid cranial index to minimize Late Quaternary discovery bias. Data points follow chronological gaps. *A,* 91 specimens less than 130,000 years B.P.; *B,* 13 specimens from 175,000 to 300,000 years; *C,* 1 specimen at 500,000 years; *D,* 7 specimens from 650,000 to 800,000 years; *E,* remainder of individual specimens; *x*-axis, log of age (× 1,000); *solid line,* regression; *dotted line,* empirical, with origin at heterographic composite.

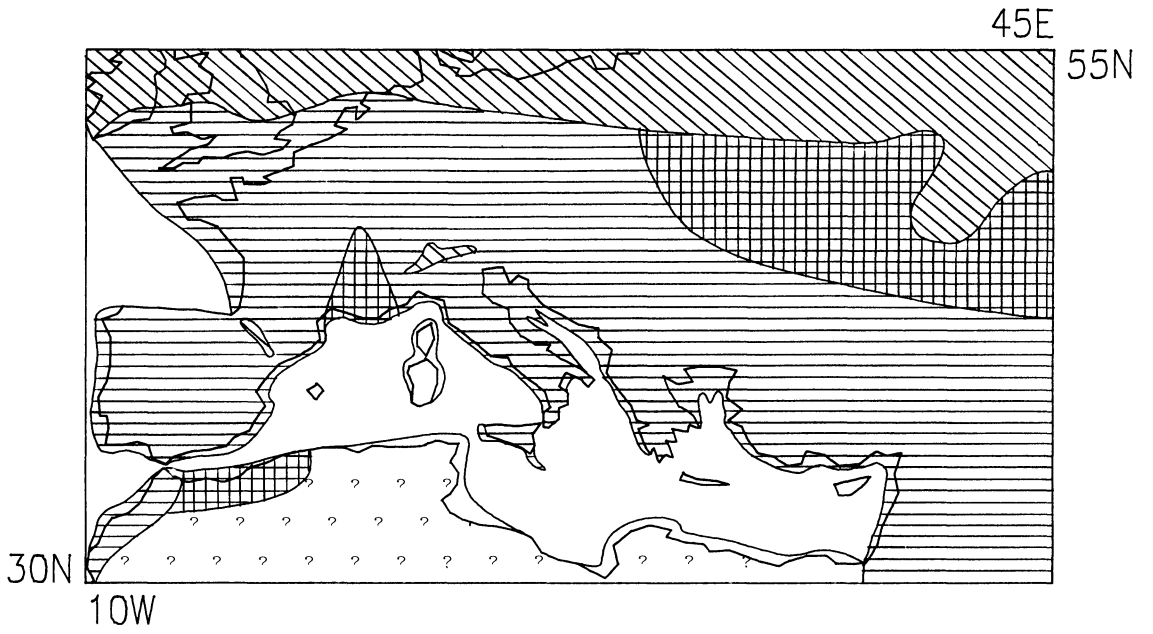

FIG. 16. Time-machine projection of cranial index around the Mediterranean at 20,000 B.P. *Horizontal striping,* 72–73.9 units; *cross-hatching,* 74–75.9 units; *diagonal lines,* glaciation; *question marks,* inadequate data for reconstruction; *solid line,* approximate coastline.

trait (from 110,000 to 10,000 B.P.). Specimens were then sorted by time, sex, and site. A multiple regression predicted values at each site as adjusted to the selected time. Distance was then added as an "experimental" stepwise variable and identified as the space between each site and Cabo da Roca in Portugal. The result is, to our knowledge, the first attempt at a clinal reconstruction of a human trait in the Pleistocene. It should be taken as an illustration of method rather than finality.

This method expands the scope of anthropology. In addition to investigating change in traits over time, it is possible to analyze geographical complexes of traits through space over time. Our attempt here to test the method and improve the files has not been notably successful. Perhaps its failure may stimulate colleagues to resolve the problems the system contains.

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