THE EVOLUTIONARY ROLE OF MODULARITY AND INTEGRATION IN THE HOMINOID CRANIUM

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Patterns of morphological integration and modularity among shape features emerge from genetic and developmental factors with varying pleiotropic effects. Factors or processes affecting morphology only locally may respond to selection more easily than common factors that may lead to deleterious side effects and hence are expected to be more conserved. We briefly review evidence for such global factors in primate cranial development as well as for local factors constrained to either the face or the neurocranium.

In a sample comprising 157 crania of *Homo sapiens*, *Pan troglodytes*, and *Gorilla gorilla*, we statistically estimated common and local factors of shape variation from Procrustes coordinates of 347 landmarks and semilandmarks. Common factors with pleiotropic effects on both the face and the neurocranium account for a large amount of shape variation, but mainly by extension or truncation of otherwise conserved developmental pathways. Local factors (modular shape characteristics) have more degrees of freedom for evolutionary change than mere ontogenetic scaling. Cranial shape is similarly integrated during development in all three species, but human evolution involves dissociation among several characteristics. The dissociation has probably been achieved by evolutionary alterations and by the novel emergence of local factors affecting characteristics that are controlled at the same time by the common factors.

Key words: Craniofacial growth, factor analysis, geometric morphometrics, heterochrony, human evolution, morphological integration, partial least squares.

Modularity is a property of complex structures or processes that are experimentally or conceptually separable into several “near-decomposable” (Simon 1962) modules. Following the lead of Needham (1933), Riedl (1978), and others, the concept of modularity has been applied in both developmental biology and evolutionary biology. Recent reviews can be found, for example, in Raff (1996), von Dassow and Munro (1999), Bolker (2001), Schlosser and Wagner (2004), and Callebaut and Rasskin-Gutman (2005). In the context of evolutionary biology, a module is usually construed as a set of morphological characters that (1) collectively serve a common functional role, (2) are tightly integrated by strong pleiotropic effects of genetic variation, and (3) are relatively independent from other modules. Wagner (1996) and Wagner and Altenberg (1996) described such a modular organization in terms of a “genotype–phenotype map” characterizing how genetic variation contributes to phenotypic variation throughout ontogeny (Fig. 1, left). A modular genotype–phenotype map can be decomposed into several independent and more local genotype–phenotype maps with fewer pleiotropic effects among the modules. If genetic changes affect only a part of the phenotype, the genome can...
responsive genetic models (Cheverud 1984; Badyaev and Foresman 2004; Hallgrímsson et al. 2004). In his theory of the “imitatory epigenotype,” Riedl (1996a). Thus, a modular organization enhances the ability of the genetic system to generate adaptive variants, which is often referred to as “evolvability” (Altenberg 1994, 2005).

The related concepts of correlation pleiades (Terentjev 1931) and morphological integration (Olson and Miller 1959) have been frequently applied in paleobiology and evolutionary biology. This literature emphasizes that traits affected by common genetic, developmental, or environmental causes will appear to be phenotypically correlated within a species. For instance, a number of morphometric studies reported tight statistical associations among measures of characteristics with a common developmental origin (e.g., Zelditch 1987; Wagner 1990; Nemeschkal 1999; Klingenberg et al. 2003, 2004; Marroig et al. 2004; Hallgrímsson et al. 2007). In his theory of the “imitatory epigenotype,” Riedl (1978) further postulated that functionally related characters will evolve a common genetic basis. He argued that when parts of an organism, for example, the elements of a bony joint, are functionally dependent, genetic and developmental integration among these parts may avoid deleterious independent variation and so facilitate adaptive evolution. This notion is supported by quantitative genetic models (Cheverud 1984; Bürger 1986; Wagner 1988) and also numerous empirical studies report concordance between functional relatedness among characters and their pattern of covariation and coinheritance (e.g., Olson and Miller 1958; Atchley et al. 1981; Zelditch and Carmichael 1989; Cheverud 1995; Badyaev and Foresman 2004; Hallgrímsson et al. 2004).

Mitteroecker and Bookstein (2007) devised a formal model of common and local developmental factors that differently affect phenotypic variables. Local factors contribute to morphological variation within one module only, whereas common factors affect traits of different modules (Fig. 1, right). Modules are thus construed as anatomical parts (sets of measured morphometric variables) that are influenced separately by dissociated local factors and that may also be integrated through common developmental factors. The model specifically emphasizes the simultaneous presence of modularity and developmental integration: some characteristics or shape features are independent across modules, whereas other properties are common to several modules—that is, they are integrated. This factor model closely resembles the genotype–phenotype map of Wagner and Altenberg. The genes in their model (the Gs in Fig. 1, left) can be separated into those with pleiotropic effects on both modules (common factors) and those with effects on one module only (local factors), resulting in the right graph of Figure 1.

The factor model differs from the genotype–phenotype map in that it is used to model the empirical covariance structure in the following statistical analysis rather than any underlying biological processes. A “factor” is taken in its most general sense, including not only genes with various pleiotropic effects, but also genetic linkage and epigenetic processes, such as chemical and mechanical tissue interactions during development (Müller and Newman 2003). Unlike Wagner and Altenberg, we do not refer to module-specific functions here. The factor model focuses on the actual integration and modularity observable on the morphological level as caused by a series of developmental processes and genomic properties, but it does not separate out these various causes.

Although our understanding of modularity is phrased causally in terms of developmental processes (in interaction with functional and selective regimes), the empirical approach to morphological integration is often based on observed correlations among morphological measures. Local genetic, developmental, and functional factors contribute to the covariances among phenotypic variables within one module, but not to covariances between modules. Hence, the assumption of many morphometric methods for identifying modules is that covariances or correlations within one module are higher than covariances between modules—groups of correlated characters (correlation pleiades or p-groups) are often interpreted as modules (see Chernoff and Magwene 1999 and Mitteroecker 2007 for review). Mitteroecker and Bookstein (2007) showed that such expected covariances may be confounded by the allometry of common and local factors and by factors with opposite effects on the same variables. The identification of modules from observed covariances or correlations alone requires very stringent and partly unrealistic assumptions and is therefore unreliable.

Empirical models of integration and modularity are nevertheless of direct relevance for phylogenetic reconstruction, estimation of selection gradients, and adaptive explanations of observed species differences (Gould and Lewontin 1979; Cheverud 1994;
Wagner and Altenberg 1996; Strait 2001; Ackermann 2002). The present article focuses on the hominoid cranium, which has undergone considerable morphological change in the course of human evolution. Numerous adaptive explanations have been devised for these alterations, typically assuming independent evolution of body components (e.g., Ruff 1994; Churchill 1998; Aiello and Dean 2002). Furthermore, most cladistic analyses treat their characters as mutually independent, providing separate evidence for evolutionary history. In contrast, empirical studies have reported various levels of integration among different cranial elements and shape features during primate development and evolution (e.g., Ross and Ravosa 1993; Ross and Henneberg 1995; Cheverud 1995; Lieberman et al. 2000a,b; Marroig and Cheverud 2001; Strait 2001; Bookstein et al. 2003; Ackermann 2005; Bastir and Rosas 2005, 2006; Gunz and Harvati 2007).

In the following analysis, we will specifically address the most prominent cranial modules, the face (viscerocranium or splanchnocranium) and the cerebral capsule (neurocranium or neurobascranial complex). We do not identify these forms from morphometric variables, but infer them from known developmental processes and functional properties of the cranial as briefly reviewed here. It is well documented that the developing brain is spatially separated very early in embryogenesis from what will later become the face and exhibits a different pre- and postnatal growth pattern. Already after the neural folds fuse to form the neural tube, the neuroectoderm and the surface ectoderm are two discrete tissues. At the end of the first month, the human face is represented by the stomodeum (the future oral cavity) and the first pharyngeal arch, which develop largely independently of the neural tube. For instance, the insertions of muscles provide a further source of epigenetic integration during the formation of the cranial skeleton, all the bone that may become massive sagittal crests as seen in gorillas (Anton and Young 1960; Enlow et al. 1969; Roth 1996). For example, the anterior part of the human cranial vault known from various cultures showed that facial and basicranial shape are significantly affected by the mechanical forces induced (Anton 1989; Cheverud et al. 1992; Kohn et al. 1993; Rhode and Arriaza 2006). Even beyond the period of neurocranial growth, masticatory muscles provide a further source of epigenetic integration between the face and the neurocranium. For instance, the insertions of the temporal muscles cause superficial modifications of the vault that may become massive sagittal crests as seen in gorillas (Washburn 1947; Riesene 1955; Robinson 1958).

RESEARCH QUESTIONS AND HYPOTHESES

Based on this extensive embryological and experimental evidence for modularity of the primate face and neurocranium as well as for their integration, we statistically estimate aspects of shape variation that are common to the hominoid face and the neurocranium (integrating common factors) and also the aspects of shape variation due to modular developmental factors (local factors affecting either the face or the neurocranium) from measured shape coordinates on dried crania. These factor estimates are then used to describe evolutionary shape changes in terms of integrated and modular developmental variation. Because different modules often serve different functions, specific selection regimes likely involve only one or a few
modules at a time. Consequently, pleiotropic effects may interfere with adaptation due to deleterious side effects in the other modules, so that common factors are expected to be relatively conserved during evolution. Local factors are less constrained and may respond more easily to varying selection pressures. This expectation seems to be supported by the fact that highly pleiotropic developmental genes have remarkably similar functions during cranial development in a wide range of vertebrate species (e.g., Morris-Kay 2001; Santagati and Rijl 2003; Hanken and Gross 2005; Helms et al. 2005). Furthermore, Khaitovich et al. (2005) found that expression levels as well as DNA sequences of genes active in more tissues have diverged less between humans and chimpanzees than have genes active in fewer tissues.

We therefore expect (1) that common factors are conserved across hominoid species, which is to say, they have similar effects in all three species and contribute little to their shape differences; and (2) that most evolutionary shape differences mainly owe to alterations of local factors. Any break-up of ancestral patterns of developmental integration in the course of evolving the actual species differences of mean shape would implicate different module-specific regimes of directional and stabilizing selection and so would suggest speculations about certain evolutionary scenarios (Wagner and Altenberg 1996; Cheverud 1996a; Wagner et al. 2005). According to the definition of a factor, developmental integration is taken here in a wide sense as due to genetic and epigenetic factors during development along with genetic linkage. In the absence of directed selective forces, within-species and between-species covariance matrices should be proportional (Lande 1979) and developmental integration would be expected to resemble evolutionary integration (covariation across the three species means).

Materials and Methods

Three-dimensional coordinates of 45 paired and unpaired anatomical landmarks and of 157 semilandmarks on ridge curves and the neurocranial surface (Fig. 2) were measured with a Microscribe 3DX digitizer (Immersion Corporation, San Jose, CA) on a cross-sectional sample of dried crania. The sample comprises specimens of both sexes from three closely related but morphologically diverse genera: 52 Homo sapiens, 49 Pan troglodytes, and 56 Gorilla gorilla. The age of the specimens ranges from newborns to adults in all three species. The landmarks cover all external parts of the face, the cranial vault, and the midline cranial base. Semilandmarks were measured on one side of the cranium only, but to enable three-dimensional surface representations they were warped and reflected with a thin-plate spline algorithm onto the other side based on the measured anatomical landmarks. For more technical details see Gunz (2005) and Mitteroecker (2007), and for information on the sample see Bernhard (2003), and Mitteroecker et al. (2004). Semilandmarks are points sampled along outlines or surfaces that are allowed to slide along their curvature so as to minimize “bending energy,” a quantity measuring local shape differences versus the mean shape. Semilandmarks can be used in the subsequent analytic toolkit of geometric morphometrics as if they were homologous point locations (Bookstein 1997; Gunz et al. 2005).

The 157 sets of 347 landmarks and semilandmarks were transformed into shape coordinates by one overall Generalized Procrustes Analysis (Rohlf and Slice 1990). Thereafter, they were separated into two modules (Fig. 2): the face with 146 (semi)landmarks and the neurocranium with 201 (semi)landmarks (see also the Appendix on alternative analyses). All morphometric and statistical analyses were performed in Mathematica 5.2 based on routines written by Philipp Mitteroecker and Philipp Gunz. Surface representations were rendered in Amira 3.0.

ASSESSMENT OF DEVELOPMENTAL INTEGRATION

To estimate common factors, that is, dimensions of shape variation that are integrated among the face and the neurocranium, we employ the two-block partial least squares (PLS) approach that is called singular warp (SW) analysis when applied to Procrustes coordinates (Bookstein et al. 1996, 2003; Rohlf and Corti 2000).

For each extracted dimension, the analysis yields two singular vectors, one for the face and one for the neurocranium, that can be construed as the two shape changes that most highly covary in the sample. In Mitteroecker and Bookstein (2007) we demonstrated that the two PLS loading vectors serve together as a common factor estimate when the vectors are scaled appropriately so that they relate to common factors in Sewall Wright’s (1932) factor analysis approach (see Appendix for algebraic details).

Based on these common factor estimates, the full shape space is partitioned into three subspaces: an integrated shape space spanned by the common factors, and two modular shape spaces, one for the face and one for the neurocranium, that complement those dimensions of integrated shape variation. The integrated space is ordinated by scores along the common factors, and the
modular spaces by scores along principal component axes of the residual data after the common factors have been removed from both blocks of variables separately. These scores let one express the observed shape variation in terms of common and local developmental processes. By design, the integrated shape space accounts for shape differences due only to common factors, whereas shape differences in the modular spaces are due mainly to local factors. To evaluate the relative contribution of integrated versus modular shape variation to the observed shape differences, specimens and ontogenetic trajectories are compared in all three subspaces (O’Higgins 2000; Mitteroecker et al. 2004, 2005). For example, if the species completely overlap in the integrated space but differ in the modular spaces, one would conclude that evolutionary shape differences among the species are due to alterations in modular developmental processes.

When relating evolutionary differences to developmental integration, the choice of the “reference” sample whose covariances drive the PLS is crucial. In analyses pooling all the adult specimens of the three species, most of the variation and covariation in shape is due to the mean species differences. Accordingly, the first dimensions of PLS would describe evolutionary integration—how the face and the neurocranium co-vary across the three species means—which is not the same as developmental integration. Although developmental integration is due to common genetic and epigenetic effects, evolutionary integration is a result of developmental integration and coinheritance in the context of selective regimes. Similarly, PLS based on the full cross-sectional sample including subadult specimen would mainly assess covariation across average postnatal age stages. The appropriate PLS analysis to assess developmental integration has to be based on the covariation among adults within one species, which is the result of common and local morphogenetic factors during the full period of pre- and postnatal development. For the present analysis of three different species, PLS is based on the pooled within-species covariance matrix. See also the Appendix for alternative analyses.

Differences of integration among species as well as differences between developmental integration and evolutionary integration can be identified in plots of the SW scores for the face against those for the neurocranium, one plot for each paired dimension (common factor). To the extent that patterns of developmental integration are identical among all species and also identical to evolutionary integration, all specimens would lie close to a straight line in these plots.

**Results**

We performed a two-block PLS analysis on the adult pooled within-species covariance matrix and extracted four common factors. Table 1 shows that nearly 90% of the squared covariance (in the pooled adult sample) is already explained by the first two dimensions of PLS, but a permutation test (see Appendix) yields four dimensions that differ significantly from a random distribution. Correlation as well as covariance among PLS scores decreases markedly after the fourth factor.

Figure 3 shows the space of integrated shape variation as individual scores along the common factors. The ontogenetic trajectories of *Pan* and *Gorilla* overlap in these four dimensions, where *Gorilla* clearly extends the common trajectory. The short human trajectory differs somewhat in direction from that of the apes, indicating less and slightly different postnatal shape change.

The shape deformations depicted by the common factors are visualized in Figures 4 and 5 as landmark displacement vectors and as deformations of a surface representation of a chimpanzee cranium extracted from a CT scan. The shape changes visualized correspond to increasing scores in Figure 3. The first common factor involves an enlargement and forward protrusion of the maxilla along with a relatively smaller cranial vault with both sagittal and nuchal crests. High scores along the second common factor correspond to a broad and large face and a broad but short neurocranium, whereas low scores are associated with long and narrow crania. The third factor involves a reorientation of the alveolar process and a shape change of the occipital. The fourth common factor is a contrast between high and more spherical versus more flat and ellipsoidal neurocrania, where the latter, elongated, shape is associated with pronounced supraorbital tori and enlarged zygomatic arches.

Figures 6 and 7 show principal component scores of the modular shape spaces that are devoid of those dimensions of integrated shape variation. Shape differences depicted by these two figures reflect differences due to local factors, which is to say, modular shape variation. In the modular space for the face, the three species-specific trajectories diverge during postnatal development, and human development is clearly distinct by the time of birth. In the neurocranial modular space, chimpanzee and gorilla trajectories overlap in the first four PCs but differ along the fifth PC. The gorilla trajectory is again much longer than *Pan’s*, and the human trajectory deviates from both of them.

**Table 1.** For the first four extracted dimensions of the singular warp (SW) analysis, this table provides the covariance (in units of squared Procrustes distance × 10⁶) and correlation among the singular warp scores of the two blocks, the percentage of the adult within-species variance explained by the common factors (scaled PLS loading vectors), the percentage of the full variance explained by the common factors, and the percentage of the adult within-species covariance explained by the common factors.

<table>
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<th></th>
<th>SW</th>
<th>Covar.</th>
<th>Correl.</th>
<th>Expl. var. pooled</th>
<th>Expl. var. full</th>
<th>Expl. covar.</th>
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<tr>
<td>1</td>
<td>4.25</td>
<td>0.85</td>
<td>32.9%</td>
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<td>71.2%</td>
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<tr>
<td>2</td>
<td>2.13</td>
<td>0.82</td>
<td>12.3%</td>
<td>30.6%</td>
<td>17.9%</td>
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<tr>
<td>3</td>
<td>0.97</td>
<td>0.75</td>
<td>5.9%</td>
<td>1.8%</td>
<td>3.7%</td>
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<tr>
<td>4</td>
<td>0.83</td>
<td>0.77</td>
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Figure 3. The integrated shape space reflects cranial shape variation due to the four common factors—variation that affects both the face and the neurocranium. Adult and subadult specimens (larger and smaller points, respectively) for all three species are shown in this space. The developmental sequence of specimens from one species traces out an ontogenetic trajectory. The approximate geometry of the three trajectories is schematized in Figure 9.

Figure 8 shows all four dimensions of singular warp scores for the face plotted against the scores for the neurocranium. These are scores along the common factors, computed separately for the face and the neurocranium, to assess the actual integration of the corresponding shape features due to the common factors. The orientation of the adult specimens’ point clouds is very similar among the three species, especially for the first two dimensions of PLS, illustrating similarity (i.e., conservation) of developmental integration patterns. That is, one unit of shape change along the neurocranial component is associated with an amount of facial shape change that is similar in all three species, irrespective of the actual average shape of the species. In the first two dimensions, all adult and subadult specimens lie along one line, suggesting that the species differences are also integrated in that way. In the third and fourth dimensions, integration in humans differs slightly from the others. Also, the human group is displaced as a whole from the diagonal, indicating that the way humans differ from chimpanzees and gorillas is not integrated in these dimensions.

Discussion
INTEGRATION DURING CRANIAL DEVELOPMENT
There is extensive embryological and experimental evidence for the presence of common developmental factors or processes (that affect both the neurocranium and the face) as well as for local factors (affecting either the face or the neurocranium) during primate craniofacial development. It is thus beyond question that the primate face and neurocranium possess some shape characteristics that are modular and others that are integrated among the two regions. Even though humans differ considerably in average cranial shape and particularly in their postnatal growth pattern from other primates (e.g., Cobb and O’Higgins 2004; Mitteroecker et al. 2004), the major developmental processes are certainly shared among all hominoids (as they are conserved even across a much wider taxonomic range; see, e.g., Morris-Kay 2001; Helms et al. 2005; Tapadia et al. 2005). Accordingly, we find that Homo, Pan, and Gorilla have very similar but not quite identical patterns of developmental integration (similar slopes within adults in Fig. 8), implying that the effects of common factors are relatively conserved among hominoids. These results support those of Ackermann (2002, 2005) and are in accordance with findings that cranial integration is similar across a broad taxonomic range of primates (e.g., Cheverud 1996b; Marroig and Cheverud 2001; Marroig et al. 2004) and even therian mammals (Goswami 2006). Claims by Polanski and Franciscus (2006) that the hominoid face is “uncoupled” from the neurocranium and that humans, in contrast to apes, are not integrated in the face is likely a consequence of their problematic methodology based on the inverse covariance matrix (cf. Mitteroecker and Bookstein 2007). In fact, a series of recent studies described tightly integrated shape features in the human cranium (Lieberman et al. 2000a; Bookstein et al. 2003; González-José et al. 2004; Ackermann 2005; Bastir and Rosas 2005, 2006; Bastir et al. 2006).

To show the actual patterns of integration, Figures 4 and 5 visualize the four pairs of SWs as common factors, that is, joint shape deformations. The first factor is mainly related to mastication—an enlarged and prognathic maxilla along with a relatively small cranial capsule is associated with cranial crests and enlarged zygomatic arches. These characteristics are epigenetically associated in primates mainly through masticatory muscle
activity. The second factor contrasts broad and short crania with narrow and long crania, including both the face and the neurocranium (brachycephalic versus dolichocephalic crania), and also involves changes in the overall size of the face relative to the neurocranium. This somewhat uniform cranial shape deformation is a commonplace finding in cephalometrics and has also been identified in previous studies of morphological integration (e.g., Weidenreich 1941; Enlow and Hans 1996; Lieberman et al. 2000a; Bookstein et al. 2003; Bastir and Rosas 2004). Interestingly, the dimensions of the nasal aperture are largely unaffected by these overall shape changes, corroborating results from Anton (1989) and Rhode and Arriaza (2006) that artificial deformations of the cranial vault do not affect the nasal aperture but only more peripheral facial structures. Shape change along the third common factor encompasses relative size of the midface and neurocranial globularity, two characteristics that are tightly associated during postnatal ontogeny. Furthermore, the positions of the foramen magnum and the superior nuchal line are related to facial kyphosis, perhaps as a joint association with locomotion and posture behavior (Schultz 1942; Manfreda et al. 2006) or with the basicranial angle as driven by relative brain size (Ross and Ravosa 1993; Lieberman et al. 2000a,b). The fourth common factor contrasts crania with a roundish and relatively short and high neurocranium to elongated, ellipsoidal crania. Exaggeration of the latter generates an occipital

Figure 4. Visualization of the first two common factors as shape deformations. The first column of images describes the according shape changes by landmark displacement vectors (from the consensus). Columns 2 to 5 are corresponding surface morphs where each morph differs from its neighbors by 1.5 standard deviations of the actual variability in the adult sample. The depicted shape changes (the sequence from the left morphs to the right ones) correspond to increasing scores in Figure 3. Each morph and also the landmark displacement vectors are shown in a frontal, a lateral, and a superior view (top, middle, and bottom images). Because no landmarks were digitized on the teeth, the dentition is not involved in the warping.
Verifikation des dritten und vierten gemeinsamen Faktors als Formverzerrungen. 


THE DEVELOPMENTAL BASIS OF EVOLUTIONARY CHANGE


**Figure 5.** Visualization of the third and fourth common factors as shape deformations.

bun and lambdoid flattening along with large browridges in the upper face—a combination of traits that is quite characteristic for archaic human morphology (e.g., Trinkaus and LeMay 1982; Lieberman et al. 2002; Schwartz and Tattersall 2002, 2003; Gunz and Harvati 2007). These four described factors do not necessarily directly relate to four single biological causes. Actual shape differences and biological processes may instead consist of linear combinations of these four factors. Also, as the shape characteristics we have been describing change jointly during postnatal development, the factors are necessarily highly correlated over ontogeny (Fig. 3).

THE DEVELOPMENTAL BASIS OF EVOLUTIONARY CHANGE

Evolutionary theory leads one to expect that characteristics induced by local developmental factors are less constrained in their evolution than such properties caused by common factors. We therefore expected that local factors would contribute most to the average cranial shape differences among species. As summarized in Figure 9, variation in both common and local factors contributes to the cranial shape differences among humans, chimpanzees, and gorillas, but contrary to our expectation, the first four common factors explain 79% of shape variation of the full data and 83% of variation among the adult species mean shapes. These numbers are only of limited biological relevance as they depend on the distribution of landmarks and other details. Still, they may indicate that cranial evolution in hominoids has to a large extent been achieved by alterations of common growth factors—mutations of genes with numerous pleiotropic effects. These findings corroborate one earlier speculation of King and Wilson (1975) that only few mutations of regulatory genes—genes with potentially many pleiotropic effects—may account for the pronounced morphological differences between humans and chimpanzees despite their close phylogenetic and molecular proximity (see,
MODULARITY AND INTEGRATION IN THE HOMINOID CRANIUM

Figure 6. The modular shape space of the facial landmarks reflects shape variation due to local developmental factors in the face. The figure shows the first three principal component (PC) scores of this space. The legend of this and the next two figures is as in Figure 3. In contrast to the integrated shape space, all three ontogenetic trajectories are clearly distinct here.

e.g., Mann and Weiss 1996; Ruvolo 1997; Mitteroecker et al. 2004).

Figure 9A schematizes that the ontogenetic trajectories in the integrated shape space, that is, postnatal shape changes due to common developmental factors, are in a common direction for all three species. Chimpanzee and gorilla trajectories overlap completely in this space, where adult chimpanzees overlap with subadult gorillas, and humans diverge only slightly from them. But in the modular components of shape (Fig. 9B,C), trajectories are all different and humans diverge markedly in the face as well as in the neurocranium. These results suggest that common factors contribute considerably to evolutionary shape differences, but mainly by extension or truncation of otherwise conserved developmental pathways—an evolutionary phenomenon that is often called heterochrony or ontogenetic scaling (Gould 1977; Zelditch 2001; Mitteroecker et al. 2005). The analysis confirms that local factors and hence modular shape characteristics possess more degrees of freedom for evolutionary change than mere ontogenetic scaling.

EVOLUTIONARY INTEGRATION AND MODULARITY

Figure 8 plots the SW scores for the face versus the scores for the neurocranium—scores for shape characteristics that are tightly integrated by common developmental factors. The association of facial and neurocranial scores among adults is similar within all three species for all four dimensions, indicating similar patterns of integration. In the first two dimensions, the specimens of all three species closely scatter around the diagonal. This single trajectory shows that evolutionary shape differences along these two components follow the common pattern of developmental integration. Along the third and also the fourth dimension, in contrast, humans deviate markedly from the common nonhuman trajectory. For these shape features, similarly integrated within all three species, humans differ from nonhumans in a nonintegrated way. Some aspects of human cranial shape thus have evolved in an integrated fashion (common factors 1 and 2) whereas other characteristics have been decoupled during human evolution (common factors 3 and 4). In contrast, evolutionary integration between Pan and Gorilla closely reflects developmental integration in all four of these dimensions.

It is unlikely that the evolutionary dissociation has been achieved through alterations of developmental integration, that is, of the differential effects of common factors, because we found that developmental integration in recent humans is relatively similar to that of chimpanzees and gorillas. Also, the physical causes underlying epigenetic integration may not be subject to evolutionary change. A more likely explanation for the evolutionary dissociation is that integrated aspects of shape—significantly controlled by common factors—may additionally be affected by more local factors. This means not only that different aspects of shape are controlled by different local and common factors, but also that
the same shape characteristics are also controlled simultaneously by local and common factors. Such overlapping morphogenetic control would allow independent response to selection for traits that are also integrated due to common genetic and developmental factors. (Compare also Hansen [2003], who argued that a combination of local and common factors optimizes evolvability when assuming a constant total variance.) The idea of redundant morphogenetic factors is related to the phenomenon of gene families consisting of numerous members with related functions but varying pleiotropic effects. The gene families involved in craniofacial development include many members (compare, e.g., the BMP gene family, Nie et al. 2006a, p. 513; even most of the corresponding receptor genes have multiple paralogs (see, e.g., the multiple roles of FGF receptor genes in causing craniosynostosis: Aleck 2004; Marie et al. 2005).

To measure the redundancy of common and local factors we computed the fractions of variance along the four SWs that remain unexplained by the common factors (pooled for all three species). These fractions depict the modular variance of characteristics that are simultaneously under strong common factor control. Along the first common factor there is considerable additional modular variance for the face (0.204) but nearly none for the neurocranium (0.007). A number of factors, including local ones, influence the outgrowth of the face and the prominence of the masticatory apparatus, whereas cranial crests (the shape features influenced by common factor 1, see Fig. 4) are largely a postnatal response to masticatory muscles, with no local factors in the neurocranium involved (Washburn 1947; Riesenfeld 1955; Robinson 1958). For common factor 2—the overall dimensions of face and neurocranium—the face exhibits a higher modular variance (0.118) than the neurocranium (0.065), perhaps because the dimensions of the cranial vault strongly influence the face but not vice versa (Weidenreich 1941; Anton 1989; Lieberman 2000a). Along factor 3, there is more unexplained variance in the neurocranium (0.172) than in the face (0.081). The corresponding neurocranial shape change mainly involves the nuchal plane and the positions of the foramen magnum and of the superior nuchal line. In addition to common factors, those characteristics

Figure 8. Singular warp (SW) scores for the face against the scores for the neurocranium. They show the actual association of facial and neurocranial shape characteristics due to the four common factors. The axes are not scaled isometrically as their scales also depend on the number of landmarks and are thus not meaningful.
Figure 9. Schematization of the geometry of the three ontogenetic trajectories in (A) the integrated shape space (see Fig. 3), (B) the modular shape space of the face (Fig. 6), and (C) the modular shape space of the neurocranium (Fig. 7). Integrated shape variation among the three species is largely constrained along one single trajectory whereas the development of modular shape characteristics varies more fundamentally.

also depend on relative brain size, body posture, and locomotion, as well as on the prominence of the nuchal muscles—factors that certainly affect the neurocranium more directly than the face and so contribute to local variance. Additional local variance along common factor 4 exists mainly for the face (0.186) and less for the neurocranium (0.057). Corresponding facial shape change involves mainly the browridges that start to develop when the brain has already ceased to grow and the overall dimensions of the neurocranium are established. There is necessarily independent local variance present in those aspects of the face.

We thus find considerable modular variance for several integrated traits in accord with our experimental understanding of cranial development. Overlap of common and local developmental control for the same shape characteristics appears as a reasonable model for dissociated human cranial evolution. It is further evident from Figure 3 that humans exhibit less variance along the four common factors than do chimpanzees and gorillas. In fact, modular factors contribute considerably more to human adult variation (65%) than to chimpanzees (48%) and gorillas (34%). Humans thus share very similar patterns of covariation between face and neurocranium, but the underlying common factors contribute less to adult shape variation. There is relatively more variation in modular processes during human development as compared to the development of chimpanzees and gorillas.

It is not clear whether all hominoids share the same pattern of genetic redundancy among common and local processes and may thus potentially have the same ability for local responses to selection, or whether only humans evolved additional local morphogenetic control. In the first case, some aspects of human morphology would owe to evolutionary change of local factors that are also present in other hominoids. These local factors need not contribute much to adult shape variation in all species. Perhaps constrained by stabilizing selection or canalizing properties, they may rather represent some “latent modularity.” Such relationships have been demonstrated recently for different traits in butterfly morphology (Beldade et al. 2002; Frankino et al. 2005). Traits that exhibit tight genetic and phenotypic correlations responded independently to artificial selection but maintained their correlations within the differently selected populations.

To address this question, we computed the modular variances along common factor 3 and 4 for each species separately. Humans have a modular variance along common factor 4 (face 0.191/neurocranium 0.047) that is comparable to that of nonhumans (chimps 0.139/0.049; gorillas 0.219/0.077) so that all three species might share the same local factors and hence the same pattern of modularity. This may reflect the fact that browridge morphology—the major effect of common factor 4 on the face—is largely determined after the neurocranium has already ceased to grow, and is thus similarly independent of neurocranial morphology in all three species. For common factor 3, in contrast, humans possess by far the most modular variance in both the face and the neurocranium (humans 0.281/0.287; chimps 0.037/0.107; gorilla 0.079/0.165). This may be indicative of a larger number of polygenic loci (cf. Bürger and Lande 1994) and thus of a (relatively) increased extent of local factors in the development of these shape features.
in humans. But it could also result from the distinctive human developmental pathway itself, for example, from increased activity of these local factors during development.

Although the evolutionary dissociation of humans along common factor 4 likely owes to local factors that are present in all three species, dissociation along common factor 3 might have required the emergence of novel local developmental control mechanisms in humans. Altenberg (1994) regarded “constructional selection,” the evolutionary emergence of new local factors, as the major mode of the evolution of modularity. This closely relates to gene duplication and divergence during evolution, increasing the number of genes with related effects that yet may differ in their pleiotropic range. Gene duplication is regarded as a major driving force of evolutionary change (e.g., Ohno 1970; Zhang 2003) and is involved in a number of aspects of primate and human evolution (Gagneux and Varki 2001; Zhang 2003), including craniofacial morphology (Fortna et al. 2004; Cheng et al. 2005). Approximately a third of the human genes are duplications (Zhang 2003) and about 33% of the human duplications are not duplicated in chimpanzees (Cheng et al. 2005); most of these differences are due to novel duplications during human evolution.

In summary, morphological differences among humans, chimpanzees, and gorillas have been achieved by evolutionary changes of both common and local developmental factors. Factors with pleiotropic effects on both the face and the neurocranium account for a large amount of interspecific variation but their differential effects on cranial shape appear relatively conserved during hominoid evolution. Local factors (i.e., modular shape characteristics), in contrast, possess more degrees of freedom for evolutionary change. However, some aspects of facial and neurocranial morphology that are tightly integrated during development evolved in a dissociated way to bring about human morphology. This dissociation has perhaps been achieved by evolutionary alterations of local factors affecting characteristics that are simultaneously controlled by common factors. For some aspects of shape, the dissociation might have required the emergence of novel local factors during human evolution.

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Appendix
ALGEBRAIC DETAILS
This appendix provides the algebraic details of the analysis of integration and modularity. Let $X = (X_F | X_N)$ be the $n \times p$ matrix of mean-centered shape coordinates, where $X_F$ is the $n \times p_F$ matrix of shape coordinates for the face, $X_N$ the $n \times p_N$ matrix for the neurocranium, with $p = p_F + p_N$, and $n$ is the total sample size. Let further $X'$ be the subset of adult specimens centered at their species-specific group mean, that is, the $i$th specimen from the $j$th species is $X_{ij}' = X_{ij} - \bar{X}_j$, where $i$ ranges over all adult specimens and $j = 1, 2, 3$. The $p_F \times p_N$ matrix $S_{FN} = \frac{1}{n-1}(X_F'X_N')$, where the superscript $'$ denotes the matrix transpose, is thus the adult pooled within-species cross-block covariance matrix between the facial and the neurocranial landmarks. Decompose this matrix as $S_{FN} = UDV'$ where $D$ is a diagonal matrix of singular values. The columns of $U$ and $V$ are the facial and neurocranial singular vectors, respectively, each representing one shape deformation that is also called a SW (Bookstein et al. 2003). The scores along the first pair of singular vectors (the first pair of SW scores) have the highest possible covariance, that is, $\text{Cov}(X_{ij}'U_1, X_{ij}'V_1) = d_{11}$ is a maximum, where $d_{11}$ is the first diagonal element of $D$, and $U_1$ and $V_1$ are the first columns of $U$ and $V$. The scores along the second pair of vectors, constrained to be geometrically (but not statistically) orthogonal to the corresponding first vectors, exhibit the second highest covariance $d_{22}$, etc. The maximal number of SWS is $\min(p_F, p_N, n - 1)$.

To decide how many dimensions of integration are worth analyzing, we tested the singular values $d_{ij}$ against a permutation distribution. Our method agrees with the procedure of Rohlf and Corti (2000) for the first test but differs for the subsequent dimensions. To test the $i$th singular value, $i > 1$, compute the residual data matrices $Z_F' = X_F' - \sum_{i=1}^{i-1} U_{i-1}'U_{i-1}X_N' = X_N' - \sum_{i=1}^{i-1} V_{i-1}'V_{i-1}X_F'$, which are projections of the data onto the subspaces perpendicular to the first $i - 1$ singular vectors. The $j$th dimension of PLS between these two residual matrices is identical to the $(i + j - 1)$th dimension of the original data. Permute the rows of one of the residual matrices and compute the first singular value for each permutation. By comparing the $i$th original singular value with this distribution, we arrive at the statistical significance level (the tail probability) of the $i$th dimension of integration (the $i$th common factor).

In Mitteroecker and Bookstein (2007) we showed that the elements of the first pair of singular vectors are proportional to the common factor loadings in Sewall Wright’s (1932) factor analysis when both are based on the same assumptions about modularity, that is, on the same blocks of variables (except that for two modules Wright’s approach requires an additional scaling step as well). Thus, when scaled correctly, the pairs of corresponding singular vectors serve as common factors in the model outlined in Figure 1 (for a proof see Mitteroecker 2007). Loadings of the first principal component of the blockwise common factor scores can be used as the necessary scaling factors. Let $C$ be the $n \times 2$ matrix of scores $(X_F'U_1X_N'V_1)$ and $e_1 = (e_11, e_12)$ the first eigenvector of $(C'C)^{1/2}C'$. The stacked vector,

$$f_i = \begin{pmatrix} e_{i1}U_1 \\ e_{i2}V_1 \end{pmatrix}$$

is then the $i$th common factor of $X$, with $F'F = I$ when $F$ is taken as the $p \times k$ column vector matrix of $k$ common factors ($f_1 \ldots f_k$).

The space of integrated shape variability (Fig. 3) is computed as $XF$, where the number of common factors $k$ was 4 in the present analysis. The residual space $R = X - XFF'$ is the subspace perpendicular to $F$, and the modular spaces for the face and the neurocranium (Figs. 6 and 7) are principal component scores of $RF$ and $RN$, respectively. Figure 8 consists of plots of $X_FU_1$ versus $X_NV_1$ for the $i$th dimension. Thus, even though PLS is based on the within-species variability only, the scores in these four figures are projections of the original data space and hence also include between-species shape differences.

The values in the $i$th row of Table 1 are $\text{Cov}(X_F'U_1, X_N'V_1)$, $\text{Cor}(X_F'U_1, X_N'V_1)$, $\text{Var}(X_F'U_1)/\text{Tr}(X) \times 100\%$, $\text{Var}(X_F'U_1)/\text{Tr}(X) \times 100\%$, and $\text{Cov}(X_F'U_1, X_N'V_1)^2 / \sum \sum (S_{FN}^{11}) \times 100\%$. The fraction of modular variance along the $i$th common factor is computed as $\text{Var}(RFU_1)/\text{Var}(XFU_1)$ for the face and similarly for the neurocranium.

ALTERNATIVE ANALYSES
We carried out several alternative versions of these analyses to check the extent to which the results depend on certain assumptions. The analyses were performed using the first 5, 10, and 20 principal components, respectively, instead of the full Procrustes coordinates, and we varied the number of common factors from 2 to 15. To enable the visualization of common factors as one joint shape deformation, the landmarks were separated in the present analysis into a facial and a neurocranial subset after an overall Procrustes fit. But we alternatively carried out separate Procrustes fits for the two modules. All these analyses yielded identical or very similar results.

As set out in the Methods section, the PLS analysis is based on the pooled adult within-species covariance matrix. Alternatively, we separately performed analyses using the pooled adult within-sex, within-species covariance matrix (the matrix ignoring variance and covariance among species means and among sex means); the adult chimpanzee covariance matrix; the adult human covariance matrix; and the pooled adult chimpanzee within-sex covariance matrix. Integrated and modular spaces remain very similar, but the actual common factors rotate when estimated.
from different covariance matrices. However, similar conclusions about evolutionary integration and dissociation emerge from these analyses.

The present article focuses on the relationship between the face and the neurocranium but we also carried out the analysis assuming four modules (vault, cranial base, upper face, lower face) instead of two (see Mitteroecker 2007 for an extension of PLS to four blocks). Some dissociation was found within the face, especially between humans and nonhumans, whereas the cranial vault and base are quite integrated. This is reflected by the fact that common factors 1 and 3 of this article affect only the upper part of the face whereas factor 4 involves only the lower part of the face. This local dissociation does not confound the conclusions drawn from the presented analysis.