ONLINE INQUIRY & INVESTIGATION

INVESTIGATING HUMAN EVOLUTION

Using Digital Imaging & Craniometry

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Human evolution is an important and intriguing area of biology (Alles & Stevenson, 2003). The significance of evolution as a component of biology curricula, at all levels, can not be overstated; the need to make the most of opportunities to effectively educate students in evolution as a central and unifying realm of biology is paramount. Developing engaging laboratory or classroom activities that investigate human evolution (e.g., DeSilva, 2004) can therefore be of significant value to students and educators.

This report describes an exercise involving comparative anatomy of hominid skulls, centering on the use of digital imaging to generate measurement data for comparison and analysis. Here, hominid refers to the family Hominidea; that is, all modern and extinct Great Apes–including humans, chimpanzees, gorillas, and orangutans. Rather than as a step-by-step fixed protocol, this laboratory is presented with options that emphasize adaptability to various pedagogical approaches and instructional levels. Versions of this laboratory have been used in college evolution and introductory biology courses; adaptations are likely to be of value for other courses, including non-majors' biology, comparative anatomy, and secondary school biology.

Features of skulls (commercially obtained skull casts) are identified and compared by students in order to develop an evolutionary analysis centered on functional anatomy. The focus of this exercise is on structural features that relate to three characteristics central in human evolutionary history: brain size, posture, and mastication. As with other published activities designed to explore hominid evolution using skull comparisons (Nickels, 1999; Nickels, 1987), various quantitative and qualitative measures are introduced and employed. However, this exercise also extends this approach in a novel way by employing quantitative craniometric relationships made using digital imaging.

This activity can accommodate a variety of approaches to investigate specific differences between species, relate structure and measures to function, and apply observations and data to evolutionary paradigms. For example, based on initial exposure to skulls and discussion or background reading, students can develop and test hypotheses about how particular measures indicative of braincase size will compare among species.

Interpretations of data collected can be made in light of current understanding of the time course and ramifications of changes in form and function associated with human evolution. Aspects of evolution are introduced in a hands-on manner in this exercise, which also supports the study of human anatomy and emphasizes functional and comparative anatomy.

Methods

As introduction to the exercise, some basic relevant functional anatomy is first reviewed using skull models, illustrations, and select reference materials (e.g., Lewin, 2005; Lewin & Foley, 2004; Campbell, 1998). Instructors have, of course, a number of options as to how this material is presented and integrated, ranging from lecture to assigned reading to more hands-on, active learning approaches. Characteristics focused on in this introduction reflect major differences among hominids involving: 1) the size of the brain case (and hence the size of the brain), 2) muscular and skeletal elements of mastication, and 3) body posture and support of the head. Emphasis is placed on encouraging students to consider interrelations between differences in skull structure and characteristics such as intelligence, behavior, nutrition, and way of living. Students first then develop familiarity with anatomical features (Table 1) relating to their comparative analysis.

Skull casts of hominids used in this exercise are available from a number of specialty suppliers (e.g., Bone Clones®, Canoga Park, CA; www.boneclones.com) and general vendors (e.g., Ward's Natural Science, Rochester, NY; www.wardsci.com). The number of students per lab group can be adapted

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based on resources and the specific design of the activity. As an example protocol, each group works with a total of four specimens (skulls), choosing any combination from the four groups listed in Table 2. Species listed in this exercise are broadly representative of hominids; other species can be added or substituted.

Table 1. Features useful for students to become familiar with in a functional anatomy-based comparative analysis of hominid skulls.

FEATURE	COMMON MEANING
Neurocranium	Braincase or cranial cavity
Orbits	Eye sockets
Supraorbital torus	Brow ridges
Post-orbital constriction	Indentations in lateral skull behind orbits
Forehead slope	Angle of the forehead (not brow ridges)
Zygomatic arch	Cheek bones
Sagittal crest	Ridge of bone along medial skull
Prognathism	Anterior extension of jaws from skull and face
Foramen magnum	Large opening in skull underside for spinal cord
Occipital condyles	Bony protuberances lateral to foramen magnum
Temporalis muscle	Chewing muscle; origin on lateral skull, insertion on mandible, runs through the zygomatic arch
Temporalis line	Marking on lateral skull at attachment site of temporalis muscle
Masseter muscle	Chewing muscle; origin on zygomatic arch, insertion on mandible
Dental arcade	Line formed by teeth in the upper and lower jaws

Table 2. Specimens included in hominid skull evolutionary analysis. Students typically analyze four skulls, selecting one from each of the four groups listed.

Group 1	*Gorilla gorilla* (Gorilla)	*Pan troglodytes* (Chimp)
Group 2	*Australopithecus afarensis* ("Lucy")	*Australopithecus boisei*
Group 3	*Homo habilis*	*Homo erectus*
Group 4	*Homo neanderthalensis*	*Homo sapiens*

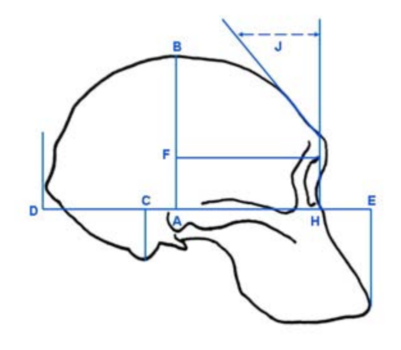
To facilitate comparison of the different species, quantitative and qualitative measures are made of features on different skulls. Examples of quantitative data that students are specifically asked to incorporate into their comparative analysis include the following measures:

- braincase size (in cm^3)
- condylar position index (ratio of CD:CE x 100, see Figures 1 and 2)
- supraorbital height index (ratio of FB:AB x 100, see Figures 1 and 2)
- maxillary prognathism index (ratio of HE:DE x 100, see Figures 1 and 2)
- angle of forehead (see Figures 1 and 2)
- post-orbital constriction index (as % of skull width; see Figure 3)

Students are asked to develop their own model for estimating braincase volumes (rulers and measuring tapes are provided). To generate the other quantitative measures listed, students take digital images (typically JPEG files) of skull casts using standard digital cameras of at least 1 megapixel resolution. Quality images are effectively obtained with the casts placed on a table-top under ambient room lighting. Appropriate software (e.g., PowerPoint) is then used to overlay lines and points in specific anatomical locations on the skull images. Details of digital imaging, image manipulation, and instructions for placement of lines and points for craniometry are provided to students (Figures 1 and 2). By measuring (directly on the computer screen or using a ruler on printouts) length of specific line segments and calculating ratios, students generate craniometric data. Note that because the ratio data have no units, relative magnification of the skulls in individual images need not be standardized. Forehead slope is measured using a protractor.

These quantitative data provide indications of anatomical adaptations relating to shifts in brain size, posture, and diet over hominid evolutionary history (Table 3). Thus – in addition to students' direct estimate of braincase volume – increased supraorbital height index, lower post-orbital constriction index and decreased angle of the forehead all correlate with greater cranial capacity. Increased condylar position index indicates both a shift in position of the spine associated with evolving bipedalism as well as expansion of the posterior skull. Decreased maxillary prognathism indices indicate a reduction in the relative size of the masticatory components of the skull.

Figure 1. Schematic provided to students as a guide for placement of lines and points used to obtain craniometric data. Horizontal line DE runs from the posterior most point of the skull to the anterior extent of the maxilla at the level of the bottom margin of the orbit. Vertical line AB runs from the superior-most point of the skull to line DE. Line F extends horizontally from the top of the orbit posterior to line AB. Line C runs vertically up from the center of the occipital condyle to line DE. Line H originates perpendicular to line DE at the anterior orbit and extends up beyond the top of the skull. Angle J is formed by line H and an intersecting line that follows the forehead slope (not the brow ridge). See text for description of calculating various craniometric indices.



In terms of qualitative analysis, there are numerous interspecific comparisons that students can make and relate to functional anatomy. For example, the angle of the foramen magnum can be assessed; this opening tends to be flat in a biped and elevated in a quadruped. Access to additional, non-hominid quadruped skulls (e.g., cat or deer) for comparison can help illustrate this point for students. The presence and relative size of a sagittal crest can be evaluated; this attachment site can provide an indication of the size and action of the temporalis muscle in chewing. The relative size of the zygomatic arch opening can also indicate size of the temporalis muscle that passes through this opening to insert on the mandible. In part, more pronounced brow-ridges help dissipate forces associated with chewing; reduction in the size of the supraorbital torus thus generally correlates with reduction in other skull masticatory structures. Also relating to diet, a number of measures involving the teeth can be made – including the molar occlusal surface area, dental formula, and the shape and relative size of the dental arcade (Arsuaga & Martínez, 2006; Campbell, 1998).

Analysis

Students' analysis of data can take a variety of forms. For example, one simple exercise is to have students identify and label important anatomical features in various images (i.e., lateral, superior and inferior, anterior and posterior views) of the skulls. They may be asked to summarize how each of the characteristics evaluated relates to brain case size, the masticatory apparatus, and posture – thereby proposing functional significance for the various features that they have examined. In fact, students can be asked at the start of the exercise to hypothesize as to what the various craniometric indices and other features "mean" anatomically and functionally; they can then evaluate their ideas by applying collected data and resource materials. Interpretations can also be drawn regarding the adaptive implications changes in these parameters would have for the organisms.

Figure 2. Examples of hominid skull images with overlaid lines and points for craniometric measures. Top: *Australopithecus afarensis*. Bottom: *Homo sapiens.* Tape near point C on both skulls is a reference mark for the location of the occipital condyle. For consistent orientation of skulls for imaging and placement of lines, the maxillary dentition should lie horizontally; this requires elevation of the posterior skull of some specimens, as seen here with *A. afarensis*.

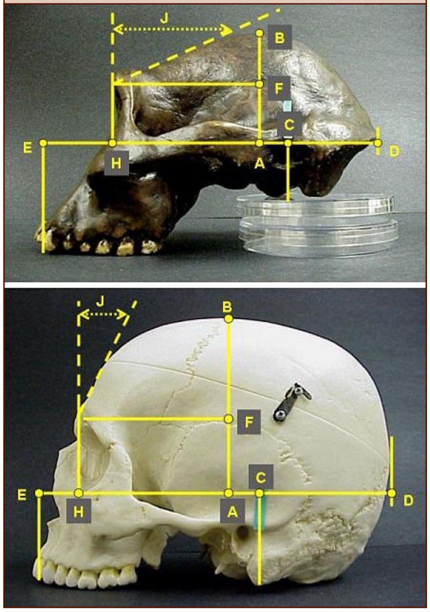
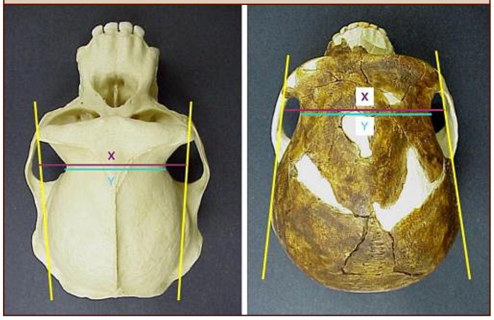


Figure 3. Illustration of calculation of the post-orbital constriction index. The more vertical lines follow the lateral contours of the braincase forward to the lateral orbit margins. Post-orbital constriction can be calculated by dividing the length of line Y by the length of line X. This value is then subtracted from 1.0 and the result multiplied by 100 to yield the index as a percent constriction of the skull width. Left: *Pan troglodytes.* Post-orbital constriction index is 31%. Right: *Homo erectus.* Index is 19%.



Typically, students are asked to use information on fossil ages available in biology textbooks and other references (e.g., Lewin, 2005; listed Internet Resources) to place the species (excluding the extant apes) they chose to work with in a chronological history of hominid evolution. They can then use this chronology as a basis to think about and analyze their data. To help focus their analysis, specific questions that might be posed to students include which characteristics show the greatest differences between species, if all the features examined evolve together, and if the traits evolve at consistent incremental rates over time.

In the evolution course, students have been asked to consider how each relevant quantitative measure relates to brain case size (i.e., positively or negatively correlated, relative significance of the measure) and to construct a mathematical index (formula) that relates these features to cranial capacity. They then apply their own skull data to their abstract cranial capacity formula, and must compare results with what is known about the relative ages and phylogenetic relation of the specimens examined. Based on this analysis, they critique their indices as a system for understanding the evolutionary history of hominids.

Another more advanced approach is to ask students to develop, describe, and apply one or more of their own quantitative craniometric measures to explore structural and functional shifts associated with hominid evolution. Such an activity is readily amenable to inquiry-based or hypothesis testing approaches. There is clearly a wealth of craniometric measures that can be identified and explored; those few illustrated in the activity described here include standard measures (e.g., condylar position index) and some developed for the activity (i.e., maxillary prognathism index). The physical anthropology literature (e.g., Whitehead et al., 2005) provides a rich resource for instructors interested in identifying or developing additional quantitative craniometric measures.

As hominid evolution is currently a very active research area, information literacy activities can also be readily integrated into the exercise. In addition to older reports, recent work describing newly discovered hominid fossils (e.g., Brown et al., 2004; White et al., 2003; Leakey et al., 2001), new techniques for comparative analyses (e.g., Zollikofer et al., 2005), and molecular phylogenetic contributions to current views of hominid relationships (e.g., Wildman et al., 2003) all could serve as related entry points leading students into the primary literature in this field. Values for some of the measures described here – or related data – are available in the literature

Table 3. Examples of some craniometric data collected from analysis of four skulls. Note that index data have no units – they are ratios of measures of line lengths made using skull images.

	P. troglodytes	*A. afarensis*	*H. erectus*	*H. sapiens*
Condylar Position Index	12	36	50	61
Supraorbital Height Index	41	47	61	58
Maxillary Prognathism Index	27	21	11	11
Angel of Forehead	47 °	65 °	48 °	28 °

(e.g., Campbell, 1998). These values might be provided or students may be expected to search for such relevant information as part of the exercise.

Moreover, a variety of media resources (e.g., videos such as Films for the Humanities & Sciences', "Challenging the Human Evolution Model," and the Nova production, "In Search of Human Origins, Episode 1: The Story of Lucy") and popular science literature (e.g., Wong, 2005; Zimmer, 2003; Gould, 1979) can be used in support of or integrated with the described exercise. "The Mismeasure of Man" (Gould, 1996) provides particularly interesting and relevant insights into the history of science and use of dubious craniometric data in advancing a deterministic social agenda.

Table 4. Basic instructions for moving images into PowerPoint and adding lines and labels.

1. Open a new blank presentation in PowerPoint.
2. Under the **Format** menu, select **Slide Layout.** Choose a blank slide layout.
3. Under the **Insert** menu, select **Picture** and **From File.**
4. Browse to the appropriate location of the file. Select (click and highlight) the image you wish to insert, then click the **Insert** button.
5. If a resolution box appears, choose the default resolution (768 X 512 pixels).
6. Your image will be placed in the PowerPoint slide.
7. You can resize your image by clicking and dragging on any ***corner*** (resizing from any side will distort the image and may introduce artifacts into the craniometric measures).
8. Under the PowerPoint **View** menu bar, select **Toolbars**, then select **Picture**. A Picture Toolbar appears that allows you to do some manipulation of the image, including adjusting the brightness and contrast.
9. Under the PowerPoint **View** menu bar, select **Toolbars**, then select **Drawing**. A Drawing Toolbar appears that allows you to do add lines and labels to your image.
10. When finished labeling the image, under the **Edit** menu choose **Select All**. This will highlight the image and all the labeling that you have added.
11. Place the mouse cursor anywhere on the image and right-click once. A box will appear. Select **Grouping** and then choose **Group**. This will fuse your labels to the image. If you do not do this, the labels will move if you move or resize the image at a later time.
12. Save the image as:
    a. JPEG file interchange format
    b. Presentation file
13. To add additional images to the same presentation file, under the **Insert** menu choose **New Slide** and repeat the above steps. In this case, you will end up with a single **.ppt** presentation file containing all manipulated images as individual slide pages. Alternatively, you can save images as separate *.jpg* image files (1 per image).

Application

Experience indicates that students have few problems with technical aspects (imaging and image processing) of this activity. The expense of skull casts is significant but not prohibitive; the author has found individual casts available at costs ranging from about $100 to about $300, depending on the species, producer, and vendor. Defined study sets of skull casts are also available, usually at some discount over individually purchased casts.

Digital cameras for this exercise are another resource to be considered. Depending on specifics of the assignment, there may not be need for each group to take a large number of images – in which case one or two cameras could suffice for even a large class. Cameras capable of capturing images of only 1 megapixel have been used very successfully for the activity. Presently, higher resolution digital cameras – taking at least 3 megapixel images – can be purchased for under $100. Images are initially captured as data files (e.g., JPEG) to the camera's internal memory or an optional flash memory card (e.g., SmartMedia or MemoryStick), and can then be downloaded to a computer. For those less familiar with digital imaging, a variety of helpful print (Miotke, 2005) and Internet Resources (e.g., Curtain, 2006) are available. For adding lines and labels to the images, a variety of software programs can be used; basic instructions for image processing in PowerPoint are provided in Table 4.

With many images of hominid skulls readily available in the literature and online (see Internet Resources below), some aspects of this exercise could be done strictly as an image-based activity. However, the hands-on tactile and true three-dimensional advantages make the use of skull casts an excellent learning experience. Additionally, digitizing software programs – a number of which are freely available for download, including Image J from the National Institutes of Health (available online at: http://rsb.info.nih.gov/ij/) – could be integrated into this lab to directly generate length, area, and angle measures from skull images.

The activity described is highly malleable; depending on the audience and the amount of time available, additional depth of material or activities can be included or the focus and scope can be restricted. Time invested in establishing appropriate specific outcomes and developing a clear and concise introduction and protocol should contribute to the success of the experience.

Based on anecdotal feedback and discussions, students react positively to the exercise. They seem to appreciate the opportunity to work hands-on with skull casts and to enjoy the imaging and collection of quantitative data. Learning about skulls appeals to many students' interest in human anatomy; many are also quite curious about evidence for and current ideas concerning human evolution. In sum, this comparative activity is an effective and engaging introduction to human evolution that draws together elements of several sub-fields of biology and other disciplines (e.g., anthropology).

Internet Resources

- ArchaeologyInfo.com Site: http://www.archaeologyinfo.com/index.html.
- Becoming Human Site. Institute of Human Origins, Arizona State University. http://www.becominghuman.org/.

- Human Origins Program Site. Smithsonian Institution. http://www.mnh.si.edu/anthro/humanorigins/index.htm.
- Online Human Evolution 3-D Gallery. University of California at Santa Barbara. http://www.anth.ucsb.edu/projects/human/.
- Prehistoric Life Site. BBC. http://www.bbc.co.uk/sn/prehistoric_life/human/.

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