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This paper proposes that human asymmetrical hemispheric function originated because of the cognitive requirements of tool-making.

The human brain can be considered to be a product of two evolutionary episodes. The first episode was shared with other mammals and resulted in a brain composed of a reptilian complex, paleomammalian and bilaterally symmetrical neomammalian structures. The second episode represents a break from a bilaterally symmetrical mammalian brain indicated by asymmetrically functioning hemispheres specialized for sequencing motor action (left) and spatial processing (right).

Several models have been advanced to explain the origin of asymmetry including: a cognitive mapping model proposed

by Webster (1977) (right hemisphere specialization); a language model proposed by Hewes (1973) and Kimura (1976) (left hemisphere specialization for language sequencing); and a praxic ordering model rooted in Kimura's language model and developed by Frost (1980) and Corballis (1982). This suggests tool behavior selected for left hemisphere motor sequencing through unimanual activity as reflected in the propensity toward right-handedness.

Any satisfactory model must account for both left and right hemisphere specializations which none of the above taken separately do. A close look at the cognitive requirements of tool-making indicates the need for both motor sequencing and spatial processing. The process of making an artifact implies a change in matter from unorganized to organized form by a series of motor actions produced in a defined sequence. That sequence, however, appears to be guided *a priori* by a mental template of the intended result. This sequence/template model of tool production requires both sequential motor action and the ability to produce mental templates (spatial images) of the intended form and suggests selection for both left hemisphere specialization and right hemisphere specialization as well as the necessity for the two processes to communicate.

Technology and the Origin of Human Hemispheric Asymmetry

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This thesis is dedicated to my father, Martin, and my mother, Evelynne.

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TECHNOLOGY AND THE ORIGIN OF HUMAN HEMISPHERIC ASYMMETRY

I. Introduction

A. Problem and Scope

The objective of this thesis is to develop an evolutionary model which suggests that human hemispheric asymmetry originated because of the cognitive requirements of tool-making technology. The problem of the origin of asymmetry is recent and due mainly to developments in neuroscience over the last thirty years which have established that the left and right hemispheres of the human brain are functionally asymmetrical (Springer and Deutsch, 1981). The left hemisphere is specialized for sequencing of motor action while the right hemisphere is characterized as specialized for spatial abilities.

Much of the literature dealing with this phenomena has focused on synchronic studies relating to morphology, physiology and psychology. There have been comparatively few studies which have approached the nature of asymmetry from an evolutionary perspective. Part of the reason for this is that evolutionary studies are frustrated by the fact that cerebral asymmetry does not appear directly in the hominid fossil record and can only be studied by inference. Secondly, synchronic studies are a necessary precurssor to diachronic studies for the simple reason that one must know what one is explaining from an evolutionary perspective before one can attempt the explanation.

Evolutionary explanation provides a temporal perspective for present phenomena and therein lies its value. This form of explanation is different from synchronic studies which can rely on experimentation and replication to establish relationships. Evolutionary explanation accounts for the appearance of phenomena on the basis of interpreting the historic (fossil or archaeological) record in light of uniformatarianist principles. Interpretations or models must account for known facts and be non-contradictory. The contribution of evolutionary explanation is the insight it provides for the present while its validity rests on the degree to which it accounts for known events. The intent of this thesis is to provide insight into the relationship of the function of the human brain and its capacity to produce technology based on an evolutionary perspective.

B. Overview

Three models have been advanced to explain the origin of asymmetry including a cognitive mapping model, a language origin model, and a praxic ordering model. This thesis builds directly on the praxic ordering model as developed by Kimura (1976), Corballis (1982) and Frost (1980). It holds that asymmetry is a product of the bimanual manipulation of tools in tool behavior and that right-handedness correlates with left hemisphere function in the sequencing of motor activity. Since the left hemisphere controls contralateral motor action, this model accounts for the propensity toward right-handedness and left-hemispheric specialization for the sequencing of motor action based on the selective advantage of technology. This model fails to account for right hemisphere specialization other than to state that spatial function was part of hominid brain function before technology.

This thesis differs from the praxic ordering model in two respects. First, a distinction is made between two fundamental aspects of technology: tool-making and tool-using. Second, it is argued that tool-making behavior selected for both left and right hemispheric specilizations.

The transformation of matter from an unorganized state to an organized state in the production of a tool requires the ability to sequence motor action in a series of steps. However, it also requires the ability to organize that sequence according to an *a priori* image or mental template of the intended outcome. Thus the production of an artifact requires that an organism have two cognitive capacities: the capacity to sequence motor actions and the capacity to produce spatial images or mental templates. The capacity to sequence motor activity is coincident with left hemispheric specialization and the capacity to form mental templates or spatial images is coincident with right hemispheric specialization. It is argued that the adaptive advantage in tool-making would have selected for this form of hemispheric asymmetry as well as the necessity for both cognitive functions to communicate in the tool-making process.

As a background to this model, Chapter II summarizes the major events in the evolution of the human nervous system.

II. The Evolution of the Human Nervous System

A. Introduction

The behavior-producing capacity of the nervous system is a product of a long evolutionary sequence represented in the fossil record and reflected in the comparative anatomy and comparative psychology of living organisms. Analysis of neural structure and behavioral capacity suggests that the human nervous system evolved in two separate episodes: first, the encephalization of successive cerebral structures resulting in a triune brain; and second, the evolution of functional asymmetry of the cerebral hemispheres. This chapter is a review of these episodes, particularly the latter, as a background for a proposed explanation of the appearance of asymmetry. In addition, it summarizes the concept of biological intelligence as defined by Jerison (1973, 1976) as a useful measure of the progressive evolution of nervous systems and builds on this concept to develop the points that a relationship exists between behavior and neural structure and that this relationship is effectively viewed as one of positive feedback.

B. The Concept of Biological Intelligence

Intelligence can be viewed from either a psychometric perspective or a biological perspective. A psychometric definition of intelligence holds that intelligence is a trait which intelligence (I.Q.) tests measure or, more specifically, is the common correlative factor in all intelligence tests. This common correlative factor is called "g" by Spearman (Gould, 1981) and is useful in the evaluative analysis of testable subjects but is not particularly useful as a concept which can be applied to the evolution of intelligence or the evolution of the nervous system.

Jerison offers an alternative to a psychometric definition by approaching intelligence from an evolutionary biological perspective. According to Jerison (1973, 1976) intelligence is a reflection of the capacity of an organism to internalize information about the external environment. In this view the degree or "quality" to which an organism can reconstruct the environment internally provides a selective advantage in the production of survival based behavior.

The biological definition of intelligence as developed by Jerison has three main attributes. First, it is interspecific and can be used as a basis for the description of intelligence between synchronic species and for the evolution of intelligence through time. Evolution is not necessarily progressive but Dobzhansky, Ayala, Stebbins, and Valentine (1977) indicate that the evolution of a particular trait can be viewed progressively in the sense that there are often trends from generalized to complex when viewed interspecifically through time. The fossil record and comparative anatomy clearly indicate a progressive evolution of the nervous system toward greater degrees of complexity.

Second, the biological concept of intelligence merges structure with behavior. It suggests that the behavior an organism is capable of is a product of the structure of its nervous system. Thus a fossil with a particular structure is capable of an inferred range of behavior.

Third, the biological concept of intelligence is compatible with models of brain function. A basic model of brain function adapted from Sherrington (1940) and Granit (1977) focuses on the nervous system's interaction with the external environment in concert with the organs of sensation and motor activity. A simplified model of brain function appears in Figure 1.

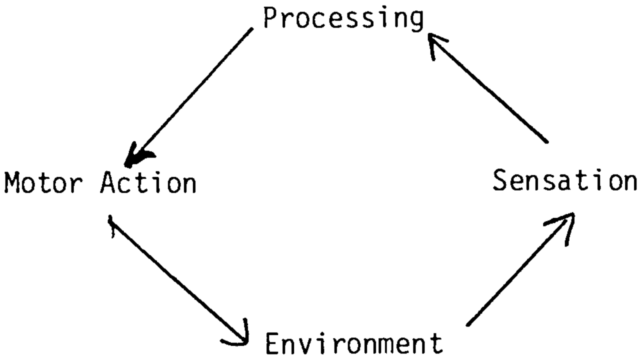


Figure 1 Model of Brain Function

This basic model has four elements: the environment, sensation, processing and motor action. The environment includes the physical, biological and cultural phenomena external to the organism. It is the context within which adaptation and selection take place. In Jerison's idea of biological intelligence the sensation and perception of the environment is the initial step in producing an internalization of the environment. Livingston (1978) defines perception as a function which involves organs external to the brain as well as mechanisms which transfer perception into signals used by the brain. The organs of perception are the familiar organs of sensation including eyes, ears, nose, tongue, and skin which function to sense images, sounds, smells, tastes, and touch. These structures vary in species according to evolutionary background (Livingston, 1978). Vision, for example, is a process of perceiving certain light wavelengths but not all wavelengths. Which wavelengths a species "sees" is a product of selection.

Sensed information is channeled to various processing centers. Most organisms appear to process information gathered by the various sensory modalities separately. However, more complex forms, especially humans, have structures which integrate information from various sensory modalities creating an added dimension of the external environment (Jerison, 1973). Grouped under the term "processing," in this simplified model, are several higher cortical functions including association areas, memory, and the ability to formulate action from the internalization of the environment. These capacities form the basis of what Granit (1977) called "purposive" behavior, in that they initiate a series of events within the brain which culminate in a behavioral act on the environment.

The production of motor activity forms the basis of the definition of behavior, and it is in the interaction between motor activity and the environment that natural selection takes place. Ultimately the importance of biological intelligence is in the production of motor action. The organism that can sense appropriate environmental information, reconstruct that information into an internal reality, make decisions, and enact those decisions into a motor activity that can affect survival will have an adaptive advantage.

C. Behavior and the Selection of Neural Structures

Livingston (1978) has suggested that brain structures are selected for indirectly through behavior, and it is behavior which provides the direct consequence in survival. The act of behaving via the motor pathways is a key in determining evolutionary success in that it is what the organism does directly in response to the environment which affects survival and with it the variation of genetic material that will be represented in the next generation. However, since behavior is produced by a circuit dependent on sensation, processing, and motor action; the selection for behavior has the consequence of determining the variation of genes which produce the biological structures of the brain. In this way behavior selects for structures of the nervous system, and those structures in turn reflect the capacity to produce behavior.

This relationship is a positive feedback (also called deviation-amplifying, Maruyama, 1962) nature and is diagrammed in Figure 2. According to this view a change in

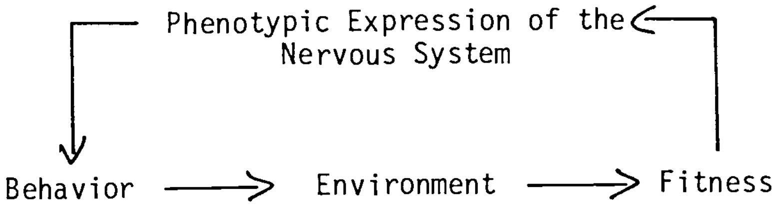


Figure 2 Positive Feedback Relationship of Nervous System and Behavior

the structure of the nervous system would have affected the capacity to produce behavior which in turn would have affected interaction with the environment. Selection, as measured by fitness, then determines the genetic component of the structure of the nervous system. This ultimately

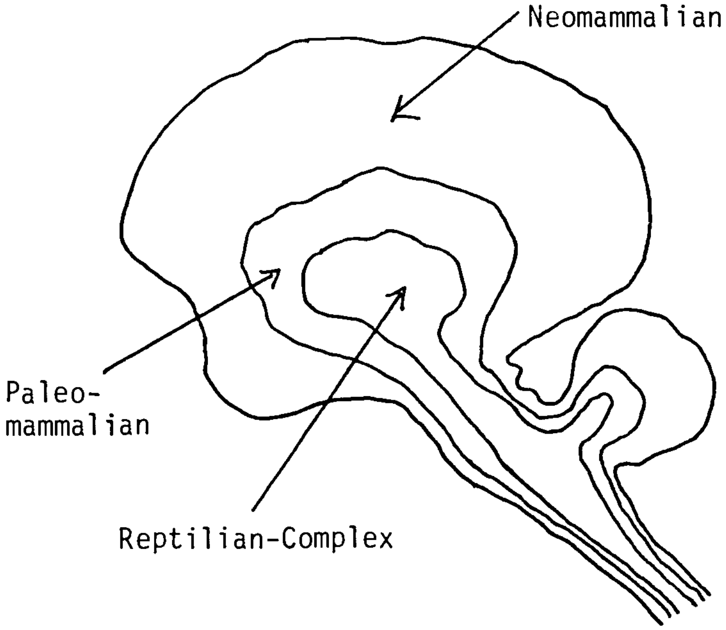


Figure 3 The Triune Brain

<ins>Note</ins>. From "A Mind of Three Minds: Educating the Triune Brain," by P.D. MacLean. In J.S. Chall & A.F. Mirsky (Eds.). Education and the Brain. Chicago: University of Chicago Press, Copyright 1978 by The National Society for the Study of Education. Reprinted by permission.

impacts the brain's capacity to produce behavior through its phenotypic expression. This feedback relationship provides a mechanism through which a behavior element and its related brain structure can interact in the evolutionary process to produce new behaviors and new brain structures.

It should be emphasized that in addition to behavior which can be called intelligent, a considerable range of behavior is produced by the autonomic nervous system. Autonomic behavior is not considered in the following discussion because it does not directly affect the evolution of asymmetry.

D. The Triune Brain

MacLean (1978) proposed that the brain is an organ which responds to evolutionary change not by overall structural modification but by "adding systems" to existing structures thereby increasing capacities while at the same time retaining the more primitive features. A structural-functional description of the brain is therefore a paleontological time map of successive stages of brain evolution. MacLean (1978) proposed a triune system consisting of a reptilian complex, a paleomammalian system and a neomammalian system as represented in Figure 3.

At the base of the forebrain is a concentration of ganglia which are histologically distinct from succeeding layers of nerve cells. These cells occur in "clumps" rather than in layers and form what MacLean (1978) has called the R-complex for reptilian complex because this structure is the dominant component of reptilian brains. Though extensive experimental evidence on reptiles is lacking, MacLean's (1978) work with mammals indicated that the R-complex played a primary role in the production of behavior associated with ritual activity. For example, removal of the pallidium or of the pathways leading to it profoundly altered ritual display in monkey behavior associated with territoriality, social grooming and agression. R-complex behavior was extended to include imitation (isopraxis), preservative, reenactment and deceptive behaviors which had a ritualistic component represented by repeated action without significant modification. Reptiles were characterized as "slaves to repetition" but, repetition is also a component of mammalian (including human) behavior, with its production directly related to capacities of the R-complex.

In terms of the concept of biological intelligence, R-complex behavior represents a rudimentary form. Learning, defined as a change in behavior, does not appear as a significant component of the behavioral capacity of the R-complex which therefore lacks adaptability. For mammals and man learning of ritual activity appears to be mediated by higher cortical functions which appear as successive evolutionary events.

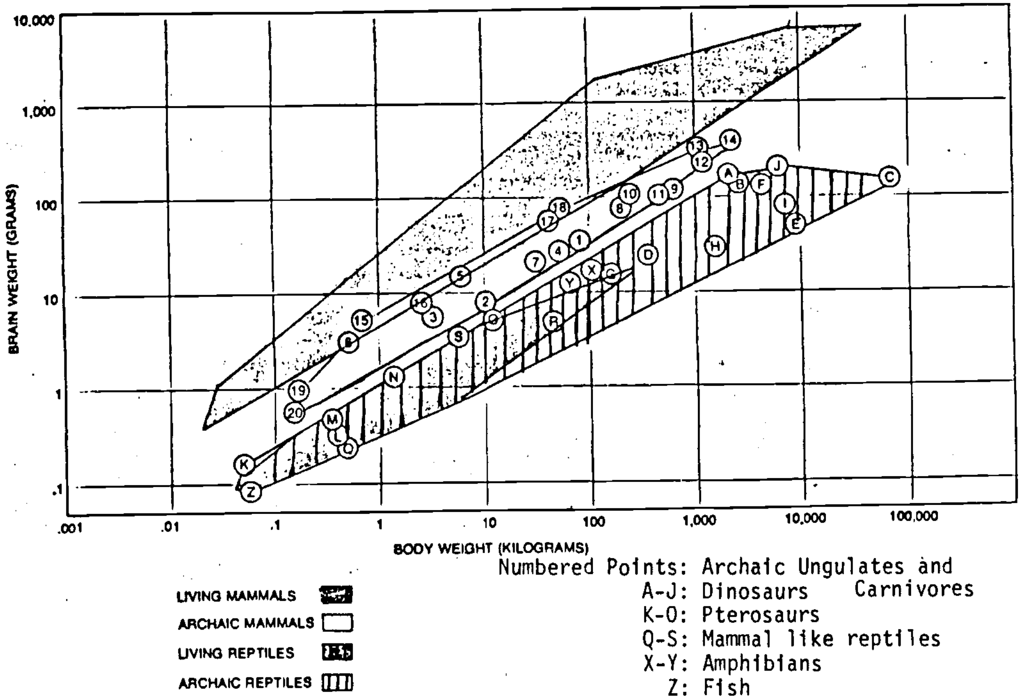
The paleomammalian system or limbic system consists of a series of structures overlying the reptilian complex and localized in three areas: the amygdala division, the septal division, and the anterior thalamic nuclei (mammalian bodies) (MacLean, 1978). Histologically these areas display rudimentary layering of cells which distinguish them from the "clumps" of the R-complex, but they are not as layered as the ascending neocortex. The limbic system and R-complex are also interconnected and do not represent entirely separate structures. The amygdala division has to do with functions concerned with the mouth and with preservation and can be generalized into feeding, fighting and self-preservation; the septal division is concerned with activities involving procreation; and the anterior thalamic nuclei is involved in parental behavior. In general the limbic system is involved in behaviors which elicit strong emotions such as mothering, sex, or protective fighting.

These strongly felt behaviors represent a distinct behavioral break between mammals and reptiles and provide an adaptive advantage in that the investment of emotive energy has a return in greater probability of survival.

The neomammalian system is represented by the neocortex and is involved primarily with the ability to remake the external environment into an internal environment and to act on the external environment. The neocortex consists structurally of two hemispheres, each divided into frontal, parietal, temporal and occipital lobes. The anterior neocortex consists mainly of motor projection areas whereas the posterior neocortex consists of sensory projection areas. In addition the two hemispheres are connected by a bundle of nerve fibers called the corpus callosum which serves to transmit information interhemispherically.

E. Encephalization

MacLean's concept of a triune braine implies three distinct evolutionary events of the nervous system correlating with the appearance of reptiles, primitive mammals,



Numbered Points: Archaic Ungulates and Carnivores
A-J: Dinosaurs
K-O: Pterosaurs
Q-S: Mammal like reptiles
X-Y: Amphibians
Z: Fish

Figure 4 Brain Weight vs. Body Weight for Reptiles, Archaic Mammals and Living Mammals

Note. From "Paleoneurology and the Evolution of Mind" by H.J. Jerison, Scientific American, 1976, 234 (1), 90-101. Copyright 1975 by Scientific American, Inc. Reprinted by permission.

and later mammals. This further suggests that there is a relationship between brain size (in relation to body size) and behavior capacity when vertebrate phyla are compared. Increase in brain size relative to body size is called encephalization by Jerison (1973) and reflects the phylogenetic evolution of intelligence in the fossil record.

Comparing encephalization data from living and fossil organisms, Jerison (1973) has demonstrated a progressive series of events in the evolution of the nervous system correlating with the emergence of reptiles, primitive (archaic) mammals, and more advanced mammals. Figure 4 is Jerison's (1976) encephalization data with brain weight (as a reflection of brain size and assuming a uniform density of neurons, neurotransmitters, and glial cells) plotted against body weight. This indicates three distinct levels of brain evolution corresponding to the three stages of the concept of a triune brain.

Jerison (1976) developed the concept of encephalization quotients (E.Q.) to numerically describe increases in brain size. Encephalization quotient is defined as actual brain size divided by expected brain size as determined by "averages" of living mammals (Jerison, 1976). Encephalization quotients are summarized in Table 1.

	Encephalization Quotient (E.Q.)
Reptiles	0.15
Primitive Mammals	0.3
Mammals (general)	1.0
Primates	4.5
Man	8.0

Table 1 Encephalization Quotients
Data from Jerison, 1976

Since the brains of the living reptiles consist primarily of an R-complex with its associated ritual behavior, it is reasonable to infer this pattern appeared with the early reptiles as they evolved from generalized amphibian forms sometime in the Permian and has remained basically unchanged to today. An animal with only an R-complex would have an average encephalization quotient of about 0.15.

An intermediate group appears with the so-called primitive (archaic) mammals which are represented in this data from the late Jurassic to the late Eocene. This group appears to correspond to the lower reaches of the paleo-

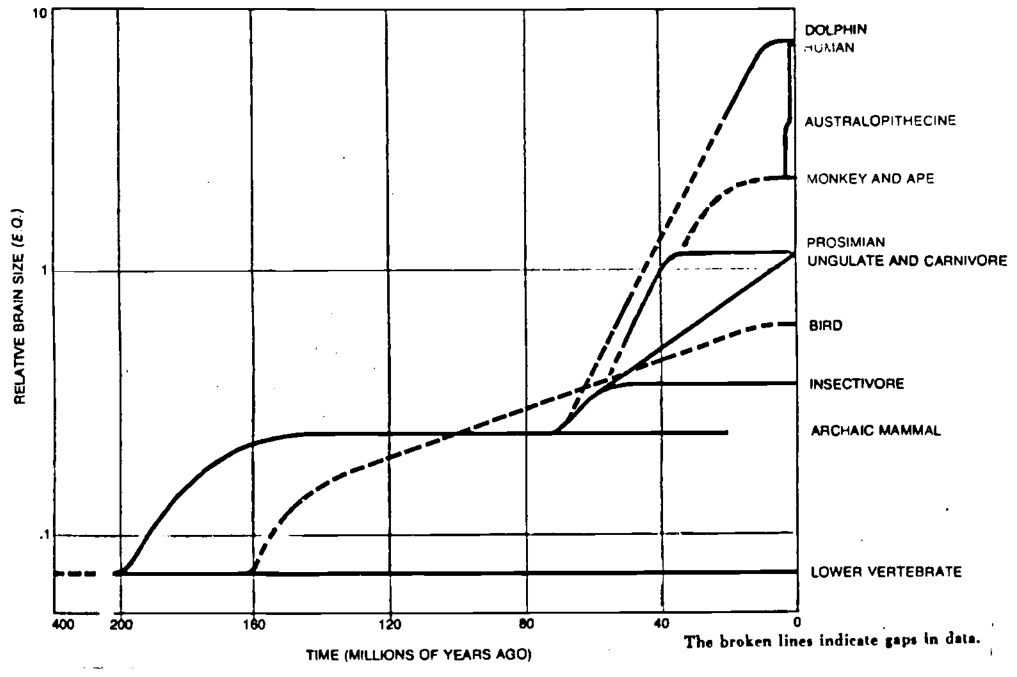


Figure 5 Rate of Brain Evolution

Note. From "Paleoneurology and the Evolution of Mind" by H. J. Jerison, Scientific American, 1976, 234 (1), 90-101. Copyright by Scientific American, Inc. Reprinted by permission.

mammalian brain with an encephalization quotient of about 0.17 for primitive ungulates to 0.41 for primitive carnivores.

A neomammalian brain appears to have evolved rapidly throughout the Tertiary and resulted in modern forms with an average encephalization quotient of about 0.9 for ungulates, and about 1.1 for carnivores. This rapid evolution of the limbic system and neocortex suggests a tremendous selective advantage for emotive and intelligent (biologically) behavior.

Figure 5 summarizes this encephalization data by plotting it against time for various categories of animals (Jerison, 1976). Whereas the average encephalization for all mammals is about 1.0, primates have quotients in the range of 4.5 while in man it reaches 8.0. The data indicate the human brain represents a culmination of a progressive evolution of the nervous system (dolphin brains are problematical and are beyond the scope of this discussion). Its emergence from a generalized mammalian brain represents one of the most rapid evolutionary changes documented in paleontology. The relative rapidity of this change suggests that this is a quantum evolutionary event as described by Simpson (1944). The focus of this change is on the neocortex and its associated function of biological intelligence. The data also suggests that the neocortex in humans has been subjected to selective forces of a different kind than that applied to mammals in general. Whereas the gross structure of the human brain shares many common attributes with other mammals reflecting a common evolutionary episode, both its size and asymmetry apparently reflect species-specific selection and a unique evolutionary espisode.

F. Symmetry and Evolution

Principles of symmetry are used in biology to describe form (morphology) which in turn is a reflection of functional adaptation and the natural selection process (Beerbower, 1968). There are four general classifications of symmetry: radial, spherical, bilateral and asymmetrical. Symmetry when coupled with the descriptor of polarity gives a morphological sketch of the organization of the organism. Symmetry is a primary concern in the description of the motor organs and sensory organs as a reflection of the organism's interaction with the environment. Since the brain receives messages from the sense organs and sends messages to the motor organs, it tends to have the same symmetry as these organs. From an evolutionary standpoint bilateral symmetry of morphological structure implies bilateral function and asymmetrical morphological structure implies asymmetrical function.

The typical mammalian pattern is bilateral symmetry for the organs of movement, sensation and for the nevous system (Corballis, 1982). This symmetry is maintained despite decussation, the contralateral control of the left motor organs by the right half of the nervous system and the right motor organs by the left half of the nervous system. This pattern appeared with the first chordates as they evolved presumably from bilaterally symmetrical invertebrates (Bilateria) with ipsilateral control (Sarnat and Netsky, 1974).

The exceptions to this bilateral pattern in mammals are the sensations of smell and taste. Organs for olfaction are very primitive, appearing with the early amphibians, and are processed in a primitive part of the brain (Jerison, 1973). Olfactory information of a directional nature is accomplished by head turning. Information on taste is likewise very primitive and is accomplished by being in direct contact with the environment. Directionality for the sensation of taste is not a factor.

However, the organs for vision, hearing and touch (somatosensory) are bilaterally symmetrical and this provides information about the environment in terms of directionality. This overall bilaterally symmetrical pattern is maintained in the mammalian organs of movement and reflects the ability to respond to the environment equally well to the left or to the right (Corballis, 1982). With the sense organs of sight, sound and touch bilaterally symmetrical and the motor organs bilaterally symmetrical, it comes as no surprise that the cerebral cortex, the chief association area for incoming perception and outgoing enaction is also structurally bilateral in the form of two hemispheres.

In general the structural-functional bilateral symmetry in mammals is a reflection of Jerison's concept of biological intelligence in that it reflects the capacity to internalize key elements of the environment including spatial information of left and right, and react to that information in the reorientation of the body in space (behavior) also in terms of left and right. Certainly other organisms also have this ability, but in mammals the bilaterally symmetrical pattern coupled with the complex "layers" of the triune brain creates a greater dimension in the ability to produce behavior and hence to affect survival.

G. Asymmetry of the Nervous System

Recent neuropsychological studies in humans have identified a functional asymmetry in the two hemispheres of the cerebral cortex. Asymmetry represents a break in the general pattern of mammalian bilateral symmetry. Human asymmetry is most pronounced in the propensity toward handedness and in the propensity toward hemispheric specialization. Morphologically neither the hands nor the cerebral hemispheres exhibit gross structural asymmetries. In the case of the hemispheres, however, some structural asymmetries have been reported (e.g., Geschwind, 1972). Though the significance of these structural differences remains problematical, functional hemispheric asymmetry in the form of specialization for sequential and spatial modes of processing is well established. If this form of asymmetry is specific to humans then it would imply that its appearance is due to selective pressures specific to hominid evolution, and its explanation would be solely in the context of that evolution. On the other hand if this pattern appears in other mammals then its explanation is not solely in terms of the events of hominid evolution. Unfortunately the evidence of hemispheric asymmetry in other mammals is not conclusive, but it does suggest strongly the asymmetric pattern of the human hemispheres is unique.

Examples of asymmetries found in animals other than primates include Nottebohm's (1977) evidence of the lateralization of vocalization in some song birds but not in others. Glick, Jerussi, and Zimmerberg (1977) demonstrated that there is an asymmetry of the neurotransmitter dopamine in rats which produced differential behavior in the amphetamine stimulation of the two hemispheres. Webster (1972) found evidence that cats trained for a specific activity sometimes stored the memory for that activity in both hemispheres and sometimes stored the memory in only one hemisphere. In addition neuroanatomical asymmetries have been reported for rats (Diamond, Johnson and Ingham, 1975) and cats (Webster, 1977), but the behavioral correlates of these have not been firmly established.

Primate structures show more evidence of asymmetry but not at the degree to which human asymmetry has been established. Warren (1977) reviewed the evidence for handedness in rhesus monkeys and concluded that though individuals display preference, this preference lacks the genetic component characteristic of human handedness. Neural asymmetry has been demonstrated in monkeys where Petersen, Beecher, Zoloth, Moody and Stebbins (1978) found auditory preference for right ear presentation of information over left ear presentation, and Dewson (1977) found removal of certain areas of the left hemisphere produced motor deficits when auditory stimuli were presented, but corresponding deficits were not produced in the right hemisphere.

The paucity of definite meaningful evidence of non-human asymmetry may be a reflection of the experimental difficulty in cross-species investigations, but for now there is little good replicated evidence of asymmetric functional organization reflecting distinct sequential and spatial processing found in any species other than humans. Webster (1977) has pointed out, however, that other mammals may have evolved other forms of neural asymmetry not necessarily corresponding to the human form of hemispheric specialization. Specialization for sequential and spatial processing appears to be a product of selection pressures unique to the human species. The evolution of this form of functional asymmetry seems, therefore, to be a separate evolutionary episode in the development of the human brain--an episode not shared with the other mammals.

H. Asymmetric Hemispheric Specialization in Humans

In most other mammals it appears that information is processed bilaterally with the left and right cerebral hemispheres acting on information in the same way (Levy, 1969, 1977). But in humans the left and right hemispheres tend to be specialized in the manner in which they process information and are asymmetrical. Evidence of this asymmetrical function comes from a number of different lines of investigation including: commissurotomy, temporary hemispheric anesthesia, dichotic listening tests, analysis of brain lesions, and EEG studies (Kolb and Whishaw, 1980). All of these studies produce generally similar results regarding the asymmetric specialization of the left and right cerebral hemispheres as characterized below.

The left cerebral hemisphere was characterized by Bogen as specialized for, "time ordered stimulus sequences" (Bogen, 1977, p. 141). It is the hemisphere in which primary linguistic ability seems to be located, particularly that aspect of linguistic ability involving temporal sequencing (Krashen, 1977). Severe damage to this hemisphere typically results in severe language loss (aphasia), but to characterize the left hemisphere as the language hemisphere is not entirely accurate. The left hemisphere appears to be involved in any serial programming involving motor sequences (Kimura, 1976). This certainly includes speech but also praxic motor activities. Kimura and Vanderwolf (1970) stated,

> the peculiar contribution of the left hemisphere to manual skill may thus consist... (of) the increased efficiency with which individual movements can be coordinated into a sequence. (p. 775)

In addition Corballis (1982) stated,

> there is now a quite widespread agreement that an essential (if not _the_ essential) component of left cerebral specialization has to do with praxic functions--the control and planning of purposeful, sequential actions. (p. 19)

Thus, the left hemisphere is specialized to process information serially or sequentially and is particularly involved in incorporating information into motor activity.

The right cerebral hemisphere was characterized by Bogen as specialized for processing, "time independent stimulus configurations" (Bogen, 1977, p. 141). Nebes (1977) described this hemisphere as:

> relying more on imagery than on language, and being more synthetic and holistic than analytic and sequential in handling data. It is certainly more important in perceiving spatial relationships. (p. 104)

Gazzanaga, Bogen and Sperry (1965) demonstrated that the right hemisphere is particularly specialized for manipulative-spatial skills. Corballis (1982) reviewed the evidence and suggested that it is the spatial rather than the manipulative component that is critical for the right hemisphere. Further, he pointed out the interaction of right hemisphere spatial abilities with left hemisphere motor abilities. Corballis (1982) stated,

> the critical lateralized component is probably spatial rather than manipulative... most normal people are better at manipulo-spatial skills with their right hands than with their left hands suggesting that normal performance depends on cooperation between the spatial skills of the right hemisphere and the dominant motor centers of the left. (p. 23)

The right hemisphere is, therefore, specialized for spatial, time-independent type processing.

The corpus callosum is a large bundle of nerve fibers whose primary function until recently was unknown but is now known to have the very critical function of transmitting information between the two hemispheres (Springer and Deutsch, 1981). The two hemispheres are specialized to process information differently, but they also communicate. The nature of this communication was suggested above by Corballis. For motor activity the right is conceptual in space while the left is temporal in sequence. The organism's function in time and space is thus determined within the context of the nervous system, and temporal and spatial information interact through the corpus callosum.

I. Summary

The evolution of the nervous system as represented in the human species can be thought of as occurring in two distinct episodes: the first as a part of an overall mammalian trend and the second as a hominid event. The human brain has shared with the other mammals the progressive encephalization of structures resulting in a triune brain with an R-complex, limbic system and neocortex and the behavior producing capacities associated with each. The appearance of these structures occurred in the first episode.

The second evolutionary episode appears to be restricted to hominids and is reflected in a shift from a bilaterally symmetrical brain to an asymmetrical brain. This resulted in a form of hemispheric asymmetry with specialization for sequential (time ordered) and spatial operations.

Utilizing Jerison's (1976) concept of biological intelligence, the first episode resulted in a nervous system with a greater capacity to represent the external environment internally and to produce action beneficial to survival. This is compatible with Livingston's (1978) idea that it is behavior which is the selective element in nervous system evolution since enaction of motor activity would result in a perpetuation of those structures of the neocortex producing the environmental representation. The first episode apparently occurred within the context of bilateral symmetry both for sensory-motor organs (with the exception of taste and olfaction) and for separate but similarily functioning hemispheres of the neocortex. This form of symmetry would have enhanced equipotential sensation and response to the environment.

In the second evolutionary episode the characteristic pattern of bilateral symmetry is broken with the appearance of functional asymmetry in the form of handedness and hemispheric specialization. Hemispheric asymmetry in the form of sequential and spatial specializations represent new capacities when viewed from the concept of biological intelligence. From the nature of the specializations these capacities would have been selected for because of a behavior requiring sequential and spatial operations. The next chapter reviews models that have been proposed to explain the behavioral selection for hemispheric asymmetry as related to temporal and spatial phenomena.

III. Proposed Explanations of the Origin of Asymmetry

A. Introduction

From a selectionist perspective the essential question is how the capacity for asymmetric hemispheric specialization could have evolved. Any such explanation must include recognition of selective agents which required sequential processing and spatial processing. In general the selection of hemispheric specialization has been approached in two ways. The first was from the standpoint that each hemisphere became specialized for separate modes of processing (Semmes, 1968). A different, but logically related view, is that specialization was selected for in order to remove interference that would occur if both temporal and spatial processing were in the same hemisphere (Levy, 1969). Whether the nature of the selection was toward specialization or away from interference would appear to be just two sides of the same coin and will be considered here as part of the same process.

Three models have been proposed to explain the origin of asymmetry: a cognitive mapping model, a language model, and a praxic ordering model. This chapter summarizes these three models.

B. Cognitive Mapping Model

Cognitive mapping was first defined by Tolman (1948) to refer to an organism's ability to perceive of itself in space and is closely tied to the concept of territoriality and the maintenance of territory. Peters (1978) suggested that the ability to produce cognitive maps was a major factor in the behavioral evolution of hominids. This can be related to the idea of pursuit hunting developed by Krantz (1968) which suggested that the size of the human brain is largely a product of memory and related functions associated with the pursuit of game as hominids moved from arboreal gathering to terrestrial hunting. Webster (1977) applied the idea of cognitive mapping to the origin of asymmetry not so much as a formal model but rather as a suggestion of possible relationships. Webster's suggestion was that right hemisphere specialization for spatial function was somehow related to the capacity to produce cognitive maps in the establishment and maintenance of territory.

This kind of spatial function would not be specific to hominids. As Webster pointed out, one would expect spatial specialization of a cognitive mapping type to occur in other species particularly carnivores in which knowledge of territory would have enhanced pursuit hunting. Peters (1978) presented evidence that wolves proceeded directly to a destination over a route never before taken which suggested the ability to produce a cognitive map of their territory. This was also experimentally demonstrated in humans (Peters, 1978) but was not specifically linked with a right hemisphere capacity.

The cognitive mapping model does not pretend to be species-specific to the hominid line, nor does it pretend to explain the left hemispheric specialization of sequencing. It does provide a plausible suggestion for the role of the cognition of space in hominid evolution which may have contributed to right hemisphere specialization.

C. Language Model

In 1864 the French anthropologist, Paul Broca, produced evidence that language is produced in the left cerebral hemisphere and that this hemisphere is specialized for the production of language (Springer and Deutsch, 1981). Modern neurophysiological research has expanded Broca's view by establishing several specific areas within the left hemisphere which typically are involved in aspects of language and speech production (Geschwind, 1972).

A model for the evolution of left hemispheric specialization with language has been proposed independently by Hewes (1973) and Kimura (1976). This model incorporated tool behavior and gestural language as preadaptations for vocal language. They have developed the evolutionary scenario that the left hemisphere became specialized for sequencing motor activities and that this sequencing was selected for through tool behavior. This led to, or was somehow interrelated with, the appearance of language of a gestural form where sequencing of symbols affected communication. Oral communication became simply a transfer from gestural motor sequences to audio-vocal sequences.

D. Praxic Ordering Model

The Hewes/Kimura model of language origin related to left hemisphere specialization rests on an initial foundation of a selection for motor sequencing through tool behavior or praxic ordering. This relationship was first noted by Sir Charles Sherrington (1940) where he implicated brain asymmetry, handedness, technology and language. Sherrington (1940) wrote,

> man is a tool-using animal and tools demand asymmetrical acts, acts which at the same time are attentive and unified.

> Man has led a tool-using life for, some say, the better part of a million of years. Most of his tools are of a right-handed use, even far back in times almost pre-human. The left-side brain is concerned with the right-side hand. The human brain's left half predominates; and speech belongs to that half of it (p. 212).

The relationship of left hemispheric specialization for motor sequencing, propensity toward right handedness, and the appearance of tool behavior has contributed to what might be called a praxic ordering model as proposed mainly by Frost (1980) and Corballis (1982). This model has relied heavily on Kimura's (1976) establishment of motor sequencing as the phenomena for which the left hemisphere is specialized.

Corballis (1982) expanded the view that the left hemisphere became specialized for motor sequencing. He cited the appearance of handedness as evidence that the evolution of lateralization has to do with programming motor acts in sequence. Left hemisphere sequencing, in this view, enervates motor sequencing of the right hand which is dominant in about ninety percent of human populations.

Frost (1980) suggested that human tool use and the sequential operations of both manufacture and activity selected for left hemisphere sequential specialization. Frost (1980) connected left hemisphere specialization with right handedness and the sequential operations necessary in tool-making and tool-use where he wrote,

> the lateralized representation of these mechanisms (right-handedness and left hemisphere specialization) is an evolutionary consequence of the requirement for asymmetric employment of the forelimbs in the making and using of tools during hominid evolution. (p. 447)

The Corballis/Frost view sees left hemisphere specialization as a consequence of the propensity toward handedness associated with sequential operations of tool behavior. In Corballis' view the right hemisphere is not specialized for specific modes of processing, as is the left, but functions in a generalized capacity. It is specialized "by default" in the sense that it reflects capacities that were properties of the brain as a whole before the onset of left hemisphere specialization (Corballis, 1982).

E. Summary

The cognitive mapping model suggests an evolutionary contribution to the right hemisphere specialization for spatial abilities. The language model and praxic ordering model suggest an origin for left hemisphere specialization of motor sequencing and hold that right hemisphere specialization for spatial processing was not selected for but was a vestige of some earlier generalized capacity. None of the models suggests a mechanism where both temporal motor sequencing and spatial capacities would be selected for together. Both the praxic ordering model and the language model employ the use of technology as a selective agent in left hemisphere specialization but do not sharply distinguish between tool-making and tool-using. In the following chapter a distinction is drawn between tool-making and tool-using, and it is suggested that tool-making specifically requires both the ability to sequence and the ability to produce spatial images.

IV. The Cognitive Requirements of Technology: Sequence and Template

A. Introduction

The evolution of the nervous system is directly tied to behavior, with behavior contributing to the selection for neural mechanisms. Thus motor action as the final act in behavior production must be taken into account in the selection for brain structure. Beginning with Sherrington (1940) the unimanual manipulation of tools has been cited as being responsible for handedness and the specialization of the left hemisphere for the sequential operations associated with technology. Praxic ordering focuses on the specialization of the left hemisphere and is further cited as a preadaptive basis for the appearance of language. The right hemisphere is seen, in this model, to be specialized for whatever both hemispheres did before left hemisphere specialization; in other words not so much specialization but unspecialization.

In this chapter a distinction is made between two fundamental aspects of technology: tool-making and tool-using. Tool-making implies tool-using but tool-using does not require tool-making. Tool-making requires an organism to have the motor apparatus (hands, etc.) to manipulate natural objects but also requires a cognitive apparatus to carry out the transformations on matter to produce tools. The term transformational technology is used to describe this process. It is suggested that transformational technology requires a cognitive capacity of both a sequential nature and a spatial nature. The sequential nature of technology is the argument of Frost as the selective agent for left hemisphere specialization. But the argument is developed here that sequencing alone does not explain the ability to transform matter. The ability to efficiently coordinate that sequence toward a desired goal implies the ability to form a mental template of both the final form and of the stages of manufacture. The transformation of matter in the production of the artifacts, therefore, requires the capacity both to produce sequences and templates and to coordinate sequence and template. This model is referred to as the sequence/template model of transformational technology.

B. Tool-use vs. Tool-making

Alcock (1972) has identified twenty-one species of animals that regularly employ tool-using as part of their food getting behavior. Alcock (1972) defined tool-using as,

> the manipulation of an inanimate object, not internally manufactured, with the effect of improving the animal's efficiency in altering the position or form of some separate object. (p. 464)

Tool-using animals according to this definition include such varied organisms as ants, birds, fish and numerous mammals. These employ a variety of techniques including using stones as anvils to crack open mussel shells (sea otter), and squirting jets of water at terrestrial prey (archer fish). Alcock (1972) suggested that tool-using does not necessarily indicate a "high level conceptual ability" and neither does it necessarily mean that tool-using animals approximate human cognitive ability. According to Alcock (1972) non-human tool-using is seldom more than a rare event and seems to be a by-product for the evolution of some other ability.

Anthropologists have long considered tool-using and tool-making as fundamentally different processes. In tool-using a natural object is used, unmodified, for some purpose. Oswalt (1976) has used the term naturfact to describe these objects. An artifact or tool, however, is defined by Oswalt (1976) as, "the end product resulting from the modification of a physical mass in order to fulfill a useful purpose" (p. 24). The use of naturfacts imposes a major restriction on technology as an adaptation because the range of tools is limited to the forms found without modification in the environment. With technology based on artifacts, however, matter can be organized and forms can be modified providing a much greater degree of adaptation.

Through a complex series of preadaptations the hominid line developed the physiological traits necessary for the making and using of tools. This included in the main: stereoscopic vision, prehensile hands, and upright posture. For technology to be realized these preadaptations had to be activated by a brain capable of directing the operations necessary to organize matter into useful artifacts.

C. The Alteration of Matter

Technology is based on the capacity to alter matter from one form to another in a predictable and replicable manner. This unavoidably necessitates the terminology of physics because the alteration of matter involves work (force x distance) which in turn involves the expenditure of energy. The recently developed connection between matter, energy, work and information (Brillouin, 1956; Morowitz, 1978) forms a basis for the measurement of the alteration of matter from unorganized to organized from the standpoint of a cultural system.

Trichner (1975) distinguished between non-purposive systems and purposive systems. A purposive system is one in which function can be deduced from the form and would include both biological and cultural systems. The alteration of matter from form to form can take place within a purposive or non-purposive context. The non-purposive alteration of matter occurs within the context of geological weathering where no particular function can be deduced from a form. The purposive alteration of matter would occur within the context of producing an artifact where the function can be deduced from the form. Within the context of a purposive system the degree to which that matter is changed (i.e., from unorganized to organized) is a reflection of the information content.

Information is used in the formal sense of the term (Shannon and Weaver, 1964) and is defined as:

$$I = - P_1 \log P_1 + P_2 + \log P_2 + \ldots + P_n \log P_n$$

where I = information, P_1 is the probability of the first event, P_2 is the probability of the second event and P_n is the probability of the nth event. Shannon originally devised information theory to describe telephone communication networks (Shannon and Weaver, 1964), but it can usefully be applied to any system in which a linear array of symbols is transmitted in a defined sequence (Morowitz, 1978). Information in this formal definition should not be confused with meaning. Information is simply a quantity associated with the probability of a sequence of messages and does not define whether or not those messages are meaningful or meaningless.

Information is related to the probability of any particular event in a series happening. Because of the way Shannon originally defined it, events with a very high probability carry little information to the extreme that an event with a probability of 1 (certainty) carries no information at all. On the other hand events with very low probability carry a great deal of information.

On the basis of the relationship of very probable states and very improbable states, Brillouin (1956) derived from Shannon's formula the expression:

$$I = \log \frac{P}{Pc}$$

where I = information, P is the number of equally probable alternatives, and Pc is the probability of the alternative specified. If Pc is 1 then the information is directly related to the number of probable alternatives.

Maruyama (1960) pointed out that organization is related to information in that highly organized systems exhibit greater information. These concepts can be applied to artifacts as organized matter within the context of cultural systems.

Using Brillouin's formula as applied to, for example, stone tools, P is the number of shapes that a given size stone can be formed into and Pa specifies the shape of the artifact. The information content of the artifact is then:

$$I = \log \frac{P}{Pa}$$

where Pa = 1. Geologically, however, all forms of a stone module are not equally probable since through weathering processes rock tends toward a sphere. The above formula is therefore modified to:

$$I\ (\text{artifact}) = \log \frac{Pu}{Pa}$$

where Pu is the probability of the unaltered shape existing in nature and Pa is the probability of the artifact shape existing in nature. This definition is close to an intuitive understanding of the information needed to produce an artifact in that it reflects how much a shape has to be changed to produce a final form. Thus a flint nodule which only takes the removal of a few flakes to produce a pebble tool reflects less information than say the production of steel which takes a great deal of information.

Trichner (1975) has pointed out that purposive energetic systems require information in order to be organized in any other than a random array. The temporal disorganization of non-purposive systems produces entropy and is governed by dissipative processes leading to increasingly probable states. Purposive systems, biology and culture, on the other hand, require information to organize energy and matter in structures that from a non-purposive perspective are exceedingly improbable. This latter produces negentropy (Morowitz, 1978) or the successive organization of matter and energy counter to the dissipative processes of entropy. The production of artifacts contributes to negentropy.

Information is a phenomenon entirely dependent upon the system which perpetuates it and does not have a separate physical identity (Maruyama, 1960). In other words the information content of a cell does not exist separately from the cell but is a quantity attributable to the improbable way in which the cell is organized. Likewise the information of an artifact is a quantity directly attributable to the improbable structure of the way the matter is organized. Of importance to this discussion is the way in which energy or matter is organized into improbable states. In biology the mechanism by which energy and matter are organized is DNA coding and the enzyme environment in which the sequence of oogenesis takes place. In technology the mechanism by which energy and matter are organized into improbable states is the sensory, cerebral processing, and motor enaction capacities of the human brain. Empirically, artifacts do not occur in the absence of a brain just as life does not occur in the absence of DNA.

It is the particular kind of information that is important in the brain's capacity to transform matter into artifacts. In the next sections the argument is made that this kind of information is of both a sequential and spatial (template) nature.

D. Sequence

Artifact productions require a sequence of motor actions (somatic or extrasomatic) in the transformation of matter into an organized form. Experimenters attempting to replicate lithic technology have reported on the critical sequencing of motor actions. Muto (1971) stated, "a reduction technology such as flint knapping by its nature produces a series of stages antecedent of the final form" (p. 111). Collins (1975) stated,

> all but the initial step are dependent upon the output qualities of the prior steps as preconditions for their interaction. Except in very rare cases, none of the basic steps can be omitted nor can their order be changed." (p. 16-17)

Gunn (1975) also demonstrated that the sequence of steps of production are critical to the form the material will ultimately take.

Shannon's version of the information theory formula can be applied to the sequencing of artifact production:

$$I \text{ (artifact)} = - P_1 \log P_1 + P_2 \log P_2 + \ldots + P_n \log P_n$$

where P_1 is the probability of applying the first motor action, P_2 is the probability of applying the second motor action and so on. However, it is important to note that this form of the information formula is an a posterori definition (Maruyama, 1960; Morowitz, 1978). It can only be empirically applied after the sequence is complete and it is known which "direction" the random components or probabilities took. An a priori application of this formula would result in a distribution of final forms (messages) proportional to the probabilities of each event.

Applied to the concept of artifact production this would mean that if probabilities of sequences were the only things governing the outcome, the range of artifacts in a toolkit would reflect the probability distribution of the events of any given step in a tool-making sequence. For example, if we specify a simple four step tool-making sequence where either of two actions could take place at any step, then the possible combinations are: 2 x 2 x 2 x 2 = 16. Without some way of specifying which is the right sequence, it would theoretically take the production of sixteen tools to produce the one intended tool. Empirically neither archaeological toolkits nor modern assemblages reflect this disproportion of unwanted forms to wanted forms.

E. Template

If there is a model of the intended form then, to a large measure, the sequence of tool-making events are specified *a priori*. For example, in the above illustration, if one of the sixteen possible forms is specified as the intended tool, then the sequence of events is restricted to actions which will realize that particular shape. Because of the model or template specifying the outcome, the sum of the probabilities (Shannon's information theory) becomes a reflection of the information necessary to direct the action toward the desired product.

This suggests that there is some other operator in the production of an artifact than a random process based on

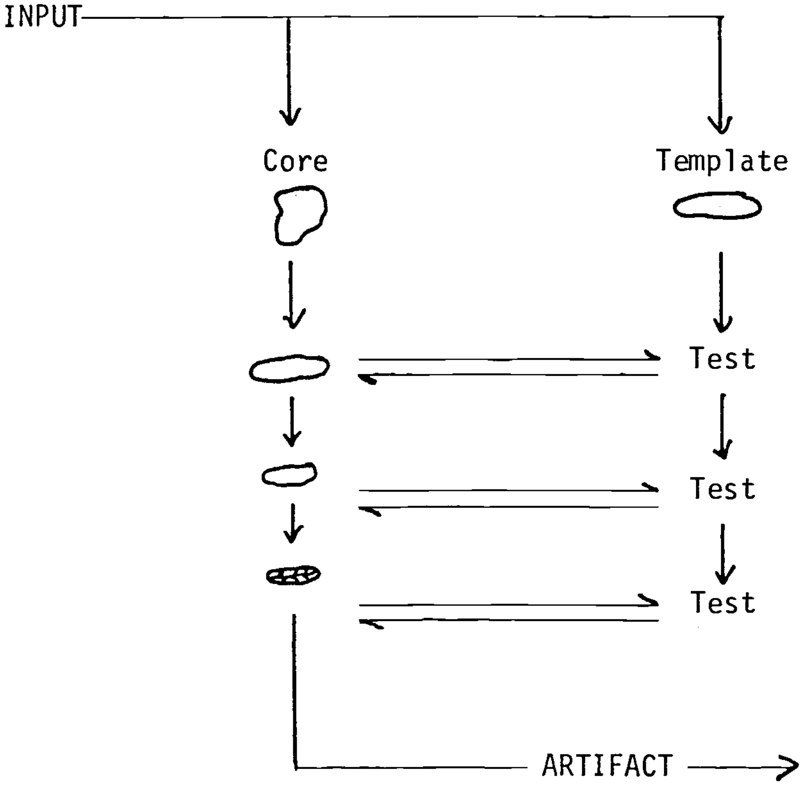


Figure 6 Gunn's Sequence/Template Model

Figure adapted from Gunn, 1975.

probabilities of events. The concept of mental template, a mental image of the form of the intended tool had been advanced as a cognitive model which guides the tool-making process (Deetz, 1969). Gunn (1975) analyzed his own attempts to replicate stone tools and found that the process could be broken down into discrete steps (though the flow of movement was often continuous) and furthermore that after each step in the sequence he cognitively compared the form he produced to a mental image of what that form should look like at that stage of the manufacturing process. He proposed not just a sequence of motor actions guided by an overall template, but also a series of templates (called tests) each one approximating the appropriate form in the manufacturing process. Figure 6 is a schematic of Gunn's model (Gunn, 1975).

This suggests a sequence/template model of tool production in which the replication of a particular form involves the interplay between the sequence of work done with cognitive templates of what results of that work should look like. The sequence is determined not by probabilities of possible movements but by an overall template and a template for the various steps in the manufacturing process.

Gunn's (1975) model can be expanded to:

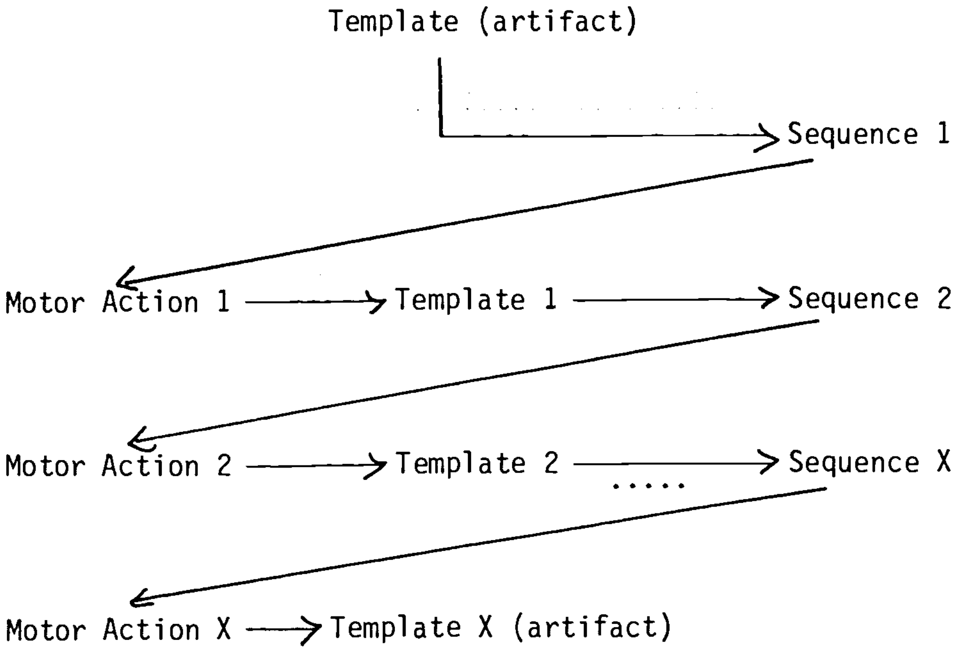


Figure 7 Sequence/Template Model

In this sequence/template model of tool production the elements on the right, sequence and template, can be described by information reflecting the transformation of an unorganized shape into an organized shape. The elements on the left, the motor actions, are the actual movements which change the shape of the matter. These motor actions involve the utilization of energy and can be described, with appropriate vectors, by the concept of work.

F. Summary

Tool-making involves the ability to transform matter from an unorganized form to an organized form. This process is counter to the physiochemical process of weathering which acts on matter in such a way as to break down natural materials and disseminate them. This dissipative process produces entropy in that matter and energy proceed toward more probable disorganization. Tool-making, however, produces negentropy, the greater organization of matter, toward highly improbable states. The production of negentropy requires the cognitive capacity to sequence motor actions in the step by step order characteristic of tool-making. However, unless directed by some a priori purposive design, sequences of motor action would simply reflect a random combination of the corpus of actions. A mental template, or spatial image of the intended result, is suggested as the critical a priori component which acts to guide and restrict the sequence of actions toward the intended result.

Since tool-making is the purposive reorganization of matter, the cognitive capacity of an organism producing tools must reflect the ability to design by intent, as well as the ability to sequence the steps of production.

V. Technology and the Origin of Asymmetry

A. Introduction

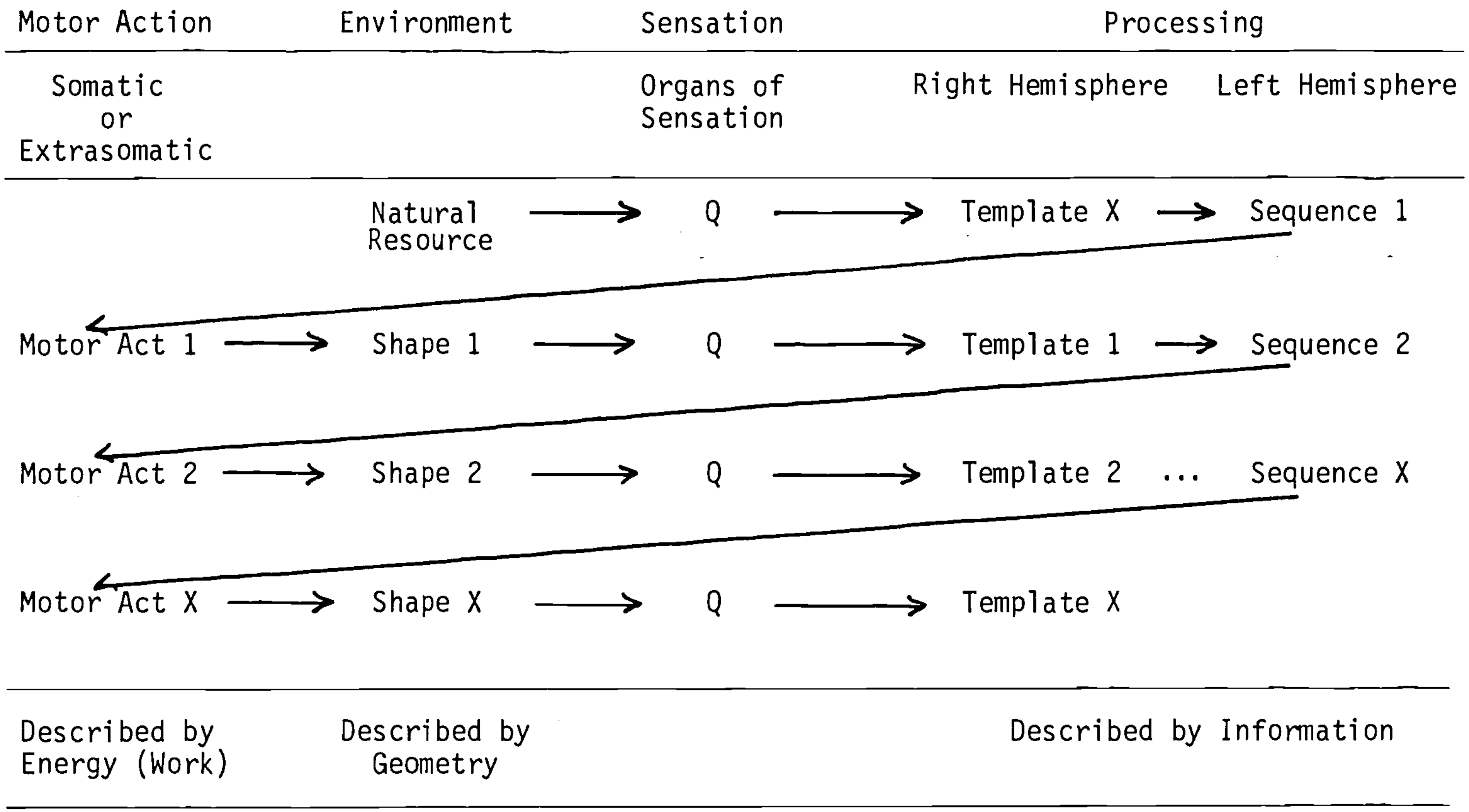
Tool-making requires the cognitive ability to both sequence motor action and guide that action by appropriate templates of spatial images. The sequence/template aspect of technology juxtaposed with the data on asymmetric hemispheric function produces a model suggesting that the origin of asymmetry in humans reflects the cognitive requirements of transformational technology.

This model is difficult to test because, though there is ample documentation of an artifact record going back about 2.6 million years, it is difficult if not impossible to document the evolution of cerebral asymmetry from the fossil record. One test of this model, however, can be made based on a prediction derived from it utilizing data from neuroanatomical disorders resulting in apraxia as discussed below.

In addition to testing the model, a second problem arises relating to the question of causation. Stated simply, if technology requires an asymmetric brain, then did technology cause asymmetry or did asymmetry cause the appearance of technology? This is discussed below along with an evaluation of this explanatory model compared with the existing models summarized in Chapter III.

B. Sequence/template Model and Asymmetric Function

The evolution of functional asymmetry in the human cerebral cortex can be viewed as an evolutionary episode which appears to be uniquely human, and its explanation must be in terms of the events of the human paleontological and archaeological record. Further, the explanation of asymmetry by its nature must account for the appearance of capacities related to motor sequencing and spatial processing. Chapter IV developed the point that tool-making requires both motor sequencing and spatial processing in the form of mental templates. Since the appearance of artifacts with the early hominids (Australopithicines) represents a distinctly human evolutionary episode and since tool-making requires both sequential and spatial processing, the cognitive requirements of technology formed a behavioral selection for human asymmetric cerebral function.



Q = sensation and perception of changes in shape via sight, sound and touch

Figure 8 Sequence/Template Model and Hemispheric Asymmetry

The realationship between asymmetry and tool-making is presented diagramatically in Figure 8. This model suggests that matter is transformed from an unorganized state to an organized state (from a cultural standpoint) in the production of an artifact through a series of motor actions which can be described by the concept of work. The organization of that work, however, requires information as ultimately reflected in the degree to which that unit of matter is changed. The information content depends upon a brain which can both sequence the motor activity and produce a template of the overall goal along with a series of templates for appropriate stages in the manufacturing sequence. Asymmetry of hemispheric specialization, therefore, reflects the cognitive demands of the ability to produce technology.

This model emphasizes that the specialties of both hemispheres must be coordinated in the act of producing a tool. In particular it suggests that spatial imagery must be translated into sequences resulting in motor action. The corpus callosum represents a structure which passes information interhemispherically and thus is a reflection of this communication process. This implies that toolmaking would have selected for an interacting form of hemispheric specialization rather than each hemisphere developing capacities exclusive of the other and operating independently.

C. Apraxia: A Test of the Model

As stated in the introduction to this chapter this model is difficult to test because of the lack of direct information in the fossil record of the appearance of hemispheric asymmetry. Even if there were fossil information, however, its correlation with the appearance and sophistication of technology would not necessarily prove interactive causation. Another way to test this model is to test a prediction logically deduced from it. This can be done using information from clinical studies of apraxia.

The sequence/template model suggests the prediction that individuals with left hemisphere neural deficits in the form of lesions or associated organic problems would display disabilities such that they would be unable to perform a given motor action or motor sequence. On the other hand the model suggests that individuals with right hemisphere neural deficits would be able to perform the required motor action but would be unable to coordinate the sequence of actions toward an intended result.

Geschwind (1975) defined the apraxias as,

> disorders of the execution of learned movement which cannot be accounted for either by weakness, incoordination, or sensory loss, or by incomprehension of or inattention to commands (p. 188).

Springer and Deutsch (1981) listed four major forms of apraxia of which kinetic apraxia, the inability to produce fine motor movements due to damage to the premotor region of the frontal lobe, and ideomotor apraxia, the inability to produce movement based on spoken commands, are not of direct concern in this discussion. The two that are of concern are ideational apraxia and constructional apraxia. Ideational apraxia is caused primarily by disorders of the left hemisphere and constructional apraxia is associated with disorders of the right hemisphere.

Ideational apraxia in the classic view developed by Leipmann (Geschwind, 1975) is a product of left hemisphere lesions or of lesions of the corpus callosum. Although there are clinical problems of definition and the exact locus of damage is difficult to pinpoint, ideational apraxia has been characterized by Springer and Deutsch (1981) as,

> an inability to formulate an appropriate sequence of acts or use objects properly. A patient seems to know how to perform isolated movements... but will do them inappropriately (p. 217).

The special role of the left hemisphere in sequencing motor action is supported by Milner (1976) in a study of normal (non-brain damaged) individuals. In this study anesthesia of the left hemisphere produced the temporary inability to perform a learned gestural sequence with either hand, whereas anesthesia of the right hemisphere produced no impairment.

Apraxia of the right hemisphere is termed constructional apraxia though again there are clinical problems of definition. Constructional apraxia is characterized by Springer and Deutsch (1981) as,

> a loss in the ability to reproduce figures by drawing or assembling. There seems to be a loss of visual guidance or an impairment in visualizing a manipulative output (p. 218).

Tests to identify constructional apraxia involve manipulating objects to produce a desired form and include such tasks as: (1) assembling a jigsaw puzzle, (2) drawing a map, (3) copying a design, and (4) building bridges, towers, etc., with blocks (Kolb and Whishaw, 1980).

Kolb and Whishaw (1980) compared the evidence of left and right hemisphere apraxia and suggested that left hemisphere apraxia involved deficits which, "result from the patient's inability to adjust the parts of his or her own body," whereas right hemisphere apraxia involved deficits where the requirement was, "that objects be ordered in extrapersonal space" (p. 237).

Though the apraxias need clearer clinical definition including studies such as Milner's (1976) with subjects without brain damage, the above evidence does support the deduced prediction that the left hemisphere neural deficits result in the inability to produce motor movement or sequences of motor movement, while right hemisphere neural deficits result in the inability to coordinate movement toward a desired result. This test of the model does support the suggestion that tool-making requires the cognitive capacities of an asymmetric brain, and therefore asymmetry and technology are mutually implicated in hominid evolution.

D. Positive Feedback Relationship

Several authors including Holloway (1968), Bielicki (1969) and Tobias (1971) think that the relationship between brain evolution and technology represents a positive feedback interaction. This relationship reflects a strong correlation between brain size increase (encephalization) and an increase in the complexity of technology through hominid evolution (Tobias, 1969). The relationship proposed in this paper between asymmetry and tool-making adds a new dimension to this positive feedback relationship.

An adaptation of the positive feedback model proposed in Chapter II to asymmetry and tool-making appears in Figure 9.

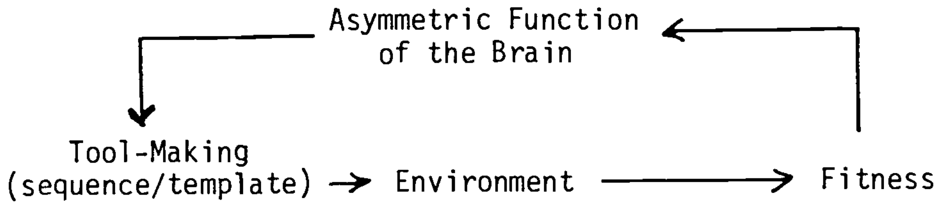


Figure 9 Positive Feedback between Tool-making and Brain Asymmetry

The survival advantage in the making of tools effective in controlling energy would affect survival (fitness).

Survival implies that those brain characteristics contributing to the production of tools would in consequence be selected for and in turn affect the capacity to produce effective tools.

The evolution of the brain and technology as it concerns tool-making and asymmetry involves a type of causation defined by Maruyama (1962) as mutual causation. This form of causation results in the interaction of two or more elements such that both are changed and requires a mechanism such that information from one can be "fed back" to the other. Figure 9 reflects a mechanism where asymmetry and technology interact in mutual causation based on positive feedback.

Asymmetry appears to be a functional reorganization of the human brain and has not been tied directly to increase in brain size. However, the very rapid evolution of the human brain during hominid evolution implies reorganization. Additionally the positive feedback nature of tool-making and asymmetry suggests a mechanism for the quantum evolutionary leap of hominid brain evolution. Prigogine (1972, 1976) has demonstrated that positive feedback relationships can initiate a series of changes in physiochemical systems leading to a redefined system. Positive feedback in the biological/-technological systems of the human species may likewise have led to the reorganization of neural structure and hence the reorganization of its behavior producing capacity.

E. Evaluation

The sequence/template model of transformational technology presented in this thesis suggests that the cognitive requirements of technology played a major role in the behavioral selection for functional asymmetry of the human brain. There are two main advantages to this model: (1) it explains the specialization of both hemispheres and (2) it is based on the known appearance of a behavioral form (artifacts) in the fossil record.

The cognitive mapping model, language model, and praxic ordering model each focus on the explanation of the specialization of the right and left hemisphere but do not satisfactorily account for the specialization of the other. According to the model developed in this thesis, technology requires specialization associated with both the left and right hemispheres and for these modes of processing to work in tandem in the production of an artifact.

The second advantage, the known appearance of the behavior involved in the selection (artifacts,or specifically,producing artifacts), provides an empirical base. Though we know that language evolved, there is no record of precisely when it evolved. The same is true of the less well-defined cognitive mapping. On the other hand, if asymmetric function is a requisite of the ability to produce tools, then it can be inferred that this asymmetry evolved along with early transformational technology.

It should be pointed out that the sequence/template model does not deny any of the above models. It is an extension of the praxic ordering paradigm and has in common the left hemisphere sequencing of motor activities associated with tool-making. It differs in the role of right hemisphere specialization, and it specifies tool-making as the selective behavior.

The sequence/template model does not contradict the language model as developed by Kimura and Hewes which proposes tool-making as a probable preadaptation to language. It should be pointed out, additionally, that this sequence/-template model is compatible with the basic principles of transformational generative grammar which hold that language is based on the ability to combine words into virtually an infinite array of sentences through the application of a few rules of transformation (Slobin, 1979). Likewise a broad array of artifacts can be developed on the basis of the rearrangement of sequences of motor action. Purposive cognition is a fundamental attribute in technology and in language.

The transformational technology model not only does not contradict the cognitive mapping model, but there is an affinity between them. Producing artifacts is only one part of a very important two-part sequence. Produced tools are only of value if they are also used effectively in securing food and related survival activities. Most artifacts of the earliest and longest span of human history, the paleolithic, reflect a hunting function and it is reasonable to infer that territorial hunting of a kind described by Krantz (1968) necessitated some form of cognitive mapping ability.

These compatibilities suggest that the selection for functional cerebral asymmetry came from a broad range of behaviors throughout the evolutionary history of hominids. The explanation presented in this thesis is advantageous, however, because it explains the selection for both left and right hemisphere specialization and because it is tied to the appearance of a behavior with a documented history. Tool-making appears to be the primary triggering agent in the shift from bilateral symmetry to asymmetry and played a major role in shaping the organization of the human brain.

If the model presented in this thesis is correct, then the evolution of human asymmetry is reflected by the archaeological record. The pace of this evolution is represented by the slow but inexorable progression of technological sophistication throughout the paleolithic. This began with only a few types of simple pebble tools occurring over more than a million years and culminated in complex upper paleolithic assemblages with innovations occurring with relative rapidity (Bordes, 1968). The paleolithic is represented by cultures with hunting-gathering types of economics where individuals or close kin groups both made and used their own tools. The adaptive advantage of tool-making, therefore, directly affected the survival of the brain that made the tool. The advent of the neolithic agricultural revolution and its associated specialization of labor changed this pattern. Because of specialization the same individuals who made tools were not the ones who also used them and derived the direct selective advantage from them. This suggests a shift from a paleolithic pattern of the selection of asymmetry through tool-making, to a neolithic pattern where adaptive advantages due to technology are a product of its social and economic distribution.

What had evolved throughout the paleolithic, however, was a human nervous system with the characteristic of asymmetric hemispheric specialization. The main implication of the interactive evolution of the brain and technology is the evolution of the capacity to produce purposive behavior of a form where a template of an intended outcome acts to determine a sequence of motor actions resulting in a behavioral transformation of the environment. This cognitive capacity would seem to be the basis not only for the transformation of matter, but also of a more generalized human capacity where an element external to the individual is affected by internally generated sequences of behavior prescribed by templates of intended outcome. This further implies that new behaviors can be produced by the formulation of new templates and the appropriate restructuring of sequences. This capacity of human innovation and transformational behavior would appear to have originated in the evolution of human cerebral asymmetry because of the cognitive demands of technology.

F. Implications for Further Research

One of the values of an evolutionary model is the implications the model suggests for further research. In a model with the scope of the one presented in this paper there are many implications. In this section comments will be restricted to four which affect education.

First, further research on the relationship of apraxia to tool-making appears promising. In particular the model suggests a design where left hemisphere and right hemisphere apraxia can be evaluated in terms of the performance of integrated sequence/template behavior. Much of the research on apraxia does not clearly distinguish between linguistic and praxic deficits. For example, the inability to move an object in space upon request may reflect a language deficit or a praxic deficit. In addition research needs to distinguish between tool-use and tool-making as different operations. If the intent is to manipulate an object then it is a reflection of tool-use and does not necessarily reflect sequential and spatial operations. However, if the research design specifies the transformation of matter toward a more organized form, then it is tool-making which implies both sequential and spatial operations.

A second major area of further research lies in the relationship of the differences in the degree to which individuals are lateralized and the capacity to produce technology. Technology is here meant to mean not only the tools we associate with direct economic function, but also "tools" associated with what is traditionally considered to be the product of artistic endeavor such as various forms of two-dimensional and three-dimensional art. Lateralization differences among individuals are characterized in a continuum ranging from well-lateralized, represented by distinct measurable forms of hemispheric specialization, to diffusely lateralized where specialization is not distinct. The detection of lateralization is a controversial issue and beyond the scope of this discussion. Assuming accurate detection techniques, the question becomes, "do differences in lateralization result in differential capacities in the ability to transform matter in the production of a tool?" One would predict from the model that distinctly lateralized individuals would be more proficient in the transformation of technology. This has far reaching implication in many areas but especially in education. In education a functional determination of the manner in which individuals produce technology (as broadly described above) would suggest curricula which would maximize those capacities.

A third and related area of research lies in the relationship between the practice of producing technology and developmental aspects of asymmetry. Since asymmetry has a significant developmental component, tool-making requiring differential cognitive capacities could conceivably act to direct the nature of this development at certain critical stages. Just as there appear to be certain critical stages for language acquisition, there might also be critical stages for the development of asymmetry through acts such as tool-making which necessitate sequential/spatial behaviors.

A fourth area of research would approach asymmetry not from the functional differences between hemispheres, but from the standpoint of the interaction of those hemispheres. It was suggested that tool-making requires a form of asymmetric specialization which necessitates communicative interaction between the hemispheres. Since the process of making a tool would fall under the general category of behavior called "creative," the model presented in this thesis suggests that the basis of creativity lies in the degree to which spatial and sequential functions interact. Though it is popular to talk of "education for the left brain" and "education for the right brain" it may very well be that it is education for the communication of the left _and_ right brain that educators should be striving for.

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