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ABSTRACT

The purpose of this paper is to explore the relationship between constructivism and neural organization. Support is given for a constructivist epistemology in current brain theory. A brief description of constructivism is provided, followed by the implication of this set of beliefs for viewing humans as self-organizing systems. What has been learned about how the brain is organized for cognitive functioning, with special attention to neuroplasticity, is described. Evidence for sensitive periods of development in the nervous system is presented. Recently developed techniques for studying human brain activity while engaged in cognitive activity are described. In the closing section of the paper, the implications of models of human brain functioning for theories of knowing are outlined, suggesting that constructivism fits well with these models. Contains 52 references. (MKR)

Models of Neural Plasticity and Classroom Practice

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The purpose of this paper is to explore the relationship between constructivism and neural organization. In just the past few years, new tools for studying the functioning of the human brain such as MRIs and PETs have emerged. For example, Kosslyn (1994) has developed a theory of mental imaging based on numerous studies of brain activity which supports the thesis that the brain organizes itself. We argue in this paper that cognition, as described by constructivism fits with what we know about how the brain works.

In this paper, we consider the support for a constructivist epistemology in current brain theory. A brief description of constructivism, as it is used in this paper, is provided followed by the implication of this set of beliefs for viewing humans as self-organizing systems. Following this, we describe what has been learned about how the brain is organized for cognitive functioning with special attention to neuroplasticity. As part of viewing the developmental aspects of the nervous system, evidence for sensitive periods is presented. Recently developed techniques for studying human brain activity while engaged in cognitive activity are described. In the closing section of the paper we outline the implications of models of human brain functioning f . theories of knowing, suggesting that constructivism fits well.

Constructivism

Constructivism is being widely debated in the mathematics education community and seems to take different forms for each person. But as Driver, Asoko, Leach, Mortimert and Scott (1994) state, "the core commitment of a constructivist position, that knowledge in not transmitted directly from one knower to another, but is actively built up by the learner, is shared by a wide range of different research traditions." (p. 5) The purpose of this paper is not to compare and contrast different meanings of constructivism. While forms of constructivism are sprouting as fast as weeds in a garden (e. g., social constructivism, emancipatory constructivism, critical constructivism, the emergent view), this paper will use constructivism to refer to the theory described by von Glasersfeld (1995) which he calls radical constructivism. The tenets of this theory can be summarized as follows:

1. Knowing is an activity in which individuals give meaning to their experiences

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which, contrary to some interpretations, includes interactions with other persons. Knowing is the result of goal directed activity.

2. The function of cognition is adaptive and serves the organization of the experiential world, not the discovery of ontological reality. We have no access to a God's eye view of the world and thus have only our experiences upon which to build our knowledge. We can consider 'reality' to be the consensual domain which become established in communities.

3. The meanings an individual gives to their experiences are not judged as true or false but tested in an intellectual community for viability.

The historical roots of constructivism lie in the works of Vico, Kant, Wittgenstein and Piaget. In constructivism, cognition is an instrument of adaptation the purpose of which is the construction of viable conceptual structures. The learner organizes and actively gives meaning rather than being hard-wired to receive stimuli.

Self Organizing Systems

A significant feature of human beings is that each is a self-organizing system. A cognizing entity organizes its experiential world by organizing itself Piaget, 1937, p. 311). We determine our goals, intentions, and actions which, in turn, cause changes in our mental organization. In acting, we experience unexpected events which we must then consider. In the process of resolving these perturbations we create new schemas and the brain actually changes physiologically. Maturana and Varela use the term autopoiesis to mean self-creating (Maturana and Varela, 1980). They use the term to describe biological systems organized such that the system self creates those components necessary to maintain its organization (Goolishian and Winderman, 1988). There is an unbroken circle of being-acting-knowing.

The human brain is currently viewed as a self-organizing system (Pribram, 1994: van Pelt, Corner, Uylings, & Lopes da Silva; 1994). Observers essentially create themselves as unique individuals as they live in action and language. To assume otherwise is to defy the knowledge of brain functioning. Language, as our primary mode of communication, plays a central role in our thought and actions. Our experience, or our description of our experience - that is, how we re-present to ourselves what we experience - is a function of our autopoietic construction. We thus live and take action in a world we define through our descriptive language.

Self-organizing systems are constantly reorganizing themselves. The brain is changing with each new experience (Kosslyn, 1994). Theories of learning which assume the brain is constructing new systems all the time seem to fit what we know about neural functioning. To assume that the brain is hard-wired, has a processor (tacitly assumed to be fixed), storage and recall systems contradicts what is being learned about brain mechanisms. What we know is what we have constructed - the sense we have made of our experiences. We see with our personal theories. There is no such thing as immaculate perception. The visual system does not function like a camera, recording in the cortex light impulses which fall on the retina. Much interpretation intervenes between light entering the eye and registering of meaning of the scene. The brain is an active self-organizing system which initiates and gives meaning in idiosyncratic ways. Many studies have provided convincing evidence that the brain is a constantly changing organ - it changes itself (Kossyln, 1994).

Based on hundreds of carefully designed research studies on animals and humans, Kosslyn (1994) has build a theory of mental imagery which explains how the human mind uses what it knows to make sense of new experiences. When a person is constructing an image, there is clear evidence of information flowing backward in the system. In the visual system, stimuli fall on the retina and begin a heavily branched path to the occipital and subsequently, parietal areas of the cortex. But remarkably, information is sent back down the line so that new experiences are interpreted in light of new schemas.

Neural Mechanisms and Plasticity

We use the term "neural plasticity" to refer to this capacity of the brain to reorganize itself in response to environmental stimulation. Originally, the term was defined in terms of the brain's capacity to reorganize after insult and restore adequate function (Will, Schmitt & Dalrymple-Alford, 1984). It was soon recognized, however, that the brain was capable of reorganizing itself in response to many other events than insult.

Konorski (1961) suggested a much broader definition. In his terms brain plasticity refers to "the adaptive capacities of the CNS or, its ability to modify its own structural organization and functioning." According to this definition a much broader range of phenomena than recovery of function is considered. Using Konorski's definition of neural plasticity allows one to consider changes in the nervous system which occur during development, learning and memory to be considered as similar phenomena.

Milgram, MacLeod and Petit (1987) have identified three general categories of neural events which have been referred to as examples of plastic neural events. Developmental plasticity refers to changes which occur early in an organism's development. Although these processes are mediated largely by internal events, environmental factors such as those discussed below can still have profound effects.

It has frequently been suggested that the cellular mechanisms producing synaptic modifications are the same during development and learning.

Anatomical plasticity refers to distinct changes in cellular structure that are experientially induced. Originally, it was thought that after the birth individual neurons could not grow or form new synapses. Research in the last two decades, however, has firmly established that this is not the case. After birth, both the spread of dendridic trees and number of synapses continue to increase in the young animal (Petit and Marcus, 1987) and even in the adult animal, synapses increase in number and change morphologically in response to activation (Petit and Marcus, 1987). Certainly, such changes could be involved in learning and memory.

Physiological plasticity is a change in level of responsiveness, threshold of firing, or pattern of activation which can be related to experienced events. The most important example of this type of plasticity is the phenomenon of long-term potentiation. Hebb (1949) first proposed this as the cellular mechanism of learning and memory, but it was not demonstrated for many years. As it has now been demonstrated, however, it may be involved in memory storage (Racine and Kairiss, 1987).

Although the ideas of neural plasticity had been used for a long time, most researchers' work was compartmentalized into areas such as "development," "learning and memory," or clinical recovery of function. During the 1960's and early 70's, the work of David Hubel and Torsten Wiesel kindled a much interest. As a result researchers began to look more globally at their work and see broader implications. A brief review of their work, and that of others that followed will be illustrative to demonstrate the tremendous capacity for the brain to self organize.

In their early work, Hubel and Wiesel (1959, 1962, 1965a) studied the electrophysiology and anatomy of cat visual system. This work served to delineate much about how the system was organized and the properties of the individual neurons, particularly in the cat's visual cortex (area 17 or striate cortex). They then deprived immature kittens of visual experience in one eye by unilateral lid suture (Wiesel and Hubel, 1963). The results of this manipulation were quite striking. In single unit recordings after the eyes were opened they were able to find very few neurons which responded to any type of stimulation of the previously sutured eye. In subsequent research they studied this effect further (Wiesel and Hubel; 1965 a, b) and found that it was permanent and that the effect of unilateral eye closure was more profound on cortical reorganization than bilateral eye closure. They proposed a number of mechanisms to account for the effects. The most relevant to our discussion is the idea of synaptic competition. In one experiment (Hubel and Weisel, 1963) they recorded from the visual cortex of young kittens before the time of normal eye opening and found some adult like properties which they had not found in the monocularly deprived cats. They therefore concluded that the experience of monocular lid suture had actually destroyed some properties of the cells which were already present and thus caused reorganization.

The cellular mechanism they proposed to account for this was referred to as "competition." During development, synapses compete for space on their target cells. Activity at a particular synapse favors it in the competition. Synapses at which there is no activity are not favored and therefore lose in the competition and die out. Since Hubel and Weisel were working in the visual system, this activity would have been provided by visual stimulation from the environment. This mechanism is very similar to that proposed by Hebb (1949), called long-term potentiation, as the synaptic basis for learning and memory.

Subsequent morphological research has at least partially confirmed this competition model for the visual cortex (Cragg, 1975; Winfield, 1981). It has been shown that after the birth of the kitten the number of synapses per neuron in area 17 of the kitten increases rapidly and arrives at its maximum value at about 6-10 weeks postnatally. These values are about 130% to 140% of those found in the cortex of the adult cat reared with normal visual experience. These data suggest that even with normal visual experience there is a "pruning out" of synapses by experience-dependent changes.

This work by Hubel and Wiesel, however, involved depriving an eye of pattern and much light stimulation. After publication of this work researchers began to wonder what would happen if the amount of stimulation in the pathways were not reduced, but the input was altered in other ways. In one experiment Hubel and Weisel reared kittens with surgically induced strabismus (Hubel and Wiesel, 1965b) so that the amount of stimulation from each eye was equal, but the input was disparate. They found an equal number of cells driven by each eye, but no cells which were driven by both. Again the nervous system had reorganized itself to correct for environmental stimulation.

Since this early work by Hubel and Wiesel many other researchers have used a variety of manipulations of visual input and studied visual areas of the brain other than straite cortex (see Hirsh, 1985; Sherman and Spear, 1982; Mitchell and Timney, 1984 for reviews). In all cases, however, the results have been basically the same. Early visual experience alters the physiology of the visual system in favor of the type of stimulation received.

It is now possible to ask the question "Does this developmental plasticity have anything to do with mathematics learning in humans?" At present we cannot answer this question with certainty, but developmental plasticity and learning have been shown to have a similar synaptic basis in at least one model system. Marcus, Emptage, Marios and Carew (1994) studied both developmental plasticity and learning in the sea slug, Aplysia. In this system it appears that there are two mechanisms responsible for learning. One of these, cell growth, is identical to developmental plasticity while the other appears to occur only in the adult system. This finding is significant because it allows investigation of plasticity at a very molecular level.

From the preceding discussion, then, it is evident that the brain is a self organizing system. It modifies itself in response to changes in the environment. Although this self organizing capacity has been most frequently studied in young developing organisms it appears that at least some of the synaptic mechanisms are the same in the adult during learning.

Critical or sensitive periods

Fundamental to the idea of developmental plasticity is the idea of critical or sensitive periods. The critical period is time, during its developmental stage, when the organism is highly susceptible to a particular type of environmental influence. The effect of this influence then becomes permanent and affects the future behavior of the organism. This idea was first conceptualized by Lorenz (1937) with respect to imprinting in precocial birds. Since his time the idea has undergone considerable modification and has been extended to include a wide range of phenomena. As Lorenz conceived the critical period it was very sharply delineated and subsequent ethological researchers have come to prefer the term "sensitive period" because it is less absolute (Bornstein, 1987). Hubel and Wiesel, however, used the term "critical period" to describe their results and this is the term that is most commonly used in the neurophysiological literature.

In the literature mentioned above in kitten visual cortex the classical critical period for these effects to occur is given as from 3 to 16 weeks postnatally (Hubel & Wiesel, 1970; Olson & Freeman, 1980; Hirsh & Tieman, 1987). Beyond this period of time no effects of monocular deprivation were seen. Effects of other manipulations in adult cats have been studied and their is some evidence that these produce similar types of effects (Brown & Salinger, 1975). At least in psychophysical studies with human subjects, however, the effects are quite profound but temporary (Brown, Berkley & Jones, 1978). In the opthalamological literature results similar to those described for kittens had been noted for years, but no explanation had been offered. It was widely reported that congenital cataracts or strabismus had to be corrected before the age of 6 if the patient was to achieve normal vision, but there was no investigation of the neural substrates for this finding. Such results, however, when compared to the kitten data suggested similar critical period effects to those found in the kittens.

Currently, research suggests that there are many sensitive periods for human development which have very direct impact on educational practice. Tamis-LeMinda and Bornstein (1987) review evidence that there are many sensitive periods in human development in which appropriate experiences must be provided in order for optimal cognitive development to be achieved. Early in the child's life, a variety of toys and an environment without physical restrictions have been shown to correlate with higher scores on intelligence tests. Later, verbal interaction at an appropriate level predicts scores on intelligence tests. It also commonly accepted that there are critical periods for the learning of both first and second languages (Johnson, 1989; Westphal, 1989), although there is some disagreement (Snow, 1987).

Since there is good evidence for sensitive periods in human cognitive abilities and language acquisition we can ask if there might be similar periods for mathematics learning. At present there is no direct evidence. Our own work, however, suggests that there may be a critical period for learning to use imagery in mathematical problem solving. One student we interviewed in fifth grade had been exposed to a purely computational background. During the course of our interviews and classroom observations she showed very little use of imagery or ability to make use of pictorial information. Even after extensive coaching by her classroom teacher and during the interviews she made little progress during the school year (Brown & Wheatley,. Other students, when, exposed to situations where they are encouraged to use imagery in second and third grades do so with great facility. Although such results are tentative they suggest grounds for further research.

<u>**New Techniques in the study of Brain Function**</u>

For decades evidence has been mounting that areas of the brain are specialized for certain cognitive functioning. In the 1970s, evidence from EEG studies showed that the right parietal lobe of the cortex was most involved in the processing of spatial activities while the left temporal was active for linguistic tasks. (Harris, 1975; Wheatley, Frankland, Mitchell, and Kraft, 1978; Whitelson, 1976; Willis, Wheatley, and Mitchell, 1979). While EEG analysis has been useful in understanding the nature of brain activity in humans, better techniques are now available and promise to give us a much better picture of the way the brain functions when performing cognitive tasks, for example, cerebral blood flow measures (SPECT and PET) and MRI.

Prior to the late 1970s research into higher cortical function was extremely limited because the techniques available for its were not available. Anatomy could only be studied by post mortum autopsy. Electroencephalogram (EEG) was useful for studying brain activity in humans, but it is a very noisy technique and lacks spatial resolution. Microelectrode recording techniques were extremely useful in studying sensory function in animals. For many topics of interest to mathematics educators, however, no animal model exists.

Within the last few years several new techniques have been developed which have given brain research exciting new directions. These are referred to collectively as imaging techniques because visual study of the intact human brain. In some cases it is possible to examine the brain anatomically, but in others it is possible to compose pictures of where in the brain neural activity is occurring. All of these new techniques were originally developed as diagnostic tools, but their usefulness in the study of cognitive functioning is quickly being recognized. None is truly nonenvasive, they all require large amounts of equipment and can only be done in laboratory situations, but they are still highly useful in understanding the brain and its functions. Below is a brief description of some of these and what types of data can be obtained.

At present none of these techniques provide direct access to detailed brain activity. Each has limitations, but they represent significant advances that allow the study of topics of interest to mathematics educators. One such topic, of particular interest to us, is the construction and transformation of images in mathematical activity. In the section below we discuss some results available in the literature.

Computerized tomography (CT). This was the first of the imaging techniques to be developed, having been in existence since the mid 1970s. X-ray photons are used in the scanning, but the procedure is quite different from conventional X-rays. It can be used to study the structure of the intact brain, although only in the transverse plane. CT is basically anatomical technique and cannot be used to study function. CT allows for good visualization of soft tissue and the ventricular system. It can also differentiate between gray and white matter, cerebrospinal fluid, and air. It is still used widely as a diagnostic technique for persons suspected as having conditions which produce structural abnormalities such as stroke. It is less expensive than many other procedures, but its usefulness in research is limited (Andreasen, 1988).

Magnetic resonance imaging (MRI). MRI can also be used to study the structure of the brain, but it has many advantages over CT. It can be used to image the brain in all planes, so it is possible to construct three dimensional images of the brain. It also has very high resolution and can distinguish features as small as 1.0 mm apart. It is most useful in research when the precise location and extent of a lesion need to be known (Andreasen, 1988).

It is easy to see, then, how CT and MRI can be used to study cognitive function in patients who have suffered some form of brain damage. Using either of these two techniques the extent and exact location of the lesion can be pinpointed. It is then possible to give the patient cognitive tasks and study any possible behavioral deficits. Both CT and MRI provide static pictures of the anatomy of the brain, however. Their main advantage is that they can be used with humans who are alive. Several new techniques, however, can provide a much more dynamic picture of the function and activity of the brain.

Positron emission tomography (PET). This is probably the most elegant of the currently available imaging techniques. PET measures the location of blood flow in the brain, and hence is able to indicate areas of increased activity. Its potentials for use in the study of brain function are very exciting. It has, however, several very serious limitations at present. First, it requires the use of radioactive isotopes in the blood stream of the subject. Although this is frightening to some people the isotopes used have a very short half-life (on the order of a few minutes) so there is minimal risk of long-term radiation ill effects. Second, cerebral blood flow is a very noisy measure of brain activity so records must be signal averaged in order to indicate areas of increased activity. This means the subject must be engaged in a single cognitive response pattern for a period of a few minutes and resolution is still not very high (about 4-7 mm). Finally, the technique is very elaborate, requiring large amounts of equipment and technical support so it is expensive and not available to many researchers (Kosslyn, 1994).

Single-photon emission computerized tomography (SPECT). In some ways SPECT is very similar to PET in that it measures cerebral blood flow and hence brain activity. Its resolution, however, is not nearly as good. Its advantages are that it requires far less equipment and technical support than PET and consequently it far more available to researchers. As a research technique it has been used as a compliment to PET, allowing the screening and pilot studies before the actual PET investigation is begun (Andreasen, 1988; Kosslyn, 1994).

Functional magnetic resonance imaging (fMRI). This is the newest brain imaging technique available and so far few studies have been published using it. It allows the researcher to see in what parts of the brain additional oxygen has been transported. Since it is a magnetic resonance technique it does not require the use of radioneucleotides. It has good spatial and temporal resolution and is readily available and inexpensive (Kosslyn, 1994).

Summary

The mind with which we think is a construction of itself. "Due to the closure of our cognitive domain, we find ourselves merged in the circularity of a world constructed by us in which we are included. It means that our structure evolves in a process of relations with its own production in the attempt at maintaining itself" (Chiari and Nuzzo, 1988, p. 92-93). Overwhelming evidence suggests that learning involves both anatomical and physiological changes in the brain (Pribram, 1994). As a learner becomes perturbed and resolves a perturbation by schema reorganization, there is a change in the neural pathways and regional activation sequences - new synaptic pathways form.

Some models of learning rely heavily on a computer metaphor, assuming a hard-wired system which processes inputs and generates outputs. Such a model of brain functioning does not fit the data well. On the other hand, to assume that the brain is a dynamic system with changes at the physiological level fits well with an epistemology which posits that the brain is constantly modifying itself through its self-initiated activity. Instruction which relies heavily on explanation and practice seems incompatible with the dominant model of neural activity reviewed in this paper.

The early emphasis on imposed computational procedures such as borrowing in the subtraction of whole numbers could very well have debilitating effect on young minds; not unlike the effect of sewing shut an eye of a kitten. The kitten never learns to see from this eye when it is opened. In a similar manner, students who have not been encouraged to construct and transform mental images may lose the capacity to do so.

We think there are profound implications of the burgeoning research on brain functioning for constructing models of mathematics learning and that this research supports a constructivist approach to designing learning environments for school mathematics.

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