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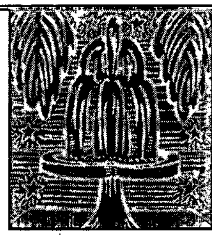

Brain and the Creative Act

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CA3 An easily distinguishable layer of cells, one of three that make up the hippocampal cortex.

Episodic Process that refers to episodes in one's own experience.

fMRI A technique of imaging body organs and tissues based on resonance with atomic nuclear oscillations.

Isomorphism Of the same shape.

Semantic Meanings that refer to objects and occurrences that can be pointed to.

Sinusoidal Wave A regular, unchanging waveform.

Synaptodendritic A connection web formed by the junctions among nerve cells.

As noted by Arthur Koestler, the pattern underlying the ***CREATIVE ACT*** *is the "perceiving of a situation or an idea in two self-consistent but habitually incompatible frames of reference. The event in which the two [frames] intersect, is made to vibrate simultaneously on two different wavelengths, as it were. [The event] is not merely linked to one associative context, but is 'bisociated' with two."*

I. INTRODUCTION

Creativity has several dimensions, only one of which will be discussed in this essay: the creative act that precipitates the creative process. As has been pointed out repeatedly, creativity is made up of 1% inspiration and 99% perspiration. Nor is reinventing the wheel a truly creative act. Part of the perspiration consists of preparing—pruning overgrowth by taking inventory of what has already been accomplished—before setting out to invent.

Koestler's poetic description of the creative act is intuitively appealing, but the job of science is to show "how" a process works. Psychological science devolves on showing how our experience comes about, and part of this demonstration centers on discovering (uncovering) the concomitant physiological processes that take place within the experiencing person.

Observations made in the clinic of persons who have sustained injuries to their brain have shown that these injuries can dramatically change the person's experience. The changes are verbally reported by the patients, and verbal tests can be devised to explore the extent and depth of the changes. Also, the changes are often expressed in nonverbal behavior and can be explored in the laboratory by carefully producing similar brain injuries in nonhuman subjects (for instance, in monkeys) and extensively studying the behavior of these subjects. Further, the anatomical connections and the electrical activity of the parts of the brain that were injured in the patients can be studied in the nonhuman subjects.

The current article will review highlights and insights of research on the hippocampal system (including e.g., the adjacent entorhinal, perirhinal, and cingulate cortices). The hippocampal system deals with recombinant processing of experience, or what Arthur Koestler called bisociation.

II. THE HIPPOCAMPAL SYSTEM

Much work has been done on the "loss of memory" with H.M., a patient whose hippocampus was removed as treatment for epilepsy and with patients with similar brain damage. Several important findings have emerged from these studies. First, under certain conditions, using probes such as parts of nonsense "words" that had to be recognized as having been encountered before, research showed that postoperative experience appears to be stored but is not ordinarily accessible to retrieval. Second, skills can be readily learned and remain accessible. Third, repeated experience that consistently refers to objects and occurrences can become stored and retrieved.

This last finding was dramatically confirmed in monkey experiments in which animals with their hippocampal system removed perfectly remembered, without rehearsal, for two years a problem they had been taught. Thus, the simple view that the hippocampal system is necessary for memory storage, which is so often found in writings about this system, is no more tenable than the view that it is the seat of emotions.

III. THE TYPES OF REMEMBERING

Independent of these brain-related studies, Endel Tulving, on the basis of studies with human subjects, was able to divide memory processing, remembering, into three fundamental classes: semantic, skill, and episodic. Semantic processing deals with reference to—the meanings of—identifiable objects and occurrences (access to a stored dictionary). The processing of skills devolves on being able to successfully manipulate one's environment. Episodic processing is the ability to more or less accurately remember episodes of events that have personal meaning and relevance.

This classification is tailor-made for correlation with the findings on subjects with brain damage. Studies on monkeys and humans had shown that carefully made removals of portions of the posterior convexity of the brain cortex, the sensory-specific "association" cortex, impairs referential processing. (The term "semantic" is ordinarily restricted to referential language abilities which are deficient in monkeys.) The role of the cortical areas surrounding the central fissure of the cortex in processing skills is well documented, and the findings on subjects with damage to the hippocampal system already described indicate that this system is involved in episodic processing.

Recent findings on children born with hippocampal damage have shown that skills and semantic processing can develop without impairment despite a totally defective episodic processing ability. (This independence of development is also true of the skill vs. semantic processing systems.) Of course, this does not mean that the three processing systems do not ordinarily interact. In fact, their interaction lies at the root of creativity.

Before detailing a model of creative interaction, we need to understand more fully what episodic memory processing entails. In the experiments with monkeys, the tasks on which subjects with hippocampal system damage are impaired are composed of ever-changing trials. Nonetheless there are recurrent regularities that make it possible to solve the tasks. For instance, reward may be dependent on always choosing a cue that had been seen just previously, or conversely choosing a cue different from the previously presented sample. A sample is not necessary, however. The task may involve going to a location other than the one that had been rewarded on a previous trial. To solve such tasks the monkey has to develop strategies such as "win–stay" or "win–shift."

The development of strategies (as opposed to tactics, which entail the development of skills) entails the use of what have been called cognitive maps. The results of animal research on the behavioral functions of the hippocampal system can thus be understood in terms of its role in the development of strategies utilizing cognitive maps. The maps form the context within which skills are carried out and within which referential (semantic) meaning becomes relevant to a more encompassing scenario.

For humans, this strategic context is composed of episodes, components that, together with other episodes, form a scenario or personal narrative. Though the hippocampal system is essential to the utilization of episodes, their construction involves other brain systems such as those centered on the amygdala, whose activity is essential to marking the beginning and end of an episode, and the anterior frontal cortex, which determines the occasions, and relationships among occasions, where and when utilization becomes effective.

IV. A MODEL OF THE NEUROPHYSIOLOGY OF CREATIVITY

So far, I have reviewed evidence regarding the development of a single strategy, the mapping of a single cognitive context within which experience is experienced and behavior is deployed. But what of creativity, the bisociation of contexts by an experienced event?

An ensemble of comprehensive contexts can become stabilized under conditions in which probabilities play a minor role. These conditions provide simple recurrent regularities, as, for example, those that often characterize physiological states such as hunger and thirst. In these instances the stabilities define steady (homeostatic) states at equilibrium. When, however, probabilities play a significant role, stabilities occur far from equilibrium. Such stabilities are subject to destabilizing influences. When stabilities far from equilibrium become perturbed, they provide the ground for creative innovation.

Research with monkeys has shown that probabilistic strategies fail to be undertaken in instrumental conditioning situations after removal of the anterior frontal cortex (and in classical conditioning situations after removal of the amygdala system). When these systems are intact, probabilistic strategies are the rule; as noted, stabilities far from equilibrium are vulnerable to perturbation. This vulnerability was shown to have the advantage that when the parameters of the conditioning situation change, the monkeys with intact brains readily adjust their behavior to the change whereas the monkeys who had been subjected to the brain resections were stuck in their behavior patterns and thus failed to adjust to the new circumstances.

Appendix C of Karl Pibram's *Brain and Perception* develops a mathematical definition of context. Two types of context are distinguished: local and comprehensive. Local contexts constitute reference frames for objects and occurrences. Comprehensive contexts are those that provide the boundaries to an experienced episode. It is these contexts that are involved in bisociation. Their development is necessary for experiences to become familiar and/or innovative. A mathematical geometry—a mathematical map—describing comprehensive contexts is presented in terms of vector spaces (vectors are lines that have length and direction).

Neurophysiologically the vectors represent the amplitude and phase of oscillations of electrochemical polarizations in the synaptodendritic processing web of the hippocampal cortex. The length of the vector indicates the amplitude of oscillation, and its direction the phase—the coherence with respect to other oscillations. The evidence on which this model is based and the manner of its operation are presented in the appendix to this article.

Appendix F of *Brain and Perception* demonstrates an additional value that accrues to probabilistic strategies. When the comprehensive contexts that map individual strategies become perturbed, the critical vectors that specify each context are no longer aligned within the map but come to point along many independent directions. Neurophysiologically, this is indicated by desynchronization of hippocampal electrochemical activity. Desynchronization allows novel associations to occur in which several independent contexts can be associated on the basis of the amount of alignment of their vectors, that is, of the alignment of phases of electrochemical oscillations. Again, the evidence on which this model is based and the manner of its operation are described in the Appendix.

V. THE ACT OF CREATION

In humans, perturbation is produced when different comprehensive contexts become equiprobable. The buildup during the telling of jokes prior to the punch line, the enhancement of suspense in a play or narrative, and the frustration accompanying an unsolved problem all provide such an increase.

In science, the creative act often employs the use of metaphor, analogy, and model building. Such activity was called "abduction" by Charles Sanders Peirce, who contrasted it with induction and deduction. In fact, Peirce indicates that abduction consists of the inspiration that produces the creative act. He relegates induction and deduction to perspiration: induction consists of preparatory activity while deduction brings the creative act to consummation. The search for the neurophysiological "how" of creativity has tracked Peirce's insights: The holographic metaphor has given rise to parallel distributed processing (PDP) models that inductively summarize current data. A critical point of issue has arisen deductively: Is the model to remain solely probabilistic or is a holographic-like process actually involved? The Appendix details this issue. [*See* ANALOGIES; ENSEMBLE OF METAPHOR; METAPHORS.]

VI. APPENDIX

The model of creativity (innovation) developed in *Brain and Perception* and in subsequent essays proposes that sensory input is relayed to the hippocampal–parahippocampal system and simultaneously to the sensory-specific "association" systems of the neocortical isocortex. When a match exists between the patterns elicited in hippocampal and neocortical systems, the input is considered "familiar" and the matching activity ceases. When, on the other hand, a mismatch exists, the input is considered "novel" and the matching operation continues interactively until the neocortical pattern has been modified sufficiently to produce a match. J. L. McClelland, in collaboration with D. E. Rummelhart and Bruce MacNaughten, has developed a simulation of this matching process using parallel distributed processing programming architectures. This simulation relies on statistical (that is, probabilistic) relations among neuronal firing patterns and does not directly entail the relations among phases of oscillatory activity within the synaptodendritic processing web of hippocampal layers. I propose in the following exchange that *both* the probabilistic and a holographic-like phase encoding are involved, and that the phase encoding takes place as a synaptodendritic microprocess while the probabilistic process is macroscopic, involving internal hippocampal circuitry.

The argument runs as follows: McClelland presents a precise model of how hippocampal intervention—which is present whenever a stimulus is novel to the organism—can lead to dysfunction (catastrophic interference) as well as to creative innovation. However, McClelland also shows how a hippocampal input to the cortex can, at other times, lead to learning. According to McClelland, nonlimbic learning is slow and is produced "via interleaved presentation on a representative sample of an entire domain of knowledge."

Learning can also occur in the absence of the hippocampal formation. Could this be due to a difference in brain organization between rodent and primate, such as the massive increase in the area of the frontal cortex? Animals with more complex nervous systems actually learned more slowly than animals with simpler nervous systems but that the range of what can be learned increases with an increase in brain complexity. McClelland's model shows precisely how an increase in the complexity of the brain can accomplish this enhanced range.

As an addition to the overall model presented by McClelland, there are elaborations of its neurological underpinnings that can fill out the particulars of the "how."

McClelland and colleague's model directly matches hippocampal activity with the activity of the cortical convexity (as would be expected of a comparator). On the input side such a model is plausible. However, their model also demands such a comparator process on the output side. This is implausible in view of results obtained by Paul MacLean and Karl Pribram when mapping cortical connectivity by strychnine neuronography. While they were able to readily show multiple inputs to the hippocampal formation, they were totally unable to activate *any* isocortical region by stimulating the hippocampal cortex. The finding was so striking that MacLean developed the theme of a schizophysiology of cortical function.

On the other hand outputs from the hippocampal system are plentiful to the amygdala, to the nucleus accumbens septi, and to other subcortical structures via the fornix. Confirmation of the difference between input (encoding) and output (decoding) operations involving the hippocampal formation has recently come from studies in humans using *f*MRI. Encoding into memory was found to activate the parahippocampal cortex (including the entorhinal and perirhinal cortex, which receives input from the remainder of the isocortex), whereas decoding (retrieval) was found to activate the subiculum, which provides the major *subcortical* output of the hippocampal region via the fornix.

The subcortical nuclei do not have the laminar structure of the cortex and so are poor candidates for the type of point to point match we might ordinarily conceive. On the other hand, a match could readily be achieved if the comparison would involve a stage during which processing entailed a distributed stage. Such a stage is present in McClelland's model and when a holographic memory is used to store and retrieve information. It is the evidence that a distributed store is, in fact, built up in the hippocampal formation during learning that makes this sort of model plausible. Philip Landfield and John O'Keefe have developed this sort of model.

Both McClelland and Pribram agree on the distributed nature of the hippocampal process. However, McLelland states his argument in probabilistic terms, while Pribram states his holographically. McClelland has the advantage that the intervention of anterior frontal processing (probably by way of the cingulate cortex) can readily alter the probability structure envisioned by McClelland. At the circuit level of processing Pribram supports his model.

Nonetheless, at the level of processing at the level of the synaptodendritic web, the level that *generates* oscillations such as the theta rhythms, holographic-like interference patterns—that is, phase encoding—is possible. In support of such a possibility, a researcher at the University of Southern California (personal communication) had the following experience: From microelectrode data, he had modeled in hardware, using parallel distributed architecture, the processes going on in CA1 and CA3. He then tried to connect the two processors and ran into an incredible mass of wires, where tracing connections proved all but impossible. As a result he gave up this approach and substituted an optical system to make the connections. Now there is a small box labeled "hologram" that makes the connections almost instantaneously. What needs to be done now is to test whether indeed phase encoding exists in the hippocampal cortex.

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