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Abstract

Emotion is defined as a property of intentional behavior. The widespread practice of separating emotion from reason is traced to an ancient distinction between passive perception, which is driven by sensory information from the environment, and active perception, which begins with dynamics in the brain that moves the body into the environment in search of stimuli. The neurodynamics of intentional behavior is reviewed, with emphasis on the limbic system that controls the autonomic and neuroendocrine systems in the brain and body, directing them for the support of the musculoskeletal system that is executing the behavior. An essential part of intentionality is learning from the sensory consequences of one's own actions. The perception of emotional states through awareness involves global states of cooperative activity in the forebrain, which have internal contributions from the many parts of the brain that join in making these states, and inevitably there are contributions from the sensory systems of the body that implement and signal emotional states. The distinction between "rational" versus "emotional" behaviors is made in terms of the constraint of high-intensity chaotic activity of components of the forebrain by the cooperative dynamics of consciousness versus the escape of subsystems owing to an excess of chaotic fluctuations in states of strong arousal.

Introduction

The problem of understanding emotion has emerged as one of the major challenges for the social, psychological, and psychiatric disciplines. The root of the problem goes very deeply into the history of Western science and philosophy, whence came the primary assumptions that people of European origin use to explain the nature of mind, and how the mind relates to the body and to the world through learning. A singular clue to the form of one of these assumptions is provided by the distinction often made between emotion and reason. This is a "common sense" notion used to explain the motives of observed behaviors. Motives are reasons that explain the actions we witness with respect to the state of mind of the perpetrators. In this philosophical interpretation, actions stem either from reasoned judgments of available options in the light of self interest or the greater good, or they are based in an internal force that is out of conscious control and beyond rational choice - blind emotion.

An alternative view, one that I will elaborate here, holds that because this dichotomy treats emotion as bad and reason as good, it fails to recognize them as properties of a larger whole. All actions are emotional, and at the same time they have their reasons and explanations. This is the nature of intentional behavior. I will begin with a historical review of the philosophical grounds in which this dichotomy arose and will follow that review with a description of brain function in the genesis of intention through the nonlinear dynamics of neural populations. I will conclude with some remarks on the interrelation of consciousness and emotion, in an attempt to recast the distinction between rational and emotional people in the light of neurodynamics.

Plato, Aristotle, and Aquinas

A major cleavage that fuels debates on the nature of mind derives the ancient Greeks: Is perception active or passive? According to Plato it was passive. He drew a distinction between intellect and sense, both being immaterial and belonging to the soul. The intellect was born with ideal forms of objects in the world, and the senses presented imperfect copies of those forms. For each object the intellect sought the corresponding subjective ideal form through the exercise of reason. Thus the experiences from the world of objects and events were passively impressed onto the senses. According to Aristotle it was active. There were no ideal forms in the mind. The organism moved in accordance with its biological destiny, which was initiated by the Prime Mover (God). The actions of the intellect were to define and seek objects with its sensorimotor power, and with its cogitative power to construct forms of them by abstraction and induction from the examples that were presented by the senses. The forms of mental contents from stimuli were inscribed by the intellect with its mnemonic power onto an initially blank slate, the "tabula rasa". Emotion was treated in both systems as an aspect of the animality of man, the rational animal, which was a residue of corporeality that was to be subjugated by reason.

In the early Middle Ages the Platonic view was dominant through the work of St. Augustine. In the 13 Century St. Thomas Aquinas transformed the Aristotelian view of biological destiny to intention ("stretching forth") by distinguishing the Christian will from largely unconscious striving, and by conceiving the imagination ("phantasia") as the source of the endogenous forms of percept ion. He had this to say in his "Summa Theologica" (Aquinas, 1272) about the nature of intentionality, as he defined it to include other animals as well as man:

Q12 Of Intention

> "A1: Whether intention is an act of the intellect or of the will? Intention, as the very word denotes, means to tend to something. Now both the action of the mover and the movement of the thing moved tend to something. But that the movement of the thing moved tends to anything is due to the action of the mover. Consequently intention belongs first and principally to that which moves to the end; hence we say that an architect or anyone who is in authority, by his command moves others to that which he intends. Now the will moves all the other powers of the soul to the end. Therefore it is evident that intention, properly speaking, is an act of the will ... in regard to the end. Now the will stands in a threefold relation to the end. First, absolutely,. And in this way we have volition, whereby we will absolutely to have health and so forth. Secondly, it considers the end, as its place of rest. And in this way enjoyment regards the end. Thirdly, it considers the end as the term towards which something is ordered; and thus intention regards the end. For when we speak of intending to have health, we mean not only that we will to have it, but that we will to have it by means of something else."

> "A4: Whether intention of the end is the same act as the volition of the means? Accordingly, in so far as the movement of the will is to the means, as ordered to the end, it is called choice; but the movement of the will to the end as acquired by the means, is called intention. A sign of this is that we can have intention of the end without having determined the means which are the object of choice."

This distinction between will or volition based in choice (for which we might now read "consciousness") and intent (which may or may not be conscious) was rapidly and wholeheartedly adopted by the Western European community, and it had far-reaching consequences for the growth of middle class morality and the belief in the capability of individuals to accept responsibility and take action to change things in the world that needed changing. In my opinion the growth of science and technology through the later Middle Ages in large part stemmed from that liberation and its philosophical justification of individual freedom. However, emotions were not given the status assigned to will nor clearly distinguished from intent. Consciousness is a modern concept for which no real equivalent exists in ancient or medieval world views, and emotions appear to be best translated as the "passions" of the soul, in reference to suffering from external forces foreign to one's true nature.

During the Renaissance Western thought returned to Plato largely through the work of Descartes, who conceived a revolutionary approach of describing the world and the mind in terms of linear algebra and geometry, without place for the faculty of imagination. In his view the animal machine in man was guided by the soul as its "pilot", who sought knowledge through reasoning about the passive imprints of sensations, in order to come to absolute mathematical truth. Fantasy, intention, and emotion were dismissed along with imagination as being non mathematical and therefore unscientific. The origin of "passions" coming from outside one's true nature was left unexplained.

In the postmodern era Descartes' pilot has been fired. The reasons usually given are either that the soul does not exist, or that the concept doesn't explain anything, or that the soul is a matter of personal belief, not a scientific principle. In philosophy intentionality was reinstated in modified form by Franz Brentano (1889) to signify the relations between representations in the mind and objects in the world, ant thereby to distinguish humans from machines. In the medical and biological sciences, explanations of the mind are sought in terms of the functions of the body through studies in behavior, and by analysis of the brain through chemistry and imaging. Emotions have become matters of central concern, particularly in the context of the affective disorders, where the tendency has been to see them as determined by the machinery of the brain, and most recently by the family of neurohormones in the brain stem, but not in relation to volition or intention.

There is another and less easily grasped reason for the decline of confidence in the Cartesian pilot. For the past three centuries the functions of mind and brain have been described in terms of the linear dynamics of Newton and Leibniz, which was enabled by the Cartesian revolution in mathematics. The passive model of perception is entirely appropriate for linear causality, in terms of conditioned and unconditioned reflexes, neural networks, and the chemistry of neuromodulators, because brain structures and operations are seen as determined by genes, developmental processes, and the environment. Perception is thought to work through the imprint of objects and events from the environment, which is called information processing. Mental contents are seen as formed by neural connections that are determined by genes, and modified by learning from stimuli, particularly during critical periods of growth. Representations of objects and events are stored in memory banks as ideal forms, each having attached to it a label as to its value for the organism, and they are used to classify new inputs by retrieval, crosscorrelation, template matching, error reduction, modification of wiring in neural networks by Hebbian synapses, and assignment of value by passage through the emotional generators of the brain in the basal ganglia and brain stem. Questions of how the brain can *a priori* create its own goals and then find the appropriate search images in its memory banks are not well handled. The loss of the Cartesian pilot has left a large gap in the theory, because no one wants a homunculus, but cognitivists have no replacement.

In the first half of the 20th century some pragmatists, existentialists and Gestaltists broke from the Platonic tradition by incorporating concepts of the source of value in action (Dewey, 1914), the importance of pre-existing goals and expectations (Merleau-Ponty, 1945), and the role of affordances in governing perceptions (Gibson, 1979). Merleau-Ponty drew heavily on the clinical neurology of his epoch to reintroduce intentionality in its Thomist sense, as the outward "tending" of brain activity with sensory consequences that completed what he called the "intentional arc". Despite the strong neural basis of these concepts, most neuroscientists have failed to respond to or accommodate them, in part because of their complexity, but in larger part because of the lack of a coherent theory of the deep origin of goal-structures in brains of animals and humans.

However, in the second half of this century a sharp break in the mathematical, physical and chemical sciences has occurred with the development of nonlinear dynamics, which was made possible by the emergence of computer technology. Recognition of "dissipative structures" by Prigogine (1980), of "macroscopic order parameters" by Haken (1983), and of "positive entropic information flows" by various authors writing on self-organization in chaotic systems has opened new avenues to pursue the age-old question: "How do goals and their derivative values and expectancies arise in brains?" Proposed new answers are expressed in terms of "circular causality" in philosophy (Cartwright, 1989), psychology (Rosch, 1994) and physics (Haken, 1983), which is a convenient term to address the intrinsic indeterminacy of feedback, by which the components of a system can in large part determine their own behavior. The theory of chaos and nonlinear dynamics, when applied to the functions of brains, can answer the fundamental mystery faced by the concept of intent, by showing how goals, their attendant values, and the creative actions by which they are pursued can arise in brains. Every intentional act is preceded by the formation of its character prior to its execution. And if perception is active, then things that are perceived in the body and the world must in an important sense pre-exist in the sensory cortices as the predicted consequences of acts of searching.

Emotion as the anticipation of intentional action

Intentional action begins with the emergent construction within the brain of goals comprising its possible future states, which will require that actions be directed by the brain in order that those futures be realized. The departure from a state of calm rest without anticipation is aptly named: e(x)motion ("ex" = "outward"). An emotional state need not be revealed in immediate overt actions, but it certainly implies the high probability of actions that will soon be directed outward from an individual into the world. Such states are easily recognized and explained as intentional in many situations, but in others they seem to boil up spontaneously and illogically within an individual in defiance of intent. The behaviors may be in apparent contradiction to sensory triggers that seem trivial, contrary, or insufficient to account for the intensity of actions. Yet they may have an internal logic that comes to light only after probing into and reflecting on the history of the individual. Philosophers refer to such actions as "incontinent" (Davidson, 1980).

A way of making sense of emotion is to identify it with the intention to act in the near future, and then to note increasing levels of the complexity of contextualization. Most basically, emotion is outward movement. It is the "stretching forth" of intentionality, which is seen in primitive animals preparing to attack in order to gain food, territory, resources to reproduce, or to find shelter and escape impending harm (Panksepp, 1998). The key characteristic is that the action wells up from within the organism. It is not a reflex. It is directed toward some future state, which is being determined by the organism in conjunction with its perceptions of its evolving condition and its history. This primitive form of emotion is called "motivation" or "drive" by behaviorists. These are bad choices of terms, because they confuse intention, which is action that is to be taken, with biological imperatives such as the need for food and water, which are the reasons and explanations for the actions. Behaviorists (passivists) treat behaviors as fixed action patterns released by stimuli from the environment, and they cannot explain phenomena such as curiosity, self-improvement, and self-sacrifice. Their terms are also commonly conflated with arousal, which is a nonspecific increase in the sensitivity of the nervous system, that need not be locked into any incipient action. In other words, the concepts of motivation and drive lack the two key properties of emotion, which are endogenous origin and intentionality, and I propose to avoid using them.

At a more physiological level, emotion includes the behavioral expression of internal states of the brain. The behaviors that are directed through interactions with the world toward the future state of an organism predictably require adaptations of the body to support the intentional motor activity. These preparations consist of taking an appropriate postural stance with the musculoskeletal system, and mobilizing the metabolic support systems. The latter include the cardiovascular, respiratory, and endocrine systems, that will be called upon to supply oxygen and nutrients to the muscles, to remove the waste products of energy expenditure, and to facilitate oxidative catabolism. It is the directedness of these preparations in the positioning of the body, the heightening of respiration, the twitching of the tail, and so on, that reveal to observers the emergence of the likelihood of approach, attack or escape.

Among social animals that live in packs and tribes, these preparatory changes in the body of an organism have become, through evolutionary adaptation, external representations of internal states of meaning and expected action. The display of panting, pawing, stomping the ground, erecting the hair or sexual organs, or moving the face or limbs can serve as signals from each organism to others in its surround (Darwin, 1872). For that to occur a basis must have been formed by previous shared experience, which requires prior intentional learning for coordinated behaviors among the members of that society. This aspect of emotion is called social communication.

At a more complex level, emotions are experiences. They are the feelings that accompany the emergent actions that address the anticipated futures of gain or loss in one's attachments to others, one's livelihood and safety, and the perceived possibility or impossibility of changing the world to one's liking or advantage: joy, grief, fear, rage, hope and despair. Though we associate them with objects in the world, these feelings, which philosophers call qualia, are internally derived and do not belong to those objects, such as the sweetness of fruit, the repugnance of carrion, the inviting softness of velvet, and so on.

The mechanisms of these feelings remain in dispute. The physiologist Walter Cannon, in the passivist-materialist tradition, identified them with the activity of neurons in the head ganglion of the autonomic nervous system, which is in the hypothalamus. The psychologist William James (1890), in the activist-pragmatist tradition, proposed that the feelings were sensed after the fact, so to speak, through the changes in the body that were made by the activity of the autonomic nervous system, such as the sinking of the stomach, which is known to occur in states of fear, the bristling of hairs in the skin, the pounding of the pulse, the flushing of the face, and so on. Physiologists view these feelings as epiphenomena. Pragmatists see them as integral parts of the ongoing interaction between one's self and one's social environment. Through these bodily processes one becomes aware of one's emotional state, and, through those signals, one's friends can typically become aware of that state at the same time as one's self. The perception of one's own action and state, and of the states and actions of one's friends, shapes the basis for one's own next action. It is neither necessary nor feasible to separate the expression of autonomic states and one's perceptions of them in the intentional loop. They evolve as an organic whole.

The perception of feelings requires the process of awareness. Behavior without awareness is called automatic, instinctive, unthinking, and implicitly cognitive. Acting in accustomed roles, engaging in highly practiced sports routine, and driving a car are examples. Are they emotional? Competitive sports and dramatic performances are obviously so. Evidence that driving a car is intensely emotional is found in the frenzy of concern that a fuel shortage causes, and in the lavish care that many owners give their machines, even in priority over their families. A behavioral action cannot be distinguished as rational or emotional by judging whether the actor is or is not aware of his or her behavioral state and action.

The most complex level of emotion involves social evaluation and assignment of responsibility for actions taken. In the classical Platonic view, in which reason is apposed to emotion, actions that conform to social standards of considerate, productive behavior are said to be rational. Actions that appear to lack the prior logical analysis called premeditation, and that bring unwanted damage to one's self and others in one's community, are said to be emotional. Yet both kinds of actions are emotional and intentional, in that both emerge from within the individual and are directed to short- or long-term goals. They clearly differ from one another. The biological basis for that difference lies in the self-organizing properties of brains through which actions are constrained or deferred by a global self-organizing process. We experience that neurodynamic process through being aware or conscious. But consciousness does not generate emotion. It has much more to do with the control of emotion, and in that respect is closely akin to its predecessor, conscience ("knowing together").

Understanding emotion at all of these levels depends on an answer to this prior question. How do intentional behaviors, all of which are emotive, whether or not they are conscious, emerge through the self-organization of neural activity in even the most primitive brains?

The architecture of stimulus-response determinism

Most people know the appearance of the human brain, because it has so often been displayed in popular publications, owing to widespread interest in brain imaging during normal human behavior. This knowledge can serve to highlight the differences in emphasis between the passivist-materialist-cognitivist view of the brain as an input-dependent processor of information and representations (Figure 1), and the activist-existentialist-pragmatist view of the brain as a semi-autonomous generator of goal-directed behavior (Figure 2).

In the materialist and cognitive conceptions, the starting point for analysis is assigned to the sensory receptors, either in the skin (as shown by the *), eyes, ears or other portal at which information from the world is transduced from energy to action potentials. Bundles of axons serve as channels to carry the information to the brain stem, where it is processed through nuclear relays and converged into the thalamus (upward arrows), which is a central sensory clearinghouse at the top of the brain stem. The information is already subdivided by the receptors in respect to its features, such as color, motion, tonal modulation, and so on. The thalamus sorts it for transmission to small areas within each of the primary sensory cortices, which are specialized to deal with their designated kinds of information. Most of the channels have some degree of topographic order, so that the information is said to be mapped from the sensory arrays into each of the small cortical areas.

Within the thalamus, each relay nucleus inhibits the other nuclei. This is called competitive inhibition. The nucleus that is most strongly excited is said to suppress the others around it. These others, being inhibited, fail to inhibit the excited nucleus, so it is sure to fire. This process is also called winner-take-all. It is thought to select information for transmission to the cortex in the process of selective attention. The hinge that squeaks the loudest gets the oil.

The sensory input is believed to excite receptor neurons, whose pulses represent the primitive elements of sensation that are called features. These representations of features are combined into representations of objects, when they are transmitted from the primary sensory cortices to adjacent association areas. For example, the integration of lines and colors might image a face, a set of phonemes might form a sentence, and a sequence of joint angles and tissue pressures might represent a gesture. The representations of objects are thought to be transmitted from the association cortices to the frontal lobes, where objects are assembled into concepts, and meanings and value are attached to them.

The architecture of the motor systems is similar to that of the sensory systems in respect to topographic mapping, both in the cerebral cortex and in the cerebellar cortex. Working backward from the muscles along the downward arrows in Figure 1, the final central relay in the outgoing channels is provided by pools of motor neurons in the spinal cord and brain stem. These are driven by networks of neurons in the basal ganglia, which include a part of the thalamus. At the crest of the chain is the motor cortex in the frontal lobe, which maintains a topographic map of the musculoskeletal system. The motor cortex in turn is controlled by the premotor and supplementary motor areas that lie progressively more anteriorly. In this view the frontal lobes are the site of selection and organization of motor activity in accordance with the objective perception of sensory input. It is there that the rational information processing selects the appropriate motor commands that are to be issued through the motor cortex. Emotion is added to color the output commands by side channels that include the amygdaloid nucleus, which is well known for its involvement in emotional behavior. Studies initiated 60 years ago by Klüver and Bucy (1939) showed that bilateral amygdaloidectomy produced hyperorality and hypersexuality and reduced tendencies to violent behavior in monkeys. The findings led some neurosurgeons to apply the operation in humans to curb violent behavior in adults (Mark and Ervin, 1970) and to diminish hyperactivity in children (Narabayashi, 1972). Extensive experience was then accumulated on the effects of stimulation in humans (Eleftherion, 1972; Mark, Ervin and Sweet, 1972). This structure has recently been given emphasis by imaging studies of the emotion of fear. In fact, the amygdala is involved in the expression and experience of all emotions, but it is much more difficult to elicit and control love, anger, jealousy, contempt, pity, and so forth in subjects who are immobilized in the machinery that is required for functional brain imaging. Sex is problematic, because of the requirement that subjects not move, and the puritanical attitudes about masturbation in public.

The pathways indicated by the arrows in Figure 1 for the transmission of sensory information about objects and the motor commands sound complicated, but the interpretations are based on straight-forward engineering concepts. They are, in fact, models that are very well supported by experimental measurements of the pulse trains of neurons in response to well-designed stimulus configurations. However, these models lead to a number of unsolved problems. First, the thalamic winner-take-all mechanism fails to account for expectancy, in which attention is directed toward a stimulus that is not yet present. Second, the corticocortical pathways that link the primary sensory cortices to the frontal lobes are well documented, but no one knows how the features in the small specialized maps are combined to represent objects, or even how an object is defined. How are the elements, sometimes called "primitives" by cognitivists, combined to obtain a table and a chair rather than a chairtable? This is known as the binding problem (Hardcastle, 1994). It is unsolved. Third, the role of the limbic system is underplayed and misrepresented. It is known to be involved with, even required for, spatial navigation, the formation of explicit memories, and the coloring of motor responses with emotions. The neural mechanisms by which the limbic system performs these functions are bundled into "higher functions" that are to be analyzed after the problems of cognition have been solved. Fourth, olfaction does not fit within these architectures and is widely ignored.

The architecture of intentional action

In the activist-pragmatist view (Figure 2) the organization of the primary sensory and motor systems, which include the receptors, the muscles, and the dedicated areas of cortex, is accepted as outlined in the preceding section, but the starting point for analysis is assigned to the limbic system (*), not the sensory receptors. This is because perception is defined as a form of intentional action, not as a late stage of sensation. The consequences of this change in perspective include reassigning the pivotal roles of the thalamus and the frontal lobes to the limbic system.

In primitive vertebrates the limbic system comprises the entire forebrain, including naturally both cortical and subcortical structures as in all definitions of "limbic". The various goal-directed activities that these free-ranging animals sustain clearly support the assertion that these animals have limited forms of intentional action.. In the human brain the vast enlargement of the neocortical lobes makes it difficult to see that the primitive components have not only persisted, but have become enlarged. For example, topologically the hippocampus still occupies part of the surface of each cerebral hemisphere, but the folding and twisting of the hemisphere during its embryological growth relocates it, so it now seems buried deeply within the brain. Although it is only one part of a distributed system of modules comprising the limbic system, its central location and characteristic cellular architecture make it a useful focus for understanding limbic dynamics. In metaphorical terms, it is more like the hub of a wheel than the memory bank or central processor of a computer.

Whereas in the salamander and other primitive vertebrtes (Herrick, 1948) the hippocampus receives input directly from the primary sensory areas, in humans and other mammals there is a collection of intervening cortical areas which feed into the entorhinal cortex. These stages include the inferotemporal cortex receiving visual input, the cingulate gyrus receiving somatic and other parietal input, the superior temporal gyrus receiving auditory input, the insula receiving visceral input, and the orbital frontal region transmitting via the uncinate fasciculus. The entorhinal cortex is the main gateway to the hippocampus. It is also the main target for hippocampal output by way of the subiculum and parahippocampal gyrus, so the two modules constantly communicate between each other. They occupy the medial temporal lobe of each hemisphere, along with the amygdaloid nucleus, the orbital striatum, and the tail of the caudate nucleus.

The most remarkable feature of the entorhinal cortex is that it not only receives and combines input from all of the primary sensory areas in the cerebral hemisphere, and it sends its output back again to all of them, after its previous activity has been integrated over time in the hippocampus. This reciprocal interaction in mammalian brains is carried out through multiple synaptic relays to and from all sensory and motor areas of neocortex. Other pathways support direct interactions between pairs of these areas, but the most significant aspect of limbic architecture is the multisensory convergence and integration that underlies the assembly of multisensory Gestalts, mediates spatial orientation, and provides the basis for recall of explicit memories (Clark and Squire, 1998).

This architecture of the limbic system is schematized in Figure 3 as a set of nested loops. The loops have been simplified deliberately by lumping together many subsidiary components and lesser loops, in order to show the forest, not the trees. At the core is the spacetime loop, which represents the interaction of the hippocampus with the adjacent neocortex, mainly the entorhinal cortex. There are two outstanding properties of this spacetime loop. First, the hippocampus has been shown experimentally to be deeply involved in the orientation of behavior in space and in time. Cognitivists attribute these functions to "place cells" (Wilson and McNaughton, 1993). These are neurons that fire pulses whenever an animal orients itself in a particular place or direction in its field of action, so they are conceived to provide spatial information for navigation.

Cognitivists believe that the hippocampus maintains a cognitive map (Tolman, 1948) and a short term memory bank, which serve to represent the environment as a part of the world picture within each animal. Pragmatists hold that there is no representational "map" in the brain, but that the hippocampal neurons maintains an experience-dependent field of synapses among its neurons. This field continually shapes and revises the action patterns that form under the interactions of the limbic system with other modules in the brain, as the animal moves through its environment. Every intentional act takes place in space through time. The space is the personal realm in which the organism has moved in previous explorations and now continues to move toward its immediate goals. The time is the personal lapse that every movement in space requires, and that orders each sequence of past, present and expected states (Hendriks-Jansen, 1996; Tani, 1996). Intentional action cannot exist without this learned framework, but it is a dynamic operator, not a repository of facts or geometric forms.

We experience this kind of navigation in our first exposure to a new city, when we can get from a hotel to a bus station by rote but not by an optimal plan. Similarly there is no global abstraction by which a machine might know where it is and where it wants to go. Humans have the high level capability for expanding and elaborating the field of action by virtue of the frontal lobes, and we experience that as having foresight, but we cannot infer that road atlases or decision trees reside there or in the hippocampus, except in a metaphorical sense. The important point here is that perception is action that is directed through space and time, and the limbic system provides that organization of action with respect to the world.

The second salient property of this spacetime loop is that the neural populations within its modules have the same and similar kinds of interconnections and interactive dynamics as those in the primary sensory cortices. The EEGs generated by these structures have similar wave forms in time and space, and they show similar kinds of change with behavioral and brain states as do the sensory cortices. In the language of dynamics the populations comprising the spacetime loop construct and maintain an array of "attractors". What this means is that the limbic system has some preferred patterns of activity, which tend to recur like good or bad habits or thoughts. Each pattern is governed by an "attractor" with a "basin" of attraction, called that in analogy to a ball rolling to the bottom of a bowl to which it is "attracted". The basin is defined by the full range of conditions of the brain in which the pattern emerges. A collection of patterns is governed by an "attractor landscape", in analogy to a set of bowls, such that the limbic system can only be in one at a time, but it can jump from one bowl to another, hence from one attractor to another. Each jump is the occasion of an instability. That is, the brain is continually changing its state, because it is volatile and unstable. Again, there are some preferred pathways among the basins, which leads to the idea of a pathway or "trajectory", which supports a habitual pattern of thought and behavior. That emerges as a sequence of briefly stable patterns, each giving way to the next after its brief moment of life, coming to awareness as a chain of movements or a familiar train of thought.

Each attractor provides for a certain brain state, and the jump from one state to another is called a state transition. These states recur at a rate of 3-7 per second in the manner of a motion picture film. That is a characteristic frequency of hippocampal EEG called "theta activity", which is provided by neuron populations in the septal nuclei and regulated by the brain stem. The spatiotemporal patterns result from the self-organizing dynamics within the spacetime loop (Freeman, 1992). They are shaped and modulated by the feedback from the larger loops in which the spacetime loop is embedded, but the locus for the critical instabilities that shape the trajectory is located in this core of the limbic system. It is the organized and fruitful evolution of limbic patterns through chaotic instabilities that governs the flow of intentional action (Freeman, 1995).

The dynamics of the motor control loops

The bulk of entorhinal output goes either to the hippocampus or back to the sensory cortices, but some of it enters into the motor systems. Similarly the bulk of hippocampal output goes back to the entorhinal cortex, but some of it also goes directly downstream. These arrangements reflect a general principle of brain organization, that the larger fraction of the output of each module goes back directly or indirectly to the module from which it gets its input, and only a smaller fraction goes onward.

There are two main motor systems that receive and respond to limbic activity, and that feed back reports about their contributions. In the lateral side of each hemisphere in the forebrain a main target is the amygdaloid nucleus already mentioned. The downward component of its outflow is directed toward the motor nuclei in the brain stem and spinal cord (Figure 1) that control the musculoskeletal system through what is called the "lateral forebrain bundle". In the medial side of each hemisphere the main targets are the septum, accumbens nucleus and hypothalamus, with relays into the ventral tegmental area, all of which control the autonomic and neuroendocrine chemical and metabolic supports for the musculoskeletal system through what is called the "medial forebrain bundle". These autonomic and hormonal supports are involved in all emotional expressions, not only in the periphery where their effects are visible to everyone, but also inside the brain itself. The internal ascending pathways from the brain stem that diverge broadly through the cerebrum are well documented. A more recent development is a better understanding of how brain tissues use neurohormones to regulate their own blood supply. The consequences of the changes that these systems bring about in the function of the body cannot fail to alter the sensory input from the proprioceptor neurons in the muscles and the interoceptor neurons in the viscera, which operate concomitantly with the exteroceptor neurons in the eye, ear and skin, and continually influence the somatosensory areas of the forebrain, including the thalamus and cortex. Considering the rapidity with which an emotional state can emerge, such as a flash of anger, a knife-like fear, a surge of pity or jealousy, whether the trigger is the sight of a rival, the recollection of a missed appointment, an odor of smoke, or the embarrassing rumble of one's bowel at tea, the occasion is best understood as a global state transition involving all parts of the brain and body acting in concert. Of course, onsets can also be gradual. However, this description of the dynamics does not yet serve to distinguish between, for example, the quale experienced in aerobic exercise from the quale of hot pursuit. There is more to emotion than the limbic system.

What role does the motor cortex in the frontal lobe have in this schema? The limbic output goes from the amygdaloid nucleus into other parts of the basal ganglia, and from the hypothalamus into the thalamus. By these routes limbic control is broadly established in the frontal lobe, which is motor in two senses. In the narrow sense the primary motor cortex (Figure 1) controls the position of the limbs, and also of the head and eyes to optimize the sensory inflow in accordance with the goal-directed actions that are initiated in the limbic system. It does not initiate the actions nor formulate their intents.

In the broad sense the frontal lobe constructs and elaborates the predictions of future states and possible outcomes toward which intentional action is directed. In primitive animals there is little or no frontal cortex, and their intentional action is correspondingly impoverished. Even in cats and dogs, and in large-brained animals such as elephants and whales, the frontal lobe comprises only a small fraction of each hemisphere. These animals are short-sighted and have brief attention spans. The great apes presage the emergence of the dominance of the frontal lobes in humans. Two aspects are noteworthy. The dorsal and lateral areas of the frontal lobe are concerned with cognitive functions such as logic and reasoning in prediction. The medial and ventral areas are concerned with social skills and the capacity for deep interpersonal relationships. These contributions can be summarized as foresight and insight. The frontal lobe guides and elaborates intentional action but does not initiate it. In respect to emotion, it provides the operations that distinguish between pity and compassion, pride and arrogance, humility and obsequiousness, and so on in an incredible range of nuances of feelings and values. The tale has often been told, most recently by Damasio (1994) of the emotional impoverishment of Phineas Gage by damage to his frontal lobes.

A remarkable feature of the human brain is a fact that embodies the principle noted above of the dominance of feedback (recursion, re-entry, self-activation) in brain architecture. This is immediately apparent on inspection of the organization of neurons in all parts of the brain. Each neuron is embedded in a dense fabric of axons and dendrites, which is called "neuropil", in which its thousands of connections form. Most of the connections for each neuron are from others in its neighborhood, but about 10% come from distant structures. For example, the frontal lobes provide about 80% of the descending axons from the forebrain into the basal ganglia and brain stem, but only a small fraction reaches the motor nuclei. Virtually all of the output of the basal ganglia goes back to the cortex, either directly or through the thalamus. Virtually all of the output of the brain stem goes back to the cortex, through the thalamus or the cerebellum. These massive internal feedback pathways are crucial for learning, practice, rehearsal, and play in forming the detailed structure of experience, which is the history of the organism that provides the wholeness and richness of texture that is unique to each individual. This texture provides the unique quale of emotion in each of us, which is our inner experience of impending action. If the classes of such action are reduced to the dichotomy of approach versus avoidance, then the experience of feeling can be reduced to the bivalence of pleasure versus pain, but that simplification leaves out the options of deferring action, of declining to act, of weaseling around in search of angles, or perhaps of just seeking more information. Curiosity can inspire growing dread of what will be found. Who can stop before it is too late?

Undoubtedly these large, strongly interconnected populations have the capacity for self-organizing nonlinear dynamics, comparable to those of the primary sensory and limbic modules. They are active participants in shaping the complex behaviors in which humans excel, far beyond the capacities of even our closest relatives among the great apes. What is important in this context is the dynamics that we share with our closest and also our more distant relatives (Darwin, 1872). The essential insights we need to explain the dynamics are most likely to come from measurements of the limbic activities during normal behavior.

The neurohumoral dynamics of emotions

An essential part of the motor systems is found in the brain stem of all vertebrates, from the simplest to the most advanced. This a collection of nuclei with neurons that are specialized to secrete types of chemicals that are called neuromodulators. Whereas neurotransmitters are chemicals released at synapses that immediately excite or inhibit the postsynaptic neurons, the neuromodulators enhance or diminish the effectiveness of the synapses, typically without having immediate excitatory or inhibitory actions of their own, and typically effecting long-lasting changes in the strengths and durations of synaptic actions. The nuclei are arranged in pairs on both sides of the brain stem, extending from the hindbrain into the base of the forebrain, everywhere embedded in the core of the brain stem, the centrencephalic gray matter, the reticular formation (Magoun 1962).

These nuclei receive their input from many parts of the sensory and motor systems of the brain. Most important is the limbic input to these nuclei that modulates the emotion of intentional action. There are several dozen neuromodulators, which are grouped in two main classes based on their chemical structure: the neuroamines and the neuropeptides (Panksepp, 1998; Pert 1997). The axons of these modulatory neurons typically branch widely and infiltrate among neurons the neuropil without making terminal synapses. They secrete their chemicals that permeate throughout both cerebral hemispheres. Their actions are global, not local. This functional architecture is a major determinant of the unity of intentionality, because the entire forebrain is simultaneously affected by the action of each pair of nuclei. To some extent the differing nuclei interact by competitive inhibition, which may enhance winner-take-all capture of the forebrain by the nuclei.

The types of modulation include generalized arousal by histamine; sedation and the induction of sleep by serotonin; modulation of circadian rhythms by melatonin; the introduction of value by the reward hormone cholecystokinin, CCK; the relief of pain by the endorphins; the release of aggressive behavior by vasopressin; the enabling of the appearance of maternal behavior by oxytocin; and the facilitation of changes in synaptic gains with imprinting and learning by acetylcholine and norepinephrine (Gray, Freeman and Skinner, 1986), which is crucial fore updating intention in the light of the consequences of previous actions; and dopamine that is involved with control of energy level and of movement as in exploratory behavior and the initiation of new projects (Panksepp, 1998).

The changes in synaptic strengths with learning, as mediated by neurohormones, are not restricted to a particular sensory modality or motor system, where a particular conditioned stimulus (CS) evokes a particular conditioned response (CR). In conformance with the unity of intentionality the changes occur everywhere in the forebrain that the simultaneous activity of pre- and postsynaptic neurons meets the conditions for Hebbian learning, in which the strength of synapses is modified by the activities of the neurons simultaneously on both sides of the synapse. They are also cumulative, which meets the requirement for continuing additions to the personal history constituting the evolving wholeness of intentionality. When a new fact, skill or insight is learned, the widespread synaptic changes knit the modification into the entire intentional structure of meaning that is embedded in the neuropil.

Neuromodulators combine their actions in the states of people and animals that we describe in terms of mood, affect, mania, depression, and so on. It is not clear how these complex interactions take place, or how the modulators are related to specific emotions of individuals, as they are experienced through awareness, but it is certain that all of them are involved in expressing emotions and learning from experience.

The dynamics of the preafference loop

When internally organized action patterns radiate from the limbic system, they are not packets of information or representational commands as empiricists or cognitivists would describe them. They are solicitations to other parts of the brain to enter into cooperative activity, by which the spatiotemporal patterns of both the initiator and the co-participants engage in a kind of communal dance. The linking together in a global pattern is not a directive, by which the limbic system imposes a predictive schema onto the motor systems. It is a process of evolution by consensus, in which each of the sensory and motor modules makes its unique contribution. Each sensory module provides a porthole through which to view the world, which is specified by its receptor neurons. The motor modules provide the linkage through the motor neurons to the movers of the body and the metabolic support systems. For the limbic system the contributions are the spacetime field, the feedback regulation of the neuromodulator nuclei in the reticular core, and the simultaneous integration of the input from all of the sensory areas, which establishes the unity of perception. That integration provides the basis for the synthesis of intent.

All of the solicitations for cooperation radiating to the motor systems are simultaneously radiated to all of the primary sensory cortices through the bidirectional connections schematized in Figure 3. The existence of these influences into other parts of the brain has been postulated for over a century. The transmissions have been called efference copies and corollary discharges. They are highly significant in perception, because they provide the basis on which the consequences of impending motor actions are predicted for the coming inflows to each of the sensory ports in the process of preafference (Kay and Freeman, 1998). When we move our heads and eyes to look, this process tells us that the motion we see is in our bodies and not in the world. When we speak, this process tells us that the voices we hear is our own and not others'. Preafference takes place entirely within the brain. It is not to be confused with the proprioceptive loop, which feeds through the body back to the sensory receptors and the somatosensory cortex.

Corollary discharges are carried by action potentials, as are virtually all corticocortical transmissions, with a subtle but significant difference from forward motor transmissions. The spacetime loop has two directions of both inflow and outflow. In my view the forward flow in from the sensory modules and out to the motor modules is carried by spatiotemporal activity patterns that are carried by pulses, whose effects are at the microscopic level to direct their targets into appropriate attractors. The feedback flow from the motor modules to the limbic system and on to the sensory modules as corollary discharges is also carried by activity patterns of pulses, but their effects are at the macroscopic level, to serve as order parameters, shape the attractor landscapes, and facilitate the selective learning that characterizes intentionality (Freeman, 1995).

Preafference in the forebrain has even more important contributions to make. When a goal-directed state emerges by a nonlinear state transition with its focus in the limbic system, it contains within it the expectancy of a sequence of sensory inputs. Those anticipated inputs are highly specific to a planned sequence of actions along the way to achieving the specific goal, as well as to a future state of reward, whether it is food, safety, or the feeling of power and comprehension that accompanies activation of the dopamine receptors. These expected inputs are the sights, sounds, smells and feels of searching and observing. The organism has some idea, whether correct or mistaken, of what it is looking for. The scent of prey combined with the touch of wind on the skin instantly involves the ears to listen and the eyes to look for waving grass. These are the Gestalt processes of expectation and attention, which are sustained by the motor control and preafference loops. Without preconfiguration, there is no perception. Without sensory feedback, there is no intentional action.

Everyone agrees that central processing takes time, whether for information, representations, or intentional states. Minimal estimates are provided (Libet, 1994) by measurements of reaction times between CSs and CRs (about 0.25 to 0.75 second), which are longer than the reaction times between unconditioned UCSs. and UCRs (less than 0.1 second). Only a small fraction of this interval is taken by the conduction delays between receptors and the brain, between the brain modules, and from the brain to the muscles. Most of the interval is required for binding features into higher order brain states, or for retrieving and matching stored representations for cross-correlation with present input, or for seeking appropriate basins of attraction and constructing spatiotemporal patterns in an itinerant trajectory, depending on one's point of view.

Neocortex as an organ of mammalian intentionality

Recent findings by recording the EEGs from the scalp of human volunteers (Lehmann, Ozaki and Pal, 1987) indicate that cooperation between the modules in each hemisphere is not by sequential transmission of information packets or representations bouncing from one area to another, with local processing by computational or logical algorithms. That hypothesis might be compared to the response of billiard balls upon the impact of the cue stick on one of them, with the outcome being determined by Newtonian dynamics. The global spatiotemporal pattern formation revealed by EEG recording shows that the sensory and limbic areas of each hemisphere can rapidly enter into a cooperative state, that persists on the order of a tenth of a second before dissolving to make way for the next state. The cooperation does not develop by entrainment of coupled oscillators into synchronous oscillation. Instead, the cooperation depends on the entry of the entire hemisphere into a global chaotic attractor.

An explanation in terms of brain dynamics is through generalization of the process by which local spatiotemporal patterns form. The microscopic activity of the neurons in each sensory cortex couples them together by synaptic transmission, and when the coupling is strong enough, the population becomes unstable and undergoes a state transition. Thereby a new macroscopic state emerges, which constrains and enslaves the neurons that create and sustain it, in the process of circular causality (Haken, 1983; Cartwright, 1989). The neurons express their membership in the coordination of their firing patterns, even though they do not synchronize to fire simultaneously. It appears that the macroscopic patterns radiate through various axonal pathways in each hemisphere. The interactions on the global scale engender state transitions of the entire hemisphere by triggering instabilities, such that new global macroscopic states are continually being created. Each global macroscopic state constrains and enslaves the modules that have created it throughout the hemisphere.

Consciousness as a dynamic operator

Neurodynamics offers a new and enlarged conceptual framework, in which interrelationships among parts creating wholes can be described without need for causal agents to effect changes. An elementary example is the self-organization of a neural population by its component neurons. The neuropil in each area of cortex contains millions of neurons interacting by synaptic transmission. The density of action is low, diffuse and widespread. Under the impact of sensory stimulation, or by the release from another part of the brain of a modulatory chemical, or by the inevitable process of growth and maturation, all the neurons together form a macroscopic pattern of activity. That pattern simultaneously constrains the activities of the neurons that support it. The microscopic activity flows in one direction, upward in the hierarchy, and simultaneously the macroscopic activity flows in the other direction, downward. With the arrival of a new stimulus or under the impact of a new condition, this entire cortex can be destabilized, so that it jumps into a new state, and then into another, and another, in a sequence forming a trajectory. There is no meaning to the question, how individual neurons can cause global state transitions, any more than it is meaningful to ask how some molecules of air and water can cause a hurricane. This way of thinking about matter has become so familiar to physical scientists since it was introduced a century ago by Boltzmann, that it is difficult to see why it is not better understood by neurobiologists working with neurons.

The primary sensory cortices are also components in a larger system, together with the various parts of the limbic system. Each of these components is liable to destabilization at any time, in part because of the feedback connections that support the interaction between populations. Perception can and does follow the impact of sensory bombardment, but that which is perceived has already been prepared for in two ways. One way is by the residue from past experience, the synaptic modifications, which shape the connections in the neuropil of each sensory cortex to form nerve cell assemblies. Each assembly opens the door to a preferred spatial pattern, which is constructed by the learned attractors in the basin formed in the past. The set of basins forms an attractor landscape. The second way is by reciprocal relations with all other sensory cortices through the entorhinal cortex. Input by preafferent pathways can bias the attractor landscapes of the cortices, and that can enhance the basins of attraction, that conform with the goals emerging through the limbic system.

The sensory cortices are continually bombarded by receptors, irrespective of intention, and each module of the brain is subject to destabilization at any time, owing to its intrinsic dynamics. Some form of global coordination must exist to explain the unity of intentional action, and the perseverance of goal-directed states in the face of distractions and unexpected obstacles. My hypothesis is that the interactions of the neural populations creates a brain-wide level of shared activity. The populations are not locked together in synchronous discharge, because they preserve a degree of autonomy. Synchrony seldom occurs among the individual neurons in the local populations, either. The entire community of brain modules must be considered as creating a global dynamic framework. The micro-macro relation that binds single neurons into populations, then, is a precursor for the binding of the limbic and sensory systems into a brain state.

This description can explain the formation of global spatiotemporal patterns but not their function and significance. It still leaves unexplained their relation to awareness. What is it? I want to propose a hypothesis as to just what is going on, in which consciousness is interpreted in neurobiological terms as a sequence of states of awareness. The limbic and sensory systems transmit to each other by action potentials as microscopic elements in a hierarchically upward direction. They create a global state, which acts downwardly to constrain the parts. The constraints are exercised by action potentials on divergent pathways that enhance the global content. The constraint of each module acting on others diminishes the freedom of all of them. The likelihood that any one of them will destabilize, go ballistic, and impose its activity onto other modules is reduced. In particular, it is less likely that any one or a subset of modules can capture the motor systems and shape behaviors with minimal contributions from the other parts.

My hypothesis is that a global spatiotemporal pattern in each hemisphere is the principle brain correlate of awareness. The interactive populations of the brain are continually creating new local patterns of chaotic activity, that are transmitted widely and that influence the trajectory of the global state. That is how the contents of meanings emerge and grow in richness, range, and complexity. Only a small fraction of the total variance of the activity in each of the modules is incorporated into the global pattern. Yet that small part is crucial. Just as the individual neuron is subject to continual bombardment at its synapses, yet can only report out a pulse intermittently on its sole axon, and just as the population is built from the seemingly random activity of millions of neurons, yet can only form one attractor pattern at a time, so the whole hemisphere, in achieving unity from its myriad shifting parts, can sustain only one global spatiotemporal pattern at a time, but that unified pattern jumps continually, giving the chaotic but purposeful stream of consciousness

The crucial role that awareness plays, according to this hypothesis, is to prevent precipitous action, not by inhibition, but by quenching local chaotic fluctuations in the manner described by Prigogine, through sustained interactions acting as a global constraint. Thus awareness is a higher order state, that harnesses the component subsystems and minimizes the likelihood of renegade state transitions in them. Consciousness as a sequence of global states is not an agent that initiates action. Nor is it an epiphenomenon. It is a state variable that constrains erratic activity by quenching local fluctuations. It is an order parameter and operator, that comes into play in the action-perception cycle after an action has been taken, and during the learning phase of perception. This is the part of intentionality in which the consequences of the just completed action are being organized and integrated, and a new action is in planning but not yet in execution. Consciousness holds back on premature action, and by giving time for maturation, it improves the likelihood of the expression in considered behavior of the long term promise of an intentional being. od of the expression in considered behavior of the long term promise of an intentional being. David Chalmers (1996) has characterized as "the hard problem" the question of why we have experience at all. The answer is simple. Humans who can't stop to think don't survive long in competition with those who can. William James (1879) described consciousness as "an organ added for the sake of steering a nervous system grown too complex to regulate itself." But it is not an organ in the sense of some new part of the brain. Instead it is a higher and more inclusive form of self-organization.

The view of consciousness as a dynamic state variable clarifies the issue of emotion versus reason. Emotion can be measured by the magnitudes of the tendencies to chaotic fluctuations in brain modules, and reason can be seen as an expression of a high level of assimilation to the world, meaning knowledge that endows a rational mind with control of remarkable power. Consciousness does not construct the trajectory of reason. It provides the global linkage for smoothing chaotic fluctuations through global interaction. By these criteria an action can be intensely emotional and yet strictly controlled. Actions which are considered to be thoughtless, ill-conceived, rash, incontinent, inattentive, or even unconscious, and which are commonly and incorrectly labeled as "emotional", can be described in dynamic terms as an escape of chaotic fluctuations from a global order parameter, prematurely in respect to unity of mind and long-term growth toward the wholeness of intentionality. Without emotion there is no action, but without conscious control, there is the potential for self-abasement, self-destruction, and the heartless infliction of violence on others.

When we speak of people as "highly emotional", in this view we refer to having high levels of chaotic activity in the various components of their brains, which cannot be achieved without a corresponding high level of the global cooperativity that manifests itself in consciousness. The levels of energy build inexorably through the dynamic tensions of controlled internal conflicts. In other words, emotionality is not a weakness but a sign of strength, because its depth, range and complexity beyond the instinctual attitudes of other animals cannot develop without structuring by reason and language. The highest and most complex levels of emotion are seen in poets and other natural leaders who have the greatest range of personal insight, cultural vision, and predictive power. Emotion is chaotic, but, after all, by one definition chaos is controlled noise.

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References

Aquinas, St. Thomas (1272) The Summa Theologica. Translated by Fathers of the English Dominican Province. Revised by Daniel J Sullivan. Published by William Benton as Volume 19 in the Great Books Series. Chicago: Encyclopedia Britannica, Inc., 1952.

"Q" refers to a topic named as a Question. "A" refers to a more specific question and answer.

Barrie JM, Freeman WJ, Lenhart M (1996) Modulation by discriminative training of spatial patterns of gamma EEG amplitude and phase in neocortex of rabbits. Journal of Neurophysiology 76: 520-539.

Brentano FC (1889) The Origin of our Knowledge of Right and Wrong. Chisolm RM and Schneewind EH (trans.). New York: Humanities Press (1969).

Cartwright N (1989) Nature's Capacities and their Measurement. Oxford UK: Clarendon Press.

Clark RE, Squire LR (1998) Classical conditioning and brain systems: The role of awareness. Science 280: 77-81.

Damasio AR (1994) Descartes' error: emotion, reason, and the human brain. New York: Putnam.

Darwin C (1872) The Expression of Emotion in Man and Animals. London: Murray.

Davidson D (1980) Actions, reasons, and causes. In: Essays on Actions & Events. Oxford UK: Clarendon Press.

Dewey J (1914) Psychological doctrine in philosophical teaching. Journal of Philosophy 11: 505-512.

Eleftherion BE (ed.) (1972) The Neurobiology of the Amygdala. New York: Plenum Press.

Freeman, WJ (1992) Tutorial in Neurobiology: From Single Neurons to Brain Chaos. International Journal of Bifurcation and Chaos 2: 451-482.

Freeman WJ (1995) Societies of Brains. A Study in the Neuroscience of Love and Hate. Mahwah NJ: Lawrence Erlbaum.

Gibson JJ (1979) The Ecological Approach to Visual Perception. Boston: Houghton Mifflin.

Gray CM, Freeman WJ, Skinner JE (1986) Chemical dependencies of learning in the rabbit olfactory bulb: acquisition of the transient spatial-pattern change depends on norepinephrine. Behavioral Neuroscience 100: 585-596.

Haken H (1983) Synergetics: An Introduction. Berlin: Springer.

Hardcastle VG (1994) Psychology's binding problem and possible neurobiological solutions. Journal of Consciousness Studies 1: 66-90.

Hendriks-Jansen H (1996) Catching ourselves in the act: Situated activity, interactive emergence, evolution, and human thought. Cambridge, MA: MIT Press.

Herrick CJ (1948) The Brain of the Tiger Salamander. Chicago IL: University of Chicago Press.

James W (1879) Are we automata? Mind 4: 1-21

James W (1890) The Principles of Psychology. New York: Holt.

Kay LM, Freeman WJ (1998) Bidirectional processing in the olfactory-limbic axis during olfactory behavior. Behavioral Neuroscience 112: 541-553.

Kling A (1972) Effects of amygdalectomy on social-affective behavior in non-human primates. pp. 511-536 in: Eleftherion BE (ed.) The Neurobiology of the Amygdala. New York: Plenum Press.

Klüver H, Bucy P (1939) Preliminary analysis of functions of the temporal lobe in monkeys. Archives of Neurology & Psychiatry 42: 979-1000.

Lehmann D, Ozaki H, Pal I (1987) EEG alpha map series: brain micro-states by space-oriented adaptive segmentation. Electroencephalography & clinical Neurophysiology 67: 271-288.

Libet B (1994) Neurophysiology of Consciousness: Selected Papers and New Essays. Boston MA: Birkhauser.

Magoun HW (1962) The Waking Brain (2nd ed.). Springfield IL: CC Thomas.

Mark VH, Ervin FR (1970) Violence and the Brain. New York: Harper & Row 111 pp.

Mark VH, Ervin FR, Sweet WH (1972) Deep temporal lobe stimulation in man. pp. 485-507 in: Eleftherion BE (ed.) The Neurobiology of the Amygdala. New York: Plenum Press.

Merleau-Ponty M (1945) Phenomenology of Perception. (C Smith, Trans.). New York: Humanities Press, 1962.

Narabayashi H (1972) Stereotaxic amygdaloidotomy. pp. 459-483 in: Eleftherion BE (ed.) The Neurobiology of the Amygdala. New York: Plenum Press.

Panksepp J (1998) Affective Neuroscience: The Foundations of Human and Animal Emotions. Oxford UK: Oxford University Press.

Pert CB (1997) Molecules of Emotion: Why You Feel the Way you Feel. New York: Scribner.

Prigogine I (1980) From Being to Becoming: Time and Complexity in the Physical Sciences. San Francisco: Freeman.

Rosch E (1994) Is causality circular? Event structure in folk psychology, cognitive science and Buddhist logic. Journal of Consciousness Studies 1: 50-65.

Tani J (1996) Model-based learning for mobile robot navigation from the dynamical systems perspective. IEEE Transaction on Systems, Man and Cybernetics 26B: 421-436.

Tolman EC (1948) Cognitive maps in rats and men. Psychological Review 55: 189-208.

Wilson MA & McNaughton BL (1993) Dynamics of the hippocampal ensemble code for space. Science 261: 1055-1058.

Figure Legends

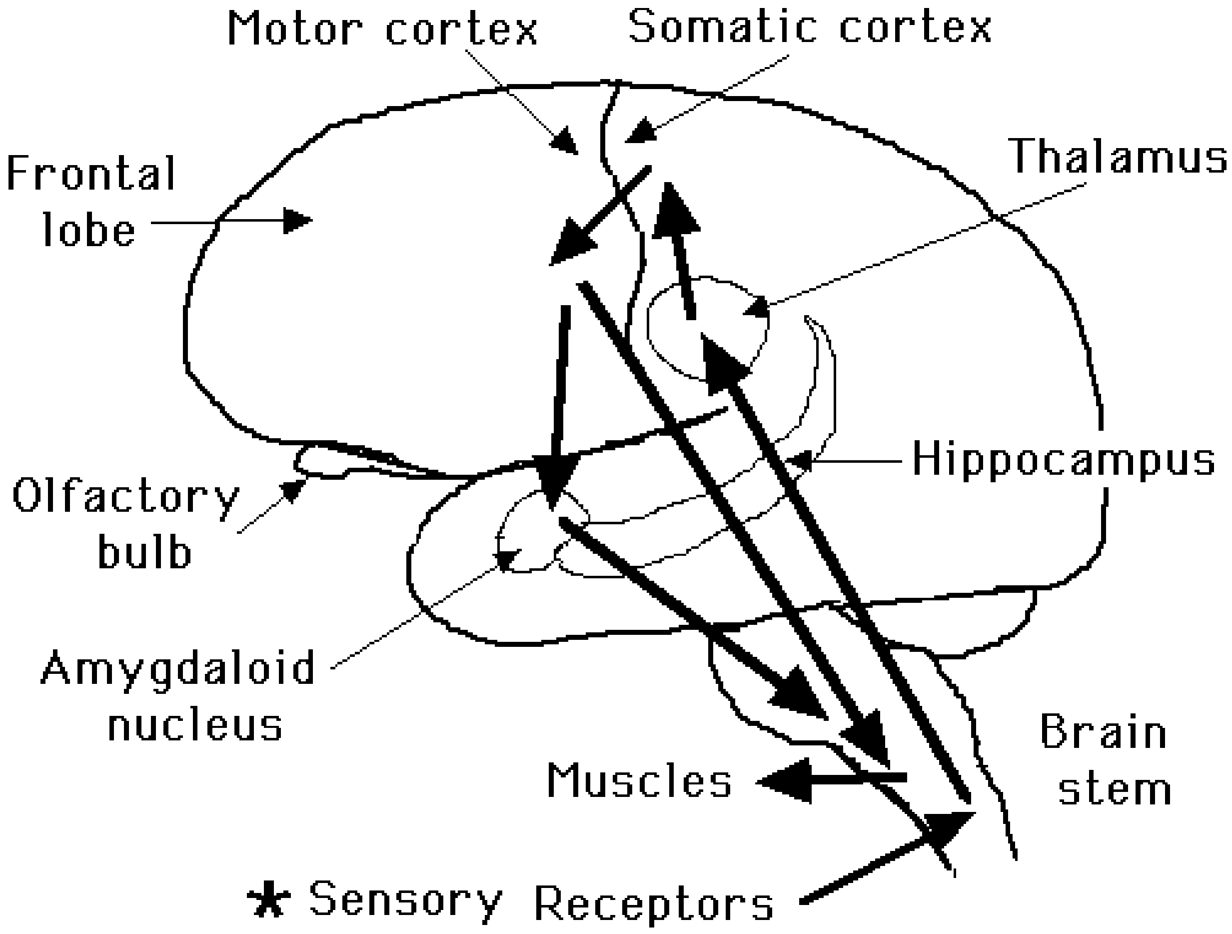

Figure 1. This schematic diagram shows the way in which perception occurs in the passivist-behaviorist-cognitivist view. It begins with sensory stimulation (*) that provides the information to be processed. Three serial neurons (upward arrows) carry it through the thalamus to the primary sensory cortex, from which it is transmitted to the frontal lobes. Similar stages hold for visual and auditory information. The processed information is sent directly to the brain stem and indirectly through the amygdaloid nucleus, where emotion is attached, before final delivery to the muscles. This serial pathway constitutes a linear causal chain.

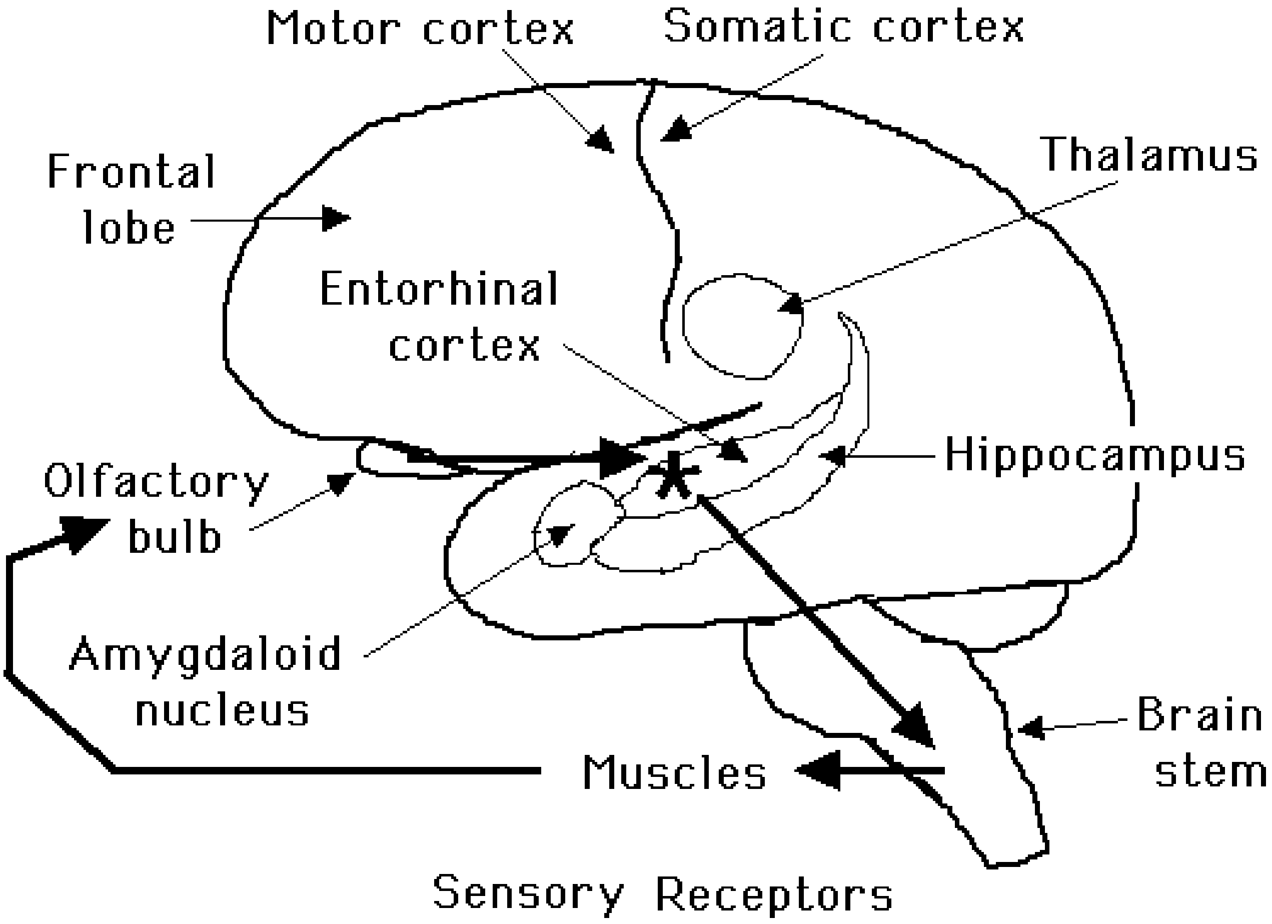

Figure 2. This schematic diagram shows the way in which perception occurs in the activist-pragmatist view. It begins with emergence of a goal through self-organizing dynamics in the limbic system (*) embedded in the medial temporal lobe. Commands sent to the brain stem cause changes in sensory inflow. At the same time, corollary discharges are sent to the primary sensory cortices to prepare them for the anticipated sensory barrage. For simplicity, only the olfactory feedback is shown. All other senses participate by transmitting to and receiving from the entorhinal cortex, which interacts with the hippocampus. The loop starting and ending in (*) illustrates circular causality.

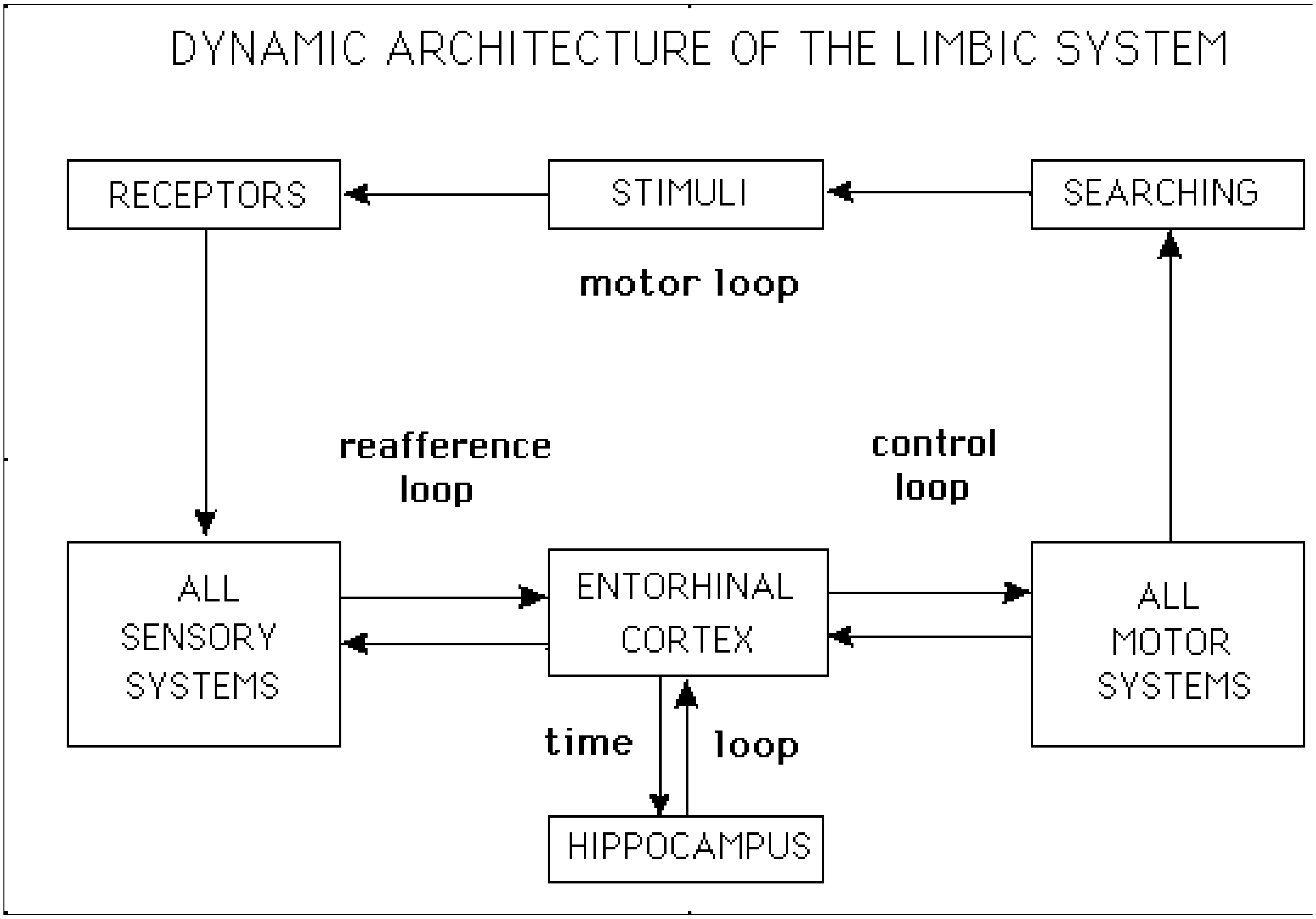

Figure 3. The organization of brain dynamics is developed from Figure 2 as a set of loops of interaction in which the limbic system is embedded. The global interaction between the self and the world is shown as the pathway through the environment from motor output to sensory receptors. The proprioceptive and interoceptive loops are closed outside the brain but inside the body. The preafferent loops are within the brain, updating the sensory cortices to expect the consequences of incipient actions. They differ from the motor control loops that include the neurohumoral regulation of the brain by itself. The spacetime loop indicates the interaction between the components of the limbic system by which experience is organized for intentional action through time and space.