A Catalytic Theory of Embodied Mind

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Abstract

This paper describes a catalytic theory that grounds cognition in biology, building on the proposals of (a) Gibson and ecological psychologists concerning the role of invariance and (b) Shepard, Gestaltists and neuroscientists concerning the role of 'resonating' neural waves. Enzyme catalysis increases the speed of a molecular reaction, perhaps via a type of wave, a soliton, whose formation, persistence and form depend on the structural invariance of its environment. Generalizing to cognition (Davia, 2006), the waves of neural activity constitute a catalytic process, with the organism's perception-action invariance playing the role of the environmental structure. This 'generalized catalysis' is a process by which an entity mediates its environment and is the organism's experience.

Keywords: Perception; Consciousness; Neuroscience

An Independent World vs. Invariance

In this paper, we will consider the relation of 'mind and brain,' a phrase that expresses a problematic duality for our field. In one attempt to bridge it, some scientists assume the reductionist stance that the 'mind' eventually will be understood in terms of the neurology or biochemistry of the brain and body. Other researchers, inspired by the computer metaphor, study the 'mind' as though it were independent of its biological implementation. But benefits might arise from examining the nature of the relation between life and its environment. We will discuss one such proposal based on enzyme catalysis (Davia, 2006). We explain how it accounts for 'sensory substitution' data that are problematic for conventional approaches and briefly consider some of its potential implications for cognitive science.

The Modal Theory

The modal theory of the relation of mind and brain is based on a causal sequence of physical processes. An event occurs in the environment; ambient energy from the event impinges on the receptors of the organism. The organism's nervous system transmits this signal to the brain. The organism's experience is a psychological correlate of the code that the nervous system uses to transmit information about the environment. In this model, the environment is independent of the organism. The model also assumes that the quality of the perceptual experience depends upon the particular sensory receptors that transmit the signal. For example, it assumes that we see because of our eyes and hear because of our ears, an assumption that is called 'Muller's Doctrine of Specific Nerve Energy.' But both this doctrine and the assumption that the perceiver is representing an independent environment have been challenged by research on 'sensory substitution.'

Sensory-Substitution Research

Over the last two and a half decades, research has demonstrated that individuals who are blind can learn to use other modalities in order to recognize objects and navigate the world (White et al., 1970). The use of the eyes is not critical to experiencing the visuo-spatial environment; instead, it appears to be dependent on the invariant patterns that relate the organism's perceptions and actions. This point is best explained by briefly describing the research.

In tactile-visual substitution systems, the input from a camera is fed to a vibro-tactile array located either on the person's back or tongue (Bach-y-Rita, Tyler & Kaczmarek, 2003). Importantly, the individual must manipulate the camera, by panning or zooming, for a tactile sensation to be experienced as an event or object. If the camera is kept in a static position, the person's experience of 'the environment' ceases. Also, another person cannot control the camera; its movements must be linked to those of the perceiver/actor. Participants initially report sensing the stimulation as coming from the location of the device. But with practice, they locate the source as outside themselves, and the patterns become interpretable in terms of visuo-spatial events and objects. The stimulation at the device's location is less salient. For example, after only 10 hrs of practice with a vibro-tactile array on the tongue, congenitally blind individuals can catch and throw balls and report perceiving the flicker of candle flame for the first time.

Another mapping is given by an auditory-visual system called vOICe (Oh-I-See). Grey-scale images from a video camera are mapped into sounds via a left-to-right scan, with pitch indicating elevation and loudness indicating brightness (Meijer, 1992). Considerable practice is needed with this device. One individual, who had lost her eye-sight as an adult through an industrial accident, practiced for two years in her bedroom, and she reported gradually acquiring spatial navigation and object recognition in that context before acquiring sensitivity to visual texture, depth, object recognition and navigation skills in new environments (Fletcher, 2002). Individuals who use sensory-substitution devices do not experience the environment in exactly the same way as someone who uses their eyes; in that way, 'substitution' may be a misleading term. But Fletcher's report and those of others suggest considerable overlap in the experiences.

This dissociation argues against Muller's doctrine that the quality of visuo-spatial experience is due to the particular sense, e.g., eyes (O'Regan & Noë, 2001). The phenomenon also provides evidence against the modal model of perception as representing an independent environment.

Perception-Action Invariance

In sensory substitution, the organism's perception depends critically on its actions. This conclusion comes not just from sensory substitution research, but also from data on 'normal' perception. For example, it has long been known that normal visual experience ceases if the visual display is stabilized on the viewer's lens, so that it moves with their eyes and no new pattern occurs as a consequence of eye movements.

The invariance arising from the interaction of an organism in its 'environment' has been a key construct in the Ecological Theory of perception inspired by Gibson (1979). The role of perception-action invariance is also evident with the skilled use of tools and athletic equipment. For example, skilled rowers report feeling the water through their oars. Given sufficient skill, the equipment becomes 'transparent,' analogous to the shift that occurs with sensory-substitution devices. Ecological psychologists argue from such data that perception is constrained by the environment, rather than dependent on sensations (Carello & Turvey, 2000).

Dynamic Systems researchers also have pointed to the intimate interrelation of perception and action, and used it to argue against the assumption of an independent environment (Kelso, 1995; Thelen, 1993). For example, the placement of the walker's feet when she is walking on a sandy beach dynamically changes the compactness and slope of the sand, which simultaneously affects her feet. After reviewing a large number of such perception-action 'contingencies' in the visual domain, O'Regan and Noë (2001) concluded that visual perception **is** visual exploratory behavior.

The idea that the environment has patterns, including complex, statistical contingencies, is the basis of many psychological studies of 'implicit learning.' Acquiring sensitivity to such patterns underlies the learning that is modeled in many connectionist models. But the data summarized by O'Regan and Noë (2001) and Ecological psychologists suggest that the invariance is not 'out there' in an environment that is independent of the organism. Rather, the invariance is in the relations of the organism's perceptions and actions. We will argue that the invariance may be only implicit relations that are made explicit in the organism's experience.

Autopoiesis and Experience

In focusing on 'experience' as a key to understanding 'mind,' we are building on the ideas of Maturana and Varela (1980, 1987), two brilliant neuroscientists who challenged the assumption that a perceiver represents information about an independent environment. They proposed a theory called *Autopoiesis*, meaning 'self-making.' To explore how the organization of a living system may give rise to cognition, they began by considering a cell. Each cell has a boundary that establishes its autonomy. The cell's metabolism determines what crosses the boundary, and it also determines what changes occur within the cell. Generalizing this insight to entire organisms, Autopoiesis proposes that the organism brings forth its environment. This theory has greatly influenced some researchers in AI (Brooks, 1987) and situated cognition (Winograd & Flores, 1986).

By rooting 'cognition' in a living cell, Autopoiesis shifted the definition of 'cognition' from the conventional meaning, 'perception, action, and (human) thought,' to 'experience,' a concept that is so basic that it is associated with life itself. Although the Catalytic theory also focuses on 'experience,' unlike Autopoiesis, it does not propose that an entity is autonomous of its environment. Rather, it proposes that the two are intimately related, specifically, that an entity lives by virtue of mediating, or catalyzing, its environment.

At this point, we have argued that the assumption of an independent environment fails, and instead, we pointed to a role for perception-action invariance. We now turn to an alternative understanding of the brain's activity in terms of the organism's perception-action invariance.

Resonance & Neural Waves

Tracing back to the Gestalt psychologists and up to the present, a minority of researchers have suggested that neural and psychological processes are characterized by wave-like activity. One of the best known proposals is Hebb's 'reverberatory cell assemblies,' and others include Ashby's 'reverberatory circuits,' Lashley's 'cortical standing waves' and 'resonance' (Lehar, 2004; Shepard, 1984). Neuroscientists have related sensory consciousness to the wide-spread, synchronized, neural traveling waves in the cortex and thalamus (e.g., Crick & Koch, 2003; Edelman 2003; Freeman, 1999; Grossberg, & Grunewald, 1997; Llinas, 2001; Singer, 1993; Thompson & Varela, 2001). For example, Freeman described his EEG results as: "…the construction by nonlinear dynamics of macroscopic, spatially coherent oscillatory patterns that cover the entire cortex…."

A few researchers, including Shepard and Gibson, also pointed to the wave-like or resonance-like nature of perceptual experience itself. Shepard (1984, p. 433) claimed that "the organism is, at any given moment, tuned to resonate to the incoming patterns that correspond to the invariants that are significant for it."

These observations may reflect a single, unifying principle; namely, the wave-like processes are the way by which living organisms mediate (catalyze) their environment, and they relate directly to the organism's experience (Davia, 2006).

Thought Experiment: Waves in the Canal

In order to make this argument, we first will convey a non-representational perspective of the wave-like or resonance-like activity of the brain. When we picture neural traveling waves in the brain, we may imagine them actually traveling like water waves that move down through a canal. However, a more helpful image reverses the two components. Imagine the neural activity as a standing wave that maintains its organization while mediating the passage of water in the canal. This alternative, but equally valid, perspective provides a different perspective on neural waves. We suggest that macroscopic neural waves maintain their structure or coherence while mediating the patterns of impinging activity in sensory, motor and other neural areas – patterns that arise from the organism's history and on-going interaction with its environment.

Applying this perspective to the sensory-substitution case, such as the vOICe system, the movements of the person's head and body and the related responses of the sensory-substitution device, imply a three-dimensional, textured field that is subsequently made explicit in the individual's experience as a 'visuo-spatial event.' Practice with the technology helps to structure the person herself, so that the waves of her brain (nervous system and body) can organize the energy, mediating the transitions that arise from her interaction with the 'environment.' It is the perception-action invariance, not the sensory modality, which gives rise to much of the invariance, and hence, accounts for its similarity, but non-identity, to vision by eye. In this view, the 'environment' depends on, and is not independent of, the organism. The organism's experience correlates with the formation and persistence of neural waves that maintain their coherence while mediating such transitions.

The Brain as an Excitable Medium Neural activity is a thermodynamic process. A neuron, for example, is an excitable medium in which energy is dissipated and then replenished as the wave of excitation travels its axon. We argue that the brain is best understood as an excitable medium as a consequence of the metabolism of glucose and other essential nutrients. This energy gradient is dissipated by neural activity that is constrained by the organism's structure, including that arising from its history and on-going activities. Thus, the non-linear neural waves can be seen as a self-maintaining and self-sustaining dynamic, a solution to the boundary conditions implicit in the structure of the organism and the relation between the organism and its 'environment.'

Catalysis and Generalizing to the Brain

In this section, we suggest that a 'high level' description of catalysis applies to macro-level phenomena, such as neural waves. Also, the same general type of wave that describes a neuron's action potential also occurs in molecular catalysis.

Generalizing Catalysis

A catalyst increases the speed by which molecular reactants form a thermodynamically more stable product, and the catalyst emerges from the reaction able to catalyze another such reaction. All catalyzed reactions run in the same direction as they would without a catalyst, but the speed increase is enormous, by factors of 10^6 to 10^{12} times. Enzymes are biological catalysts, typically proteins. Enzyme catalysis involves changes in the positions of electron(s) and proton(s). Most researchers believe that enzyme catalysis is ubiquitous in metabolism.

Theories of how enzymes work in metabolism increasingly resemble massively parallel networks of intercorrelated relations. The earlier model of metabolism in biology was that enzymes worked in a specific linear sequence to control a pathway. Such models are giving way to models of metabolism as self-reinforcing cycles of enzyme-catalyzed reactions (Weber & Depew, 2001), essentially dynamic systems. Bechtel (1998) illustrated the two contrasting models for the process of fermentation, as shown in Figure 1.

In enzyme catalysis, the reaction ultimately occurs because the product(s) is/are more thermodynamically stable than the individual reactants. The catalytic process facilitates the transition from the reactant(s) to the product(s) by overcoming the structural constraints of the reactants' structure and dynamics. Research suggests that catalysis takes advantage of the invariance (symmetries) of the biological structure (the protein-substrate complex) to deliver energy where it is needed to change the molecular structure. The process appears to be 'vibrationally-assisted,' a wave-based facilitation that involves a type of localized, non-linear wave, called a *soliton*.

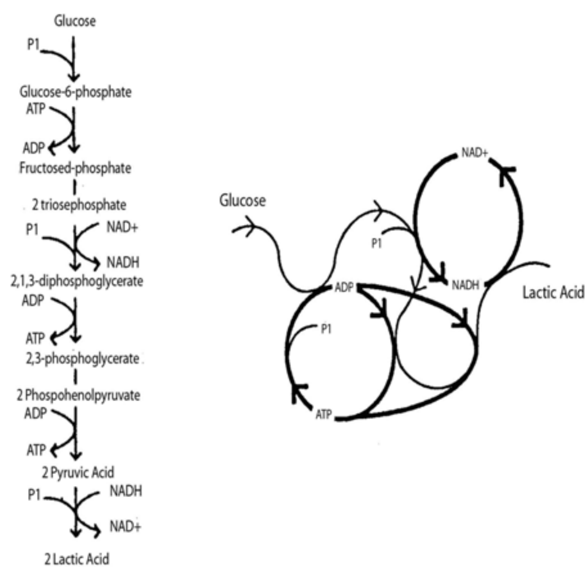

Figure 1. A pathway representation (on the left) with a series of co-enzymes as side loops, and as a dynamic system of enzyme-catalyzed cycles (on the right) for the fermentation process (from Bechtel, 1998, Figure 3, p. 310).

Soliton Waves A soliton wave in water was first described in the mid-1800's by J. Scott Russell when a boat stopped suddenly in a canal, and a solitary wave formed and moved, maintaining its structure for over two miles (Remoissenet, 1999). Soliton waves are localized, can be very robust, and occur in many types of nonlinear media (Filippov, 2000). Solitons may be relative simple structures, but also may manifest as complex, multidimensional spatio-temporal structures. As in the case of action potentials, a soliton-like wave may be started by an initial impetus above a threshold, but its duration and form depend on the symmetries (invariance) of its environment. Soliton-type waves occur in both quantum and classical regimes; like quantum phenomena, they exhibit both wave and particle-like characteristics. Although distinctions among several related types of waves (solitons, instantons, polarons) are major research topics in biophysics and mathematics, what is important for the current proposal is that the wave be a localized, nonlinear solution to the boundary conditions that constitute its environment.

Main Theme If the essential theme of catalysis involves overcoming structural constraints to dissipate energy, the term 'catalysis' may be generalized to other micro-level and macro-level processes involving soliton-like waves that facilitate such transitions (Davia, 2006). Examples of such processes occur throughout physiology, both at the micro-level (such as neuronal action potentials, DNA zipping and unzipping), as well as in macro-level systems (e.g., the heart). These can be viewed as examples of this generalized definition of catalysis. Thus, the catalytic principle is applicable at many scales, from enzymes, to cells, organs and entire organisms: A living organism can be understood as a unitary process of catalysis, mediating its environment.

The Brain Mapping this proposal specifically to the brain, the metabolic waves of the brain may constitute a unitary process of catalysis (Davia, 2006). As mentioned earlier, the brain is maintained in a far-from-equilibrium state through the metabolism of glucose. The paths by which this energy may dissipate are determined not by the brain itself, but by the structural constraints arising from the organism's history and interaction with its environment, the perception-action invariance discussed above. Thus, the perception-action invariance acts as a set of boundary conditions (symmetries) that are mediated by the neural activity to dissipate energy.

The brain and body can be understood as the medium of catalysis. According to this theory, the objects and events of the environment are not necessarily unified entities in themselves, in spite of their appearance. Rather, they are unitized by virtue of the organism's experience, by neural standing waves. A rotating cube, for example, does not constitute a continuous, unified dynamic. However, if we perceive a rotating cube, the neural waves associated with that perception-action invariance constitutes a unified dynamic. It is a solution to the boundary conditions arising from our eye movements, our head movements, and so forth, interacting with impinging energy. Our experience manifests the perception-action invariance as a unified event that is more thermodynamically stable than non-unified patterns. This point is consistent with perceptual learning phenomena. When a novice first hears notes from an unfamiliar instrument in a foreign musical tradition, it is not experienced as a melody. The experience of a unitized melody only arises after repeatedly hearing that musical tradition. 'Implicit learning' structures the organism (Rumelhart & McClelland, 1986). As we described earlier in the context of sensory substitution, practice gives rise to coherent neural activity, a soliton-like wave that maintains its organization, mediating the impinging transitions and giving rise to the organism's experience.

Motor Activity The motor activity generated by the locomotion of many species, including snakes and fish, has been identified as soliton waves (Petroukhov, 1999). Although waves may be obvious in the motor behavior of eels, fish, centipedes and insects, even mammals move via coordinated waves of leg activity. These data make the 'input-process-output" view of the neural activity somewhat less compelling (Davia, 2006). The modal model assumes that the activity of the nervous system is a code that is needed to translate between 'input' (perception) and 'output' (action). However, soliton-like waves occur in motor behavior, as well as in physiology, including neural action potentials. If the same 'vocabulary' occurs in all of these domains, then there may be no need for translation!

This model has implications for how we understand motor behavior. We suggest that motor behavior is what an observer perceives of the organism's catalytic process. Thus, a millipede's solitonic motion as it crosses a sand dune (to morph Herb Simon's classic example of the ant) is an observer's perspective of the millipede catalyzing an aspect of its environment. These findings, if generalized, may point toward a non-reductionist reconciliation of the observation of waves in physiology and the observation of waves in behavior; that hypothesis, however, requires further development.

Molecular Catalysis Process

The details of the process of enzyme catalysis may further clarify the proposed generalization of it to macro-level processes. Initially during catalysis, the enzyme binds with the reactants, forming an enzyme-substrate complex. Enzyme catalysis requires the precise application of energy along a reaction coordinate, and how this occurs is still a matter of research. Previously it was believed that the enzyme facilitated the reactants going to an intermediate configuration, the transition state, solely via a classical process that influenced the height of the energy barrier. However, this common textbook explanation is no longer accepted as sufficient or complete for catalysis at physiological temperatures. Recent research suggests that a vibrational mode of the enzyme-substrate complex facilitates the transition (Knapp & Klinman, 2002; Sutcliffe

& Scrutton, 2002). It has been proposed that the vibratory mode involves solitons or soliton-like waves (Sataric, Zakula, Ivic, & Tuszynski, 1991). The protein chains of the enzyme may support soliton waves that alter the conformation of the enzyme-substrate complex, affecting the width of the energy barrier. The conformational change lessens the distance between specific parts of the enzyme and thereby lessens the distance between the molecular reagents that are bound to it. This shortening increases the possibility of 'quantum tunneling' and increases the reaction rate. This occurs because quantum mechanics treats a particle as a probability-wave function. A particle cannot exist near a barrier without its wave function extending into the barrier. If the particle is near a barrier, and if the barrier is narrow enough, the wave function may extend through the barrier completely. Thus, there is a chance that the particle will disappear from one side of the barrier and appear on the other side, which is quantum tunneling. Classical and quantum solitons have similar properties, which may assist any transitions between quantum and classical processes. Pragmatically, this observation helps us to circumvent the debate about how widespread quantum processes are in neural and biological systems (Tegmark, 2000).

Discussion

The Fractal Catalytic theory suggests that an organism is intimately related to its environment; life is a process *of* the environment, not *in* the environment. Life's robustness may depend on this relation. If the environment changes so drastically that it cannot be mediated, then the life process becomes incoherent and the entity dies. For example, if a bacterium is removed from its environment, it dies. This implication may be less obvious for humans. Unlike most organisms, which depend on a specific type of environment, humans are extraordinarily adaptive and able to mediate a variety of environments. Nevertheless, the theory proposes that our experience arises by virtue of the same catalytic principle as in the case of a cheetah, a bacterium, or a single cell.

Related Approaches The Fractal Catalytic theory builds on insights from Dynamic Systems Theories (DST) and connectionist models, particularly their focus on time-varying, massively parallel, correlated processes. Both express the nonlinear, non-stationary nature of living systems, and the ability of such systems to self-organize and manifest emergent properties. Also like some DSTs, Autopoiesis, and Gibson's Ecological Psychology tradition, the Fractal Catalytic theory suggests that our field move away from the assumption that an organism is representing an independent environment. A more fruitful theoretical construct may be the invariance of an organism's perception-action relations. This suggests a partial re-construal of the connectionist agenda; at least we need to re-evaluate the common conception of 'representation' (Bechtel, 1998). A greater conceptual leap is the emphasis of the present approach on 'experience' and its proposed role of making explicit what may be otherwise implicit. The emphasis on experience, rather than behavior, is a change in focus, and interrelating the two foci, experience and behavior, stands as a challenge.

The Fractal Catalytic theory may illuminate the correlation between different experiences and different patterns of neural activity. Although we have discussed ordinary sensory experience in terms of awareness of objects and events, it need not entail a separation of the self and the environment. When individuals are in a 'flow' state, skillfully performing a task that is at the cusp of their competence, they may not experience themselves as separate from the event (Csikszentmihalyi, 1993). Heidegger argued that everyday cognition is fundamentally this type of embodied know-how, awareness without separating oneself out from the activity (Wheeler, 2005). Catalysis may also illuminate some of the more familiar correlations between states of awareness and neural patterns, for example, as measured by the cortical electroencephalograms (EEGs). For example, similar EEG parameters are found at multiple spatial and temporal scales (Freeman, 1999). Self-similar parameters are not an obvious prediction of the modal model that largely conceives of neural activity as local responses to functionalist challenges. Self-similarity seems more consistent with processes that are coordinated by instantiating the same general principle at multiple scales: mediation of the entity's environment.

Functionalism This current approach raises the issue of how we should understand 'functions' (such as encoding, memory retrieval, recognition, etc.) that are invoked in most standard accounts of cognition. Functionalism assumes that there are abstract functions that can be described separately from their metabolism. This assumption may be based on a misleading analogy to computers because a computer's function depends on the program's logic, which is separate from the circuit boards and so forth that make up its metabolism. However, for living processes, the concept of function only makes sense from the perspective of an observer who is situating the process in a larger context (Maturana & Varela, 1987); a function is not a description that is given from the organism's perspective.

Dualism The current proposal challenges the dualism that is reflected in the usual concepts of 'mind' and 'brain,' a Cartesian split that underlies the modal model. It is typically assumed that an entity, its energy, and any conscious state associated with it, are all different things. The current proposal is that the distinctions break down in situations where structure and energy come together. Einstein's famous equation, $E = MC^2$, showed that energy and mass are the same thing at the quantum level. But such unified states of matter and energy do not make up much of the classical world. A cardboard box is comprised of many discontinuous particles that may be unified individually, but which do not add-up to a unified state of energy and form at the macroscopic scale of the box. But enabling unified states at macroscopic scales may be what life does in the classical world. The wide-spread, complex oscillatory patterns observed in the nervous system of animals constitute large-scale, unified states. These states may be understood as generalizations of enzyme catalysis, a process that removes the discontinuity between energy and biological structure.

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