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2016 Conference Proceedings

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Time is of the essence

Permalink

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Publication Date

2018-01-08

Peer reviewed

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Time is of the essence

Proceedings of A Body of Knowledge - Embodied Cognition and the Arts conference
CTSA UCI 8-10 Dec 2016

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I. Introduction

This paper outlines two ideas. The first proposes a basic high-level neuropsychological and neurophenomenological cybernetic framework for discussing the structure of mind and experience. The second is that much, perhaps even most, informational processes in the brain are inherently temporal in nature, i.e. that they are subserved by temporal neural codes. To paraphrase Mari Reiss Jones, in the study of mind and brain, “time is our lost dimension” (Jones 1976). In this view, there is pervasive, common temporal structure in the internal neural representations that subserve both perception and action. This common temporal structure permits perception to facilitate, inform, and even bootstrap action, and vice versa. Time structure in perception, action (movement, behavior), cognition, affect, motivation (drives, goals), and memory may allow these different mental faculties to mutually influence one another.

II. A functionalist psychological framework

A basic neuropsychological framework can be laid out that consists of complementary semiotic (informational) and systems functionalities: sensing (of external and internal states), effecting, coordination (mapping of sensory states to motor-action states), memory (short and long term), cognition (pattern analysis, recognition, and generation), affect, motivation (needs, drives, goals) and switching of internal modal behavioral states. The framework comports with much of standard psychology. The framework is *cybernetic* in that it conceives of minds and brains in terms of purposive, purposeful systems (Craik 1966; Ackoff and Emery 1972; DeYoung 2015; Powers 1973) whose behavior is mostly driven by embedded goal-seeking feedback mechanisms (Rosenblueth and Wiener 1950; Rosenblueth et al. 1943; de Latil 1956).

All organisms are engaged in self-maintenance (homeostasis) and continual self-construction that realizes a self-production organizational network, an *autopoiesis* (Maturana and Varela 1980). All of them are embedded in external environments and are constantly reacting and responding to sensed changes in it. Animals are organizationally closed by virtue of their self-production and construction, but informationally open by virtue of inputs that they do not control.

Semiotic systems. An *informational system*, in the sense used here, is a system whose behavior is mediated by sign-distinctions, i.e. pattern- or configuration-based switchings, such that its behavior can be effectively described and predicted in such terms. This contrasts with systems and processes, such as digestion, that do not enable such semiotic descriptions. Whereas the behavior of an informational system can be effectively described both in terms of sign-distinctions and physical processes (e.g. dynamical systems models), some systems (rivers) and processes (digestion) are only effectively described in terms of dynamical systems.

Sign-mediated percept-action systems. Animals with nervous systems are semiotic systems because their behavior can be effectively described in terms of sign-distinctions in the form of neural spike train signals. Neural signals are patterns of activity that are involved in informational functions. To paraphrase Bateson these are different patterns of spikes that make a difference in terms of functional states and behaviors. Types of patterns that make specific functional differences are called neural codes (in the same way that nucleotide sequences that are functionally meaningful to transcription-translation systems constitute the genetic code).

All organisms, including those without nervous systems, to some degree act on the basis of distinctions (signs) in that they make discrete behavioral choices. The ability to switch between alternative behaviors dramatically increases in complexity and effectiveness with the evolution of nervous systems in animals. Animals are motile organisms that do not produce their own source

of food (stored energy). As such, animals must depend, directly or indirectly, on organisms (algae, plants) that are capable of collecting and converting energy into storable form. Being motile, they must navigate their environments and encounter different local situations. This in turn necessitates sensing the environment — making distinctions — and acting in a flexible manner that is contingent on current distinguished situations and conditions.

Nervous systems are specialized internal signaling systems that provide 1) sensory functions that transduce environmental states and events into neural signals, 2) coordinative functions (communication, command, control) that regulate internal bodily functions and organize behavior, and 3) effector functions (muscles, secretory organs) that operate on the realm outside the body (action). These functions are schematized in Figure 1.

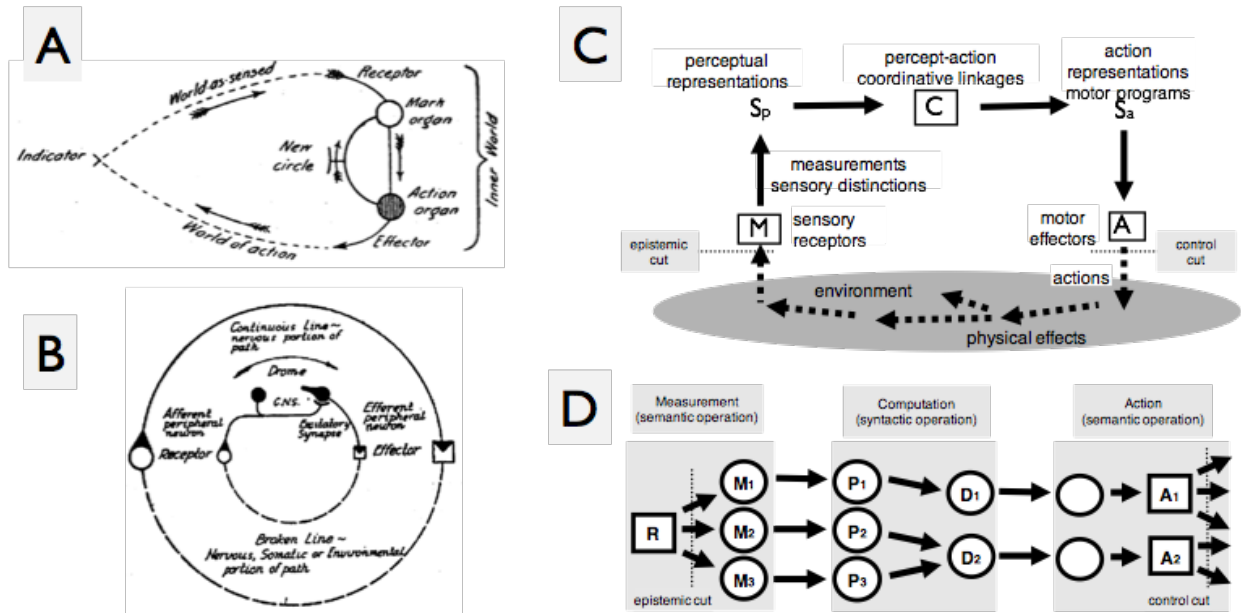


Figure 1. Percept-coordination action cycles and state-transition structure. A. Uexküll's percept-action and internal cycles that define an organism's *umwelt* (Uexküll 1926). B. McCulloch's circular causal percept-action paths that run within the nervous system and through the environment (McCulloch 1946). C. Operational structure of percept-action cycles (Cariani, 1989, 2001, 2011, 2015). D. State transition structure of a percept-coordination-action sequence. Measurements, coordinations ("computations"), and actions have fundamentally different operational state-transition structures. Here "computation" means reliable, determinate sequences of functional states (each predecessor state has one successor state). Sensing involves registering the outcomes of contingent interactions with the external environment (one predecessor reference state R to one of several possible successor states M_1, M_2, M_3), whereas action involves producing changes in the environment. Epistemic and control cuts define functional boundaries between contingent and determinate state transitions that distinguish an internal realm of reliable (self) control from an external realm of uncontrolled processes (the environment).

Sensory functions ("measurements") involve making distinctions that reduce uncertainty vis-a-vis (perceived) environmental states (Ashby's concept of "information" (Ashby 1956)). Effector systems (muscles, secretory organs, electric organs) cause environmental changes ("actions"). Coordinative functions involve choosing which actions are to be carried out given different perceived environmental contexts. Coordinative functions in higher animals include processes of perception, cognition, conation, memory, imagination/simulation, deliberation, affect, and control of behavioral mode and systems state (e.g. waking-sleeping-hypnotic state).

It has been argued at length elsewhere (Cariani 1989, 2001b, 2011; Cariani 2015b) that the basic functionalities of sensing, coordinating, and effecting can be clearly, operationally distinguished

on the basis of the state-transition structure of functional states (contingent vs. determinate, externally- vs. internally-driven). This demarcation (Fig. 1 bottom, dotted lines) depends on choosing an appropriate observational frame, i.e. the set of observables through which the behavior of the system is viewed.¹

The clearest examples lie in the operational structure of scientific models, where we can distinguish between ill-defined, contingent measurement operations and well-defined formal symbolically mediated processes of calculation and prediction. If one adds effectors and uses the predictive apparatus to drive them, one has a robotic devices with discrete internal states that can act on its environment. Although systems with identified discrete functional states are easiest to describe in these operational terms, the methodology can also be applied to analog systems that have attractor basins in their dynamics (alternate modes).²

Percept-action cycles. In waking, acting states, animals are constantly engaging in transactions with their environments. Effective action entails ongoing, iterated cycles of perception, coordination, and action. Because these are circular-causal processes, one can view action as being contingent on perception and coordination, or perception being contingent on action (Powers 1973).

Sensory systems. Animals have an array of means of sensing states and events inside their bodies and in the world outside their bodies. Internal senses, such as body position (proprioception, kinesthesia, posture), muscle tension, balance, pain, hunger/satiety, thirst, and emotions provide a read-out on the state of the organism. External senses, such as vision, audition, touch, temperature-sense, smell, and taste are directed towards realms outside the body. Sensory systems interact with the external environment and subsequently register one of several possible alternative sensory states, contingent on the current state of the environment. The process of reading out one definite outcome from many possible ones provides “information” related to the sensor-environment interaction that reduces uncertainty. Because of its operational state-transition structure and the functions that it affords, sensing is fundamentally different from coordination or action, in the same way that measurements play a fundamentally different role in predictive scientific models from formal computations.³

¹ There is no “correct” or “incorrect” frame, only those that are pragmatically more or less useful for a given predictive, explanatory, or practical purpose. Those interested in dissolving boundaries and functional distinctions will choose one set of observables (e.g. low-level physical dynamics), whereas those interested in clearly drawing boundaries and distinctions can choose those frames (e.g. neural signals, neural representations) that suit those purposes. For most animals with nervous systems these distinctions can be clearly drawn because the requisite underlying structure exists, but for most inanimate material systems (e.g. the sun, clouds, rivers), it may be impossible to find any frame that will allow the system to be seen as autopoietic, semiotic (sign-driven), purposeful, or anticipatory because the internal relations that support these functional organizations simply don’t exist in those systems.

²The attractor basins of the dynamicists are the symbols of the computationalists. There is a third path that incorporates the strengths of both paradigms. I have argued for intermediate level analog signal descriptions of brains that involves an internal dynamics of mixed analog-iconic and digital-symbolic neural signals (Cariani 2001b; Cariani 2015a, 2017), cf. intermediate level neural signal dynamics of (Prinz 2012). The question is not whether mind/brain functions are to be described either in terms of symbols, signals, or dynamics, but which of these types of descriptions best fits for what one wants to explain. This is in keeping with Pattee’s notion of complementarity between different modes of description (Pattee and Raczaszek-Leonardi 2012).

³ Processes of measurement (sensing) are external to formal systems. In terms of Turing’s theory of deterministic automata, any contingent inputs from without are not part of the automaton, but constitute arbitrary inputs from “oracles” whose origins are ill-defined from the perspective of the formal description. Similarly, measurements and formal computations play categorically distinct roles in scientific predictive models, as von Neumann argued in the 1930’s debate over the foundations of physics.

Motor systems. Effector systems realize actions. Effectors act on the external world to change it in some way. Almost all actions involve voluntary movements that are mediated by muscles. These voluntary movements permit animals to move around their environments, obtain food and water, eat, drink, defend themselves, and mate. Effecting also includes non-motoric actions, such as secretions (e.g. ink, venom, digestive juices, pheromones, sperm) or production of electric fields for stunning prey (electric eel).

Coordinative systems. Coordinative systems choose which actions to pursue given current perceived affordances (conditions and opportunities), goal-related drive-states, inherited predispositions, and estimations of effectiveness based on previous experience. The coordinative functionality of Fig. 1 would include the goal selection and steering processes of Fig. 2 and all of the circular-causal loops in Fig. 3.

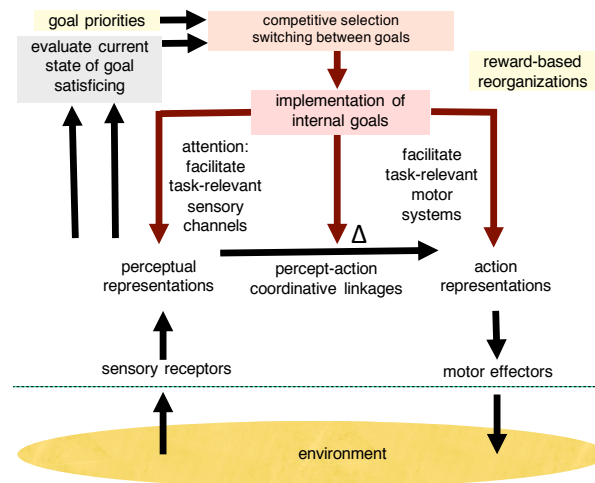


Figure 2. Embedded goals and percept-action cycles. Evaluative processes and competitive goal selection mechanisms switch between dominant goals. Sensory channels, percept-action mappings, and motor routines relevant to current goals are facilitated, whereas others are inhibited. Reward mechanisms reorganize task-relevant switchings so as to increase the probabilities of actions that achieve rewards and/or avoid punishments.

Purposive systems. Animals are purposive, purposeful systems in that they are feedback-control systems whose behavior is guided by embedded goal-states. The goals range from low-level system-imperatives for homeostasis (maintain adequate oxygenation, hydration, ionic balances, blood-sugar, adenosine clearance via sleep) to higher level imperatives important for survival (find food and water, avoid/flee/fight predators) and reproduction (courtship, mating) and beyond. Maslow's hierarchy of needs further extends these goals to safety, security, social status and self-actualization.

The goals are in constant competition for control over the behavior of the animal, but they are defeasible constraints such that their priorities are not fixed, but depend on several factors. These include drive state (how well a given goal is being realized or satisfied and how urgent is the goal, i.e. how important is it to pursue *this goal now*), perceived opportunity for achieving the goal (what goal-related affordances are perceived to exist in the current situation) and what are the perceived odds of their success (based on past experience).

Purposive systems thus have internal evaluative measures of how well goals are being met as well as mechanisms that mediate the competition between competing goals and that bias the behavior of the system towards the realization of those goal-choices that are dominant at any given moment.

In Fig. 3 this competitive process is depicted goal-dynamics. The Russian psychologist Ukhtomsky (1845-1942) proposed such a “dominance principle” for behavior (Zueva and Zuev 2015):

“... in the nervous system, there is at each moment only one active dominating dynamic structure or constellation of excitation, which is associated with the most actual, urgent ongoing needs and desires. This excitation structure plays the role of a situational nervous network, an agency for organizing the physiological and behavioral response directed to satisfying these needs. At the same time all other goals and desires are suppressed.” (Kazansky 2015)

“What is the difference between a bodily physiological mechanism in an animal and a technical mechanism? Firstly, the former is generated during the course of the reaction itself. Secondly, once chosen, the behavior of a technical mechanism is secured once and for all by its construction, whereas in a reflex apparatus it’s possible to successively realize as many different mechanisms as there are available degrees of freedom in the system. Each of the successively realized mechanisms is achieved through the active inhibition of all available processes, except one.” A.A. Ukhtomsky, quoted in(Kazansky 2015)

Goal-dynamics in brains. The notion of competitive goal dynamics fits current conceptions of brains as sets of competing circuits that steer behavior in service of different purposes (goals, end-states, drives, desires, internal imperatives). The inhibitory suppression all goal-related behavioral patterns save the one being currently realized fits with emerging theories of the basal ganglia/striatum as enabling and facilitating those motor and sensory circuits needed to perform specific tasks. Below each patch of cerebral cortex is an associated stratum of basal ganglia. This circuitry involves an inhibitory-inhibitory pathway that acts as a generalized double-inhibition braking system (increasing the activity of the first inhibitory link decreases the activity of the second inhibitory link, thereby disinhibiting (facilitating) the target neural populations. Brakes thus can be selectively released to facilitate thalamic sensory and motor neural subpopulations that are relevant to a particular task (the presently-dominant goal). On the motor side, this facilitates particular neural assemblies that subserve task-specific actions, whereas on the sensory side, it facilitates particular sensory channels carrying task-relevant information, thereby realizing a neural gain-control mechanism for attention.

In the normal resting state, inhibition makes neural loop-gains slightly attenuating, such that incoming signal patterns rapidly die out. When a brake is applied, the ensuing disinhibition changes these loop-gains to slightly amplifying, such that neuronal sensory and motor signals related to the current goal become the predominant signals within the system. It is as Ukhtomsky said: "Each of the successively realized mechanisms is achieved through the active inhibition of all available processes, except one" (Kazansky, 2015).

Adaptive systems. Systems are adaptive if their structures and functions can be altered, on the basis of past and present experience, in such a way that performance vis-a-vis embedded goals is improved (goals are better or more reliably attained). In percept-coordination-action systems, percept-action mappings can be altered contingent on experience. There are two different kinds of adaptive processes, two modes of creating novelty (Cariani 2012). In *combinatorial adaptivity* new mappings between existing percepts and actions are chosen. In *creative adaptivity* emergent novelty is generated by producing new primitives. For example, entirely new types of perceptual distinctions can be created by evolving structures that enable new sensory distinctions, such as the ability to distinguish additional colors.

Functional and phenomenal boundaries. Sensors and effectors create functional boundaries between the inner states of the percept-action system that in Üexkull’s terms constitute its *umwelt* or life-world and the external environment (Fig. 1A). The boundaries reflect the structure of

contingent vs. determinate and externally-driven vs. internally-driven circular-causal changes. The epistemic and control cuts demarcate an internal realm of self-produced and self-controlled activity (organizational closure) vs. an external realm that is outside the full control of the percept-action system. Percept-action systems are thus *informationally-open* (to environmental changes that are registered by sensors), but *organizationally-closed* (they determine their own internal structure and choose which sensors on which they base their current behavior). When a percept-action system gains the ability to fully control some part of the world outside of its sensors, effectors, and coordinative parts, that newly controlled part of the world becomes part of the realm of the functional boundaries of that system move outward.

Phenomenologically, the boundaries created by these contingencies appear to correspond to our sense of self (what is under our control, part of ourselves) and non-self (what is independent of our control, separate from ourselves). Addition of a prosthesis pushes the realm of control outward from our physical bodies such that the epistemic or control cut moves to the point of contingency, which now lies at the distal end of the prosthetic device.

Anything that can be attached to and reliably controlled by a percept-action system, such as devices that augment our senses (microscopes, telescopes, geiger counters), our cognition (computer programs, the internet), our memory (pencil-and-paper memos, the memories of other people) or our motor systems (tools, cars and other vehicles) can function as a prosthetic device that enables extended perception, cognition, memory, and action. The construction of external prosthetic devices extends the mind beyond the boundaries of the biological body.

Functional and phenomenal boundaries can also move inwards into the nervous system by means of iconic neuronal representations that preserve the correlation structure of the sensory flux (Cariani 2012). By virtue of the temporal correlations between stimulus structure and spikes, iconic temporal codes for pitch, rhythm, visual form, and optic flow bring the form of sensory flux into the nervous system. Neural assemblies that recognize particular forms then function as internal sensory surfaces that can subsequently switch behavior. It is thus possible to think of the formation of new neural assemblies in terms of creating new concept-primitives, which serve as new windows on the internal milieu of iconic neuronal representations that in turn carries the correlation structure of the external world within it.

Organization embedded in matter. All of these functionalities are due to relational organizations embedded in material systems. The working ontology is a form of Aristotelian hylomorphism, which sees functional properties as dependent on organization that is embedded in matter (Graham 1987; Modrak 1987).

To summarize these organizational dependencies, animals are *living systems* by virtue of the active regeneration of their organization (material components and relations), conceived in terms of self-production, autopoiesis, metabolism-repair, kinematic self-reproduction, autocatalytic nets), self-modifying systems, and/or semantically-closed self-interpreting construction systems. They are *semiotic systems* because their internal operation can be effectively described in terms of sign-distinctions conveyed via neural pulse codes. They are *informational systems* in that their behavior is mainly determined by distinctions rather than through energetic mechanisms. They are *autonomous purposive systems* because they are mainly driven by internal goals. Animals have their own *agency* to the extent that they have embedded goals (internal motivation), requisite ability (the right mechanisms needed for action) and sufficient freedom of action (autonomy) to reliably achieve particular goals. Animals are *anticipatory systems* if they have learning and memory mechanisms that allow them to project the past into the present so as to predict future consequences of current courses of action. They are *adaptive* because they can modify themselves

in a manner that improves their performance vis-a-vis evaluative criteria (survival, reproduction, health). They are *emergent* both because they can create both new combinations of existing structural and functional primitives and because in some cases they can create new primitives as well.

If one defines these different attributes in terms of these specific, distinguishable kinds of *functional organizations*, then a system, such as an autonomous robot, need not be living to be semiotic, autonomous, purposive/agentive, anticipatory, and/or adaptive. In this view, because these functional attributes depend on different aspects of organizations, although biological organisms have all of these attributes, it is not necessarily the case that *living = purposive = semiotic = anticipatory = adaptive = emergent* (see discussion of teleology and autonomy in (Thompson 2007)).

III. A neuropsychological and neurophenomenal framework

Neuropsychology involves the relation of neural processes to mental operations and functions. A more explicitly neuropsychological framework for mental operations and neural processes is shown in Figure 3. It includes operations related to perception (sensations), cognition (recognitions, thoughts), emotion (feelings), conation (goals, drives), memory (short- and long-term), global state control (wake-sleep cycles), and mechanisms for switching between behavioral programs associated with different goal states (action-switching and attention). Although they constantly interact and influence one another, the processes of perception, cognition, emotion, conation, memory, and the execution of action nevertheless involve distinct and relatively autonomous *types* of operations.

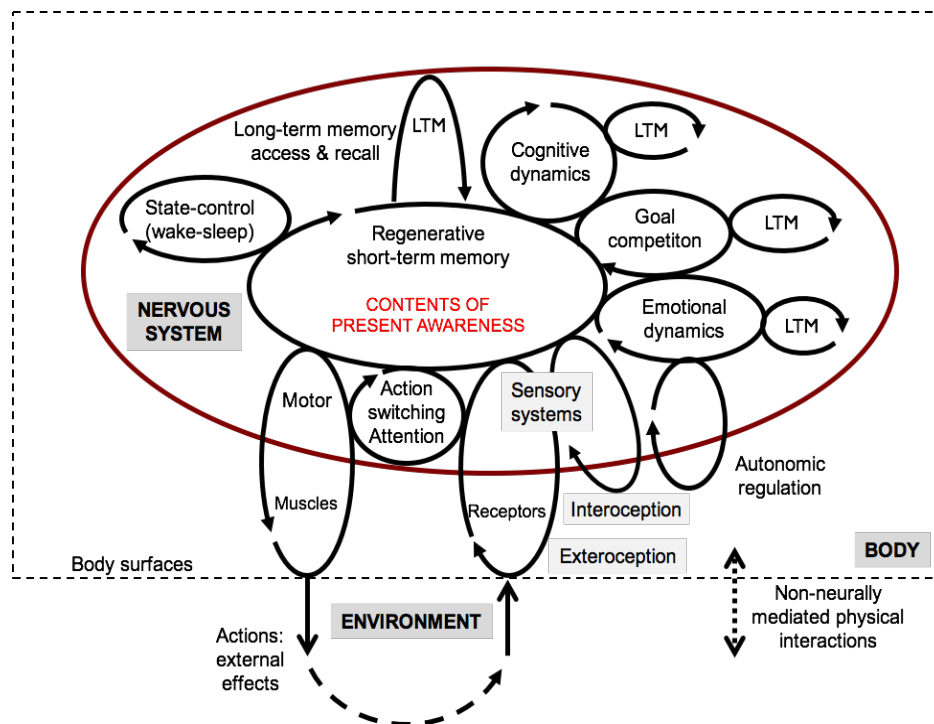


Figure 3. Mind-brain as a network of circular-causal processes. The three realms of environment, body, and nervous system are outlined. Within each of the loops, alternative sets of competing neural signals related to different types of distinctions (sensory, motor, cognitive, affective, conative, state-associated) build-up, compete, and are actively regenerated or die out. Those signals that are actively regenerated in global short-term memory are hypothesized to

form the contents of conscious awareness at any given moment. The model is signal-centric (vs. connection-centric) in that the signals are assumed to be complex, higher-dimensional temporal patterns of spikes that interact on selected dimensions, such that signal dynamics realizes most informational functions.

The schematic demarcates boundaries between environment, body, and nervous system. Each functionality itself has many subdivisions that are not shown. For example, the sensory functionality would include exteroceptive senses such as vision, audition, touch, temperature, smell, taste and interoceptive senses such as pain. In addition to the operations discussed above in the context of percept-coordination-action cycles, this framework explicitly adds short-term reverberating, dynamically regenerative memory and long-term memory storage and retrieval processes, as well as neural circular-causal loops that mediate goal-competition (conation), affect, cognitive processing, regulation of system state (wake-sleep-hypnosis), and the switching of attention. This more detailed framework comes closer to a high-level model of animal minds and mind-body-environment relations than the more abstract and general framework of percept-coordination-action.

Memory and anticipation. In addition to embedded goals, percept-action systems can also have memory mechanisms, which enable vastly more efficient adaptive learning mechanisms. Systems without memory are reactive, they are determined by their immediate inputs, whereas the behavior of systems with memory depends not only on current outputs but also on their past history. Memory involves the making of records that persist in time such that they can be read-out and utilized at future times. All organisms have a genetic memory embedded in their DNA that contains sequences of nucleotides that specify the construction of specific proteins.

In percept-action systems, memory permits action to be made contingent on temporal sequences and patterns of perceived events rather than on only current perceptual states. Memory also permits actions to be sequenced and timed to form complex patterns of linked actions. The ability to handle temporal patterns of sensations and actions dramatically increases the dimensionality of percept-action spaces. Memory enables anticipation of future events and rewards on the basis of past experience combined with current conditions. Memory mechanisms that record sequences of internal state transitions can be used as templates for guiding behaviors that increase likelihoods for reward and decrease those for punishment (Cariani 2017).

System modes. Almost all animals have cycles of activity and inactivity associated with wake-sleep cycles. Many animals exhibit short-lived quasi-hypnotic states (birds, reptiles) and orgasmic states. Humans also have various system-states that are associated with different states of consciousness: e.g. hypnagogia, hypnosis, trance, meditation, ecstatic spiritual states.

Behavioral modes. Animals engage in a relatively limited number of behavioral modes that include basic activities such as drinking, eating, eliminating, fleeing, fighting, grooming, courting, mating, resting, exploring, playing (Kilmer and McCulloch 1969). Many, but not all, of these modes, involve actions.

Neural implementation. Each functionality is subserved by sets of recurrent neuronal circuits. The brain is a network of recurrent, cyclic paths, i.e. circuits, “loops” that realize circular-causal feedback processes. For example, the neural interconnections between thalamus and cortex and between cortical regions are reciprocal — for every “forward” projection there is a re-entrant “reverse” projection. The hippocampus itself contains an array of recurrent paths that have been thought to implement an autoassociative memory.

In the brain different types of structures appear to perform different classes of functions. Roughly, the cerebral cortex performs pattern-analysis, recognition, and generation; the striatum switches between motor programs and attentional facilitations of sensory information according to

immediate goals (tasks); midline dopamine circuits engage in reward evaluation, predictive timing, and adaptive reorganization of neural circuits; the hippocampus rebroadcasts neural signals related to hedonically salient events to enable formation of long term memories; the cerebellum carries out fine timing adjustments; the amygdala carries out threat assessments of novel stimuli.

Different regions of the cerebral cortex realize different functions mainly due to the correlational structure of their inputs, which depends on how they are situated in relation to sensory and motor surfaces and to other cortical regions. However, a given patch of cortex may realize multiple functions simultaneously (e.g. encoding multiple attributes of a sound or visual event), and regions of cortex deprived of their normal inputs (such as the visual cortex in a blind person) can eventually be repurposed to subserve other kinds of perceptual and cognitive functions. It now appears that music perception and cognition activate most of the same cortical territories as speech and language functions. All of this casts doubt on the kinds of extreme modularities and dedicated functional specificities that some neurocognitivists ascribed to particular cortical regions.

Neurophenomenology. Neurophenomenology involves the relation of neural processes to the structure of experience, both the requisite conditions for having an experience (NCCs, “neural correlates of consciousness”, (Koch 2004), i.e. neural requisites for states of consciousness) and the specific conditions that produce a specific experience (NCCCs, “neural correlates of the contents of consciousness”, i.e. the neural concomitants of qualia). Neurophenomenological theories have always existed alongside neurological, neurophysiological and neuropsychological investigations (Boring 1933, 1942; Troland 1929; Fessard 1954; Köhler 1947) as theorists have attempted to relate the structure of neural activity with that of their own subjective experience, e.g. (Varela 1996).

This framework assumes that neural signals, however structured, circulate in the various functional circuits that subserve the different functionalities. My working hypothesis is that the phenomenal concomitants of sets of neurally-coded signals that are actively regenerated in global loops at any given moment constitute the contents of awareness. Further, the contents of awareness at any given moment is isomorphic to the specific neural signals that are present in those loops.

Neural codes. The nature of the neural signals circulating in the circuits is critical. The neural coding problem entails identifying which aspects of neuronal activity subserve informational functions and phenomenal distinctions (which aspects of neural activity constitute differences that make a difference for mental functions and subjective experiences). For perception, the neural coding problem entails identifying which aspects of neuronal activity are related to different perceptual attributes (e.g. for a musical note, its loudness, duration, pitch attributes, timbral qualities, and apparent spatial location).

A working assumption is that in order for neural signals to be propagated and regenerated within the system their constituent patterns of neural activity must be organized in a form that is meaningful to the system, i.e. it must be in the form of a recognizable *neural code* (Perkell and Bullock 1968; Cariani 1995a, 2001c).

Neural codes can be divided into channel codes and temporal codes, depending on how informational distinctions are represented within the system, i.e. which aspects of neuronal activity convey information. Channel codes depend on which neurons are responding, and rate-channel codes depend on profiles of firing rates across neurons, i.e. which neurons are firing how rapidly. Temporal codes, on the other hand, depend on different patternings of spike timings, rather than which particular neurons are producing them. Figure 4A shows some examples of simple and complex temporal codes.

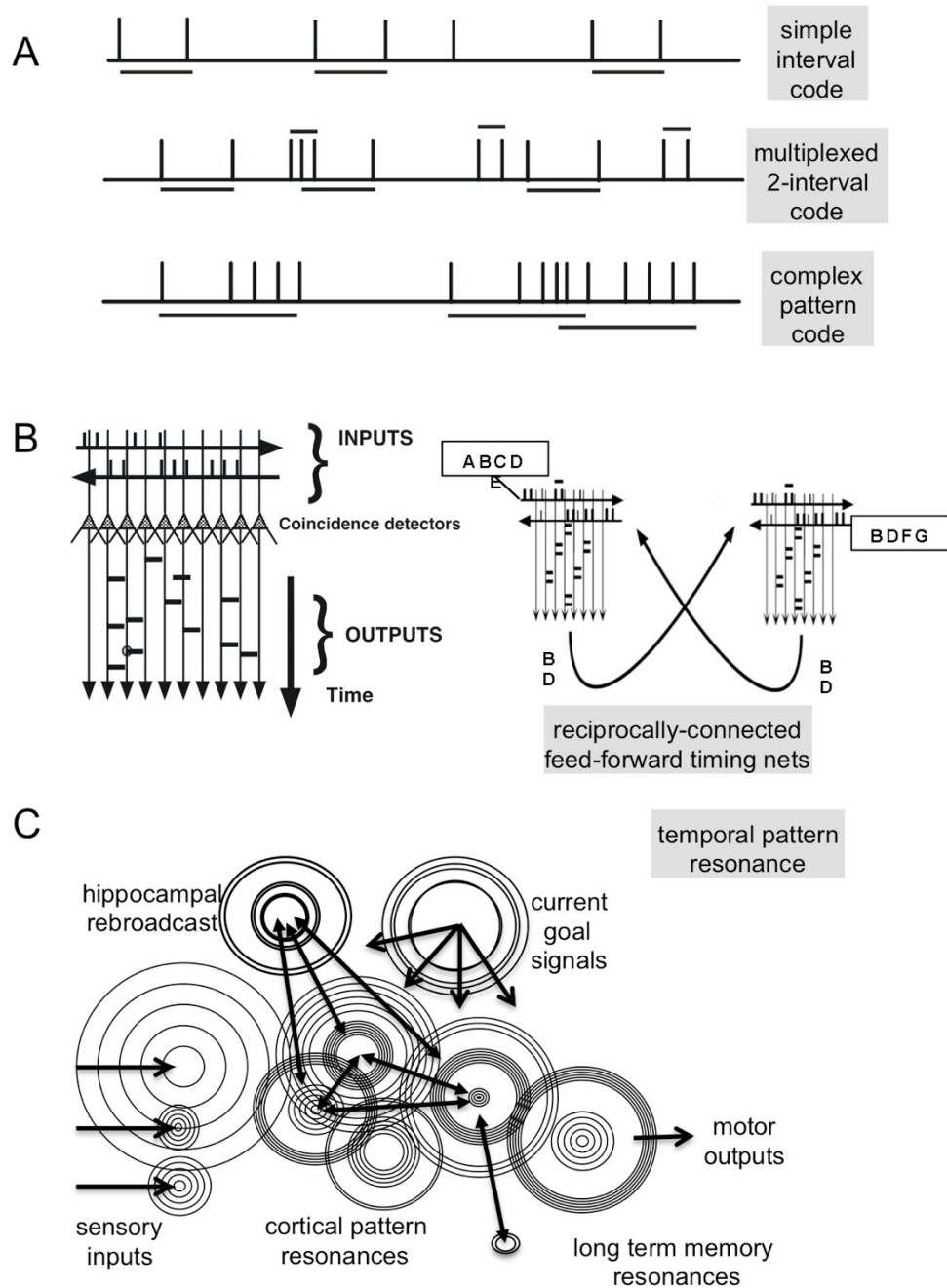


Figure 4. Temporal codes, neural timing nets, and signal dynamics. A. Examples of simple and more complex temporal codes. Complex temporal codes permit signal multiplexing – multiple types of distinctions to be conveyed over the same transmission lines. B. Neural timing nets and signal dynamics. When signals in two reciprocally-connected regions share the similar feature-related subpatterns, they mutually reinforce each other, such that the common signal-dimensions build up. C. Interference and reinforcement dynamics of neural signals. Broadcast of temporally coded signals. Neural assemblies tuned to particular combinations of temporal patterns emit characteristic tag patterns that indicate the recognition of that particular feature-combination. From Cariani (2015).

Temporal pulse codes have a number of advantages vis-a-vis rate-channel codes. First, signals are no longer tied to particular transmission lines or paths (liberation of signals from wires permits broadcast strategies of coordination). Simple signals can be combined (multiplexed) to form vectorial signals that can be multiplexed, i.e. transmitted concurrently over the same lines.

Temporal codes. Temporal codes can be found in many diverse places in the nervous system (Cariani 1995b, 2001c; Mountcastle 1967). I have investigated the neural coding of pitch, mainly in early auditory stations, and the evidence for temporal coding of pitch at that level is quite strong. Given the statistics of neural spike timing patterns (interspike intervals) it is possible to predict with a high degree of accuracy and reliability which pitches will be heard under normal circumstances (Cariani and Delgutte 1996; Cariani 1999). Random, uncorrelated neural activity does not normally appear to contribute to specific perceptual qualities or we would constantly experience the flicker, roar, smell, and taste of spontaneous activity in our brains.

All distinctions that our brains make and of which we are consciously aware are presumed to be conveyed, processed, stored, and regenerated in the form of properly structured neural codes. Further, it is hypothesized that all attributes associated with sensations, thoughts, feelings, motivations, and memories are encoded in a single framework, a *lingua franca* of the brain that is analogous to that of the cell, the genetic code.

Brain function through signal dynamics. The temporal theory of brain function holds that the brain is a vast network of delay loops in which neural signals in the form of correlated temporal patterns of spikes are actively regenerated through neural pattern-amplification processes. The functional states of the brain involve recurrent activity in which signals persist over time (tens to hundreds of milliseconds or more). Those sets of neural signals that are actively circulating at any given time determine the contents of awareness, whereas the ability of the system to actively regenerate signals determines the state of consciousness (e.g. waking vs. anesthetized). Which circuits of the brain can support active regeneration determine the particular state of consciousness. For example, the waking, alert state is associated with regeneration in both local and global networks, whereas sleep is associated with regeneration in only local networks. Trance, hypnosis, meditation, and other kinds of states may be associated with particular patterns of signal regeneration in subsets of circuits.

The crucial difference between those waking states that support conscious awareness and anesthesia- and seizure-produced states that do not is due entirely to the differences in the organization of neural activity. The main effect of general anesthetic agents in abolishing awareness may involve disruption of neuronal temporal response properties that are critical for signal regeneration, in effect scrambling temporally coded signals rather than suppressing gross levels of neural activity (Cariani 1997; Cariani 2000a).

The proposed theory is very similar to neural local and global workspace theories of the neural basis of consciousness in that these also hold that the contents of our awareness are determined by patterns of activity in global and/or local recurrent networks. The reason that recurrent activity is critical is due to the self-regeneration of neural signals – closing the loop allows signals to amplify themselves and therefore to persist within the network.

Although the temporal theory has some commonalities with Varela and Thompson's theory that relies on dynamics of nonlinear oscillators (Thompson and Varela 2001), it differs from that theory in that the temporal theory relies on asynchronous temporal spike patterns rather than on neuronal synchronies and oscillations (the neural correlates of perceptual features were never clearly spelled out in their theory).

The temporal theory also assumes that there is a strong dimensional structure to perception (not unlike the structuralism of Wundt, Titchener, and Boring (Boring 1942)) that is a reflection of a the dimensional structure of neural coding space (Köhler's concept of psychoneural isomorphism between percepts and underlying neural processes).⁴

The temporal theory comes out of temporal models of pitch (Cariani 1999; Cariani and Delgutte 1996), which explain a wide array of pitch percepts in terms of patterns of spikes in neuronal ensembles – temporal codes based on interspike interval patterns (Fig. 4A top spike train). The temporal theory differs from connectionist models in that the neural signals are temporal patterns of spikes present in populations of neurons (spike correlation patterns, irrespective of which particular neurons are involved) rather than patterns of average firing rates amongst neurons (which neurons fire how often). Arguably, purely connectionist architectures, because of their need to highly regulate neural transmission paths and connection-weights, are inadequate to account for the flexibility of mental processes.

As an alternative to connectionism, I have proposed neural timing nets (Fig. 4) that consist of arrays of delay lines and spike-timing-facilitated coincidence elements that would implement reverberating short-term memory circuits and pattern analysis (Cariani 2001a; Cariani 2002; Cariani 2004). The neural timing networks are "signal-centric" in that the expressive combinatoric potential of the system relies on complex multidimensional signals and relatively simple neural substrates. This contrasts with the anatomical, "connection-centric" connectionist schemes which rely on simple scalar signals (running firing rates) and very complex patterns of synaptic connections and efficacies. Connectionist networks operate through summation and thresholding of weighted scalar signals, whereas timing nets carry out "delay path computations."

Complex temporal codes potentially support multidimensional representations, signal multiplexing, and broadcast-based coordinations (Cariani 2017, 2015a). Complex temporal codes also potentially support signal dynamics, in which complex temporal patterns interact to mutually reinforce those subpatterns that are common to them. It is then possible to envision a bottom-up dynamics of neural signals that obviates the need for the symbols-and-rules schemas that are typical of computationalist models of cognitive processes.

In the neural timing theory, the regeneration of signals in neural delay loops creates self-sustaining patterns of neural activity. Signal regeneration is needed to create sustained functional brain states that can switch behavior. The ability to regenerate signals within global loops is the necessary and sufficient condition for conscious awareness in the waking state. The particular signals that are regenerated in global loops at any given time determine the contents of awareness. This hypothesis is similar in many respects to current theories of the neural requisites for conscious awareness that rely on re-entrant neuronal activity in local and global circuits (Dehaene 2014; Lamme 2006).

An analogy can be made with autopoiesis, which entails networks of material components and relations that interact to regenerate the constituent components and relations. In the neural case, rather than material components, distinctions in the form of internally-distinguishable pulse patterns (neural signals) are regenerated (Cariani 2000b). Such self-production networks realize organizational closure by creating an inside and an outside. The inside is an internal realm of autonomous circular-causal control by the self-production network and the outside is an external realm that is not under the control of the self-production network.

⁴ Neural dynamical systems typically have much, much higher degrees of freedom, so to effectively model the lower dimensional structure of perception, with its stimulus equivalences and relative invariances under transformation, it is necessary to find lower dimensional descriptions of neural dynamics.

The theory is still rudimentary and its details are still being worked out, but what it means is that there are alternatives to both the symbols-and-rules computations of symbolic AI and symbolic cognitive science and the standard connectionist neural networks.

Similarities with other theories. The theory does share many assumptions with connectionist theories of brain function and consciousness (Rose 2006). Both connectionist and neural timing theories assume that our immediate awareness is mediated by short-term memory mechanisms (sensory memory, working memory), which is labile such that it is subject to disruption by sleep, anesthesia, attentional changes, and additional stimuli. Long-term memory is mediated by a quasi-permanent storage and retrieval process that is highly resilient to these aforementioned disruptions. Both theories hold that the contents of our awareness depend on the neural activity patterns that are actively regenerated in reverberating short-term memory loops. Connectionist theories emphasize ensembles of neurons that maintain higher firing rates through short-term synaptic facilitations, whereas the temporal theory emphasizes the active maintenance of temporal patterns in reverberating delay loops through spike timing dependent facilitations.

Differences with complexity-based theories. The theory diverges from those that postulate a necessary threshold degree of informational complexity for awareness (Tononi 2005). In the theory proposed here organizational closure (through signal regeneration) rather than informational complexity per se is the critical organizational substrate.

Differences with strong enactivism. This proposed neuropsychological and neurophenomenal theory is embodied and supports mental functions that are extended into the environment (e.g. extended cognition). It is weakly enactivist in that it holds that externalized action is the central *raison d'être* for most mental functions. However, it departs from strong enactivism on several fronts: 1) there are other modes of activity that are inwardly focused such that action is not the absolute end-all and be-all of existence⁵, 2) conscious awareness is a product of activity in the brain (consciousness and meaning are in the head), and 3) although perception and other mental operations are influenced by action, strong motor theories of perception (i.e. no perception without motor system activation) are easily falsified (Hickok 2014). The relation between processes of action and those of perception, cognition, affect, conation, and memory appears to be more bi-directional and reciprocal in nature than would be assumed by strong motor theories. In my view, each process has some relative autonomy vis-a-vis the others.

Some of the disagreements may also be more rhetorical than substantive, and stem from redefinitions of terms such as consciousness, cognition, information, representation, and computation. In many of the talks about the philosophy of enactivism at the conference, a

⁵ Action isn't everything we do or experience. Externalized action is not the only activity that mind and brain engage in. In listing different general modes for audition, I count an *ecological mode*, in which we listen in order to gain information about our environments for purposes of orientation and action, a *communicative mode*, in which we listen to speech in order to discern a message, an *aesthetic mode*, in which we listen (usually to music) in order to modulate our own internal psychological states in desirable ways, and an *annoyance mode*, in which we are forced to listen to sounds that interfere with our desires (goals). Orientation is not action *per se*. Understanding speech is not itself action. In the case of listening to music in the aesthetic mode, the purpose does not involve externalized action on the world, but an internal change in the contents of awareness. Many forms of meditation and thoughtful reflection are similarly inwardly-directed. In contrast to strong-enactivist perspectives that mandate that everything we experience must necessarily be related to externalized action, these counterexamples suggest that while the coordination of action may be the most important of all mental activities, certainly in terms of survival and reproduction, there are nevertheless realms of mental activity and experience that are not themselves directly related to it. Action (overt behavior) is not all that there is to brain, mind, and experience.

dichotomy of perspectives was presented that pitted symbolic AI and computationalist cognitivism against dynamicist-enactivist frameworks, without any third or fourth alternatives. Discussions of these definitions and perspectives are sometimes much more nuanced and flexible in the enactivist literature (Thompson 2007).

I have agreed all along with many of the deep criticisms leveled at the platonic ontology and realist epistemology that animates computationalism (Cariani 1989). The computationalist ideology marginalizes interactions with the environment (perception and action) and precludes even the possibility of the emergence of fundamental novelty (Cariani 1992; Cariani 2012). However, in formulating alternatives, it is critical to avoid false dichotomies, because there are almost invariably multiple perspectives that incorporate, subsume, and sometimes transcend the presumed dichotomies. It is absolutely necessary to get beyond both symbols and rule-systems and low-level dynamics if we are to understand minds and brains work (Cariani 2001b). In this respect my approach, at the level of interactions of analog temporally-patterned neural signals, is similar to the middle-level representations of Prinz (Prinz 2012).

IV. Temporal commonalities of perception and action

Traditional theories of brain function are largely atemporal in that they assume that perception and action are mediated by average rates of neural firing. However, there is strong evidence that many percepts depend on stimulus-driven temporal patternings of spikes. Here sensory stimuli impress their temporal structure on the firings of neurons, on both microtemporal scales (e.g. pitch, timbre) and on macrotemporal scales (rhythm).

Rhythm may well be directly temporally-coded. Rhythmic patterns consisting of discrete sensory events separated by 100 ms or more produce brisk event-onset responses that reproduce the temporal structure of the rhythms in sensory pathways up to and including the cortex. It has been known for quite a long time that such rhythmic patterns can be observed in cortical gross potentials (auditory evoked potentials, event-related potentials). For the most part, rhythm has been modeled in terms of clocks, modulation-tuned neurons, and nonlinear oscillators rather than as a direct temporal code. Recently temporal correlates of both experienced and imagined rhythms have been found (Nozaradan 2014; Nozaradan et al. 2013; Nozaradan et al. 2011). These would be similar to the temporal patterns that would be generated in motor regions in producing the same rhythms.

Recently, experiments with passive haptic learning have demonstrated that presenting temporal patterns of experienced pianists to the fingertips of untrained subjects greatly accelerates the learning of piano pieces (Starner 2013).

Such temporal codes produce iconic internal neural representations that import the correlation structure of the environment into the nervous system. Likewise, on the motor side, coordinated action requires precise temporal patterning (relative timing) of muscular activations. When muscles contract, stretch receptors and mechanoreceptive afferents produce spikes that are phase-locked to the resulting movements. These temporal patternings of body movements are in turn fed back into the brain such that the brain is continually bathed in the temporal structure of actions. The ensuing action on the environment, such as drumming the rhythmic pattern, creates still other temporal feedbacks in other sense modalities (vision, touch, hearing).⁶

⁶ It is also conceivable that our emotions are conveyed via characteristic temporal pattern codes (Clynes 1977), such that music and dance evoke emotional feelings by directly, albeit weakly, creating internal temporal patterns that mimic those codes. There exist pervasive parallels between music, movement, and emotion (Sievers et al. 2013). This

Thus, there may be a common neural language that underlies the temporal aspects of perception and action, such that perception and action can mutually inform each other in a direct manner. Hearing a musical rhythm provides a temporal scaffold for timing movements, and the timing of movements reinforces the perceived rhythmic structure of the music.

V. Acknowledgement

I would like to thank the Office for Faculty Development at the Boston Conservatory @ Berklee College of Music for generous travel support that enabled me to attend this meeting.

VI. References

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would be a means by which the *form* of music and dance could itself be emotional (Langer 1942), and it provides a possible explanation for why these temporal art forms have the manifold expressive emotional powers that they do.

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