

Outline of a Temporal Theory of Brain Function

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Alternatives to purely connectionistic neural networks are possible. Whereas classical connectionist, "switchboard" theories of brain function assume rate-channel neural coding of information (which neurons fire how often), evidence for temporal codes (characteristic temporal patterns of correlated spikes) has been found in nearly every brain region. Can central brain functions be reconceived in terms of temporally-coded neural signal dynamics rather than patterns of channel activations? Here we outline a putative, high-level temporal architecture for brains based on multiplexed, multidimensional temporal codes and neural timing nets (Cariani, 2015).

Connectionist networks are notoriously inflexible, requiring many training signals and adaptive iterations. The reason is inherent in the basic neural coding assumptions of connectionism, viz. functional brain states can be completely characterized in terms of neural firing rates, synaptic connection weights, and membrane thresholds. Signals require two independent dimensions: signal type (category, observable) and signal value (what is the specific distinction being conveyed). In connectionist systems, network-identities of particular neurons convey signal types, whereas firing rates (or other markers, such as relative spike latencies) convey unitary signal values. The scalar, unitary nature of firing rates precludes multiplexing. Signals are tied to particular neural elements and transmission paths, committing these neural networks to switchboard-like information processing architectures.

In contrast, temporal pattern codes bear type information in their form. Population temporal pattern codes convey information via the mass, neural population statistics of temporal correlations between spikes. Because these codes are not tied to specific, individual neurons, such codes permit signal multiplexing and flexible broadcast strategies for communication and coordination. Compare telegraph networks with scalar signals bound to specific wires to radio and computer networks, where multiplexed signals are liberated from specific transmission paths.

Temporal pattern codes range from simple iconic codes (e.g. iconic interspike interval codes for pitch and rhythm that follow stimulus periodicities (Cariani, 1999, 2019)) to more complex temporal pattern sequences (Emmers, 1981). Temporal patterns of spikes can be found in virtually all sensory modalities (e.g. pitch, timbre, rhythm, color, visual form, depth, gustation, olfaction, (Cariani, 2001c) as well as in complex motor functions.

Neural networks that operate temporal codes require temporal precision. Historically, *time-delay neural networks* (Jeffress, Licklider) have used arrays of delays, coincidence detectors, and coincidence rate counters to convert incoming temporal patterns of spikes into rate-channel activations for central connectionist networks. Rather than converting coincidences into rate-channel patterns, *neural timing nets* are arrays of delay-coincidence feedforward and recurrent paths that operate on temporally-coded signals to produce temporally-coded outputs. These networks can realize a host of powerful, elegant signal processing operations in the time domain: filtering, correlation, convolution, demultiplexing (Cariani, 2001a). Brains can be regarded as networks of delay loops in which neural conduction and recovery delays and coincidence elements can compare, attenuate, amplify and actively regenerate incoming and circulating temporal patterns of spikes. Coincidence detections that produce output spikes may occur at whole neuron levels or amongst subsets of synapses (intraneural multiplexing).

The result is a signal-centric view of brain function based on temporal pattern resonances and delay-path computations. Those sets of neural signals circulating through delay paths constitute functional brain states at each given moment. Temporal coding supports vectorial representations and signal processing operations that

can constitute a *lingua franca* for all types of information (sensory, cognitive, affective, conative, hedonic, motoric, mnemonic). Although the precise nature of central neural codes is still unknown, our working assumption here is that each sensory or cognitive attribute, including internal goals and hedonic associations, has a distinctive temporal spike pattern within local neural ensembles. The distinctive patterns may be present in individual spike trains, interspersed with other patterns (Emmers, 1981), or distributed over multiple neurons.

Temporally-coded signals can be bound or separated on the basis of common times of occurrence and/or internal temporal structure (Cariani, 2004). Common temporal patterns related to event timings may permit integration of multimodal event-related information arriving at slightly different times.

We assume memory traces are temporally-coded. The purpose of remembering the past is to anticipate the future. A "tape recorder memory" containing temporal sequences of internal neural events, including rewards, when read out faster-than-real time (as in hippocampal replay) can function directly as an anticipatory predictive mechanism to guide prospective behavior (Cariani, 2001b, 2016, 2017). Temporal memory traces may be subserved by transient spike coincidence-based facilitations of specific delay paths, active sustained regeneration of signals in reverberating hippocampal/cortical circuits, long-term temporal pattern storage (molecular-coded? time cells?), and a process for constructing event timelines from distributed temporal fragments.

Objects and events are represented by integrated combinations of temporal pattern primitives, whose signals interact to produce "symbolic" marker tags characteristic of the composite whole (semantic pointers a la Barsalou, Eliasmith). Bottom-up tag activations signify classificatory recognitions whereas top-down tag activations produce neural signals of the constituent features (temporal convolution/deconvolution, Longuet-Higgins, 1989).

This architecture bears some of the attractive features of both classical symbolic systems and parallel, distributed neural systems. It flexibly enables compositional representations, permitting combinatoric creativity. Adaptive modification of neuronal assemblies to create new symbolic tags enables open ended increase in the dimensionality of the signal-system, permitting emergent creativity: new symbols and concepts (Cariani, 2012).

Conscious awareness depends on the organization of neuronal spiking activity. As in neuronal global workspace theories (Dehaene, Lamme), those neuronal signals that are actively regenerated and stabilized via global circuits are hypothesized to constitute the contents of conscious awareness at any given time. General anesthesia, seizure, sleep, and coma interfere with the coherent regeneration and global integration/stabilization of sets of self-sustaining, mutually-reinforcing neuronal signals. Conscious awareness may depend on organizational closure via regenerative, coherent patterns of neuronal spiking activity, i.e., an autopoiesis of neuronal signal productions, (Cariani, 2000, 2016) rather than the surmounting of a threshold of informational complexity (Tononi).

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