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Outline of a cybernetic theory of brain function based on neural timing nets

Cybernetic
theory of brain
function

1219

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Abstract

Purpose – The purpose of this paper is to outline an integrative, high-level, neurocomputational theory of brain function based on temporal codes, neural timing nets, and active regeneration of temporal patterns of spikes within recurrent neural circuits that provides a time-domain alternative to connectionist approaches.

Design/methodology/approach – This conceptual-theoretical paper draws from cybernetics, theoretical biology, neurophysiology, integrative and computational neuroscience, psychology, and consciousness studies.

Findings – The high-level functional organization of the brain involves adaptive cybernetic, goal-seeking, switching, and steering mechanisms embedded in percept-action-environment loops. The cerebral cortex is conceived as a network of reciprocally connected, re-entrant loops within which circulate neuronal signals that build up, decay, and/or actively regenerate. The basic signals themselves are temporal patterns of spikes (temporal codes), held in the spike correlation mass-statistics of both local and global neuronal ensembles. Complex temporal codes afford multidimensional vectorial representations, multiplexing of multiple signals in spike trains, broadcast strategies of neural coordination, and mutually reinforcing, autopoiesis-like dynamics. Our working hypothesis is that complex temporal codes form multidimensional vectorial representations that interact with each other such that a few basic processes and operations may account for the vast majority of both low- and high-level neural informational functions. These operational primitives include mutual amplification/inhibition of temporal pattern vectors, extraction of common signal dimensions, formation of neural assemblies that generate new temporal pattern primitive “tags” from meaningful, recurring combinations of features (perceptual symbols), active regeneration of temporal patterns, content-addressable temporal pattern memory, and long-term storage and retrieval of temporal patterns via a common synaptic and/or molecular mechanism. The result is a relatively simplified, signal-centric view of the brain that utilizes universal coding schemes and pattern-resonance processing operations. In neurophenomenal terms, waking consciousness requires regeneration and build up of temporal pattern signals in global loops, whose form determines the contents of conscious experience at any moment.

Practical implications – Understanding how brains work as informational engines has manifold long-reaching practical implications for design of autonomous, adaptive robotic systems. By proposing how new concepts might arise in brains, the theory bears potential implications for constructivist theories of mind, i.e. how observer-actors interacting with one another can self-organize and complexify.

Originality/value – The theory is highly original and heterodox in its neural coding and neurocomputational assumptions. By providing a possible alternative to standard connectionist theory of brain function, it expands the scope of thinking about how brains might work as informational systems.

Keywords Cognition, Consciousness, Neural nets, Cybernetics, Autopoiesis, Brain

Paper type Conceptual paper

Introduction

How brains operate as informational engines is still largely an unsolved mystery, and it is far from clear that current connectionist neural network theories can provide adequate explanations. This paper outlines an alternative, cybernetic theory of brain function based on temporal codes and computations.



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Embedded goal systems within percept-action cycles

It has been long recognized by biologists and psychologists that animals perceive their current surrounds and act accordingly, usually appropriately, in successive on-going cycles of sensation, decision making, and action. Processes of deliberation, how an animal decides what to do in a given perceived situation, involve embedded goal systems, and anticipatory action-selection mechanisms that coordinate perceptions and actions.

Nervous systems that implement these coordinations can thus be regarded as cybernetic percept-action systems (Cariani, 2011), i.e. purposive systems whose behaviour is contingent on internal goals, anticipatory prediction and feedback control mechanisms, memory of prior experience, and current sensory inputs (Arbib, 1972; Sommerhoff, 1974; Powers, 1973). The highest level of feedback control switches between largely discrete behavioural modes such as fighting/fleeing/exploring/sleeping/eating/mating (Kilmer and McCulloch, 1969). Affect plays a pivotal role in switching between most of these modes (Barrett and Bliss-Moreau, 2009). Within each mode, various goal circuits compete for control of behaviour on the basis of goal priority (immediate urgency) and current degree of satisfaction (see Verschure *et al.*, 2014 for a contemporary model).

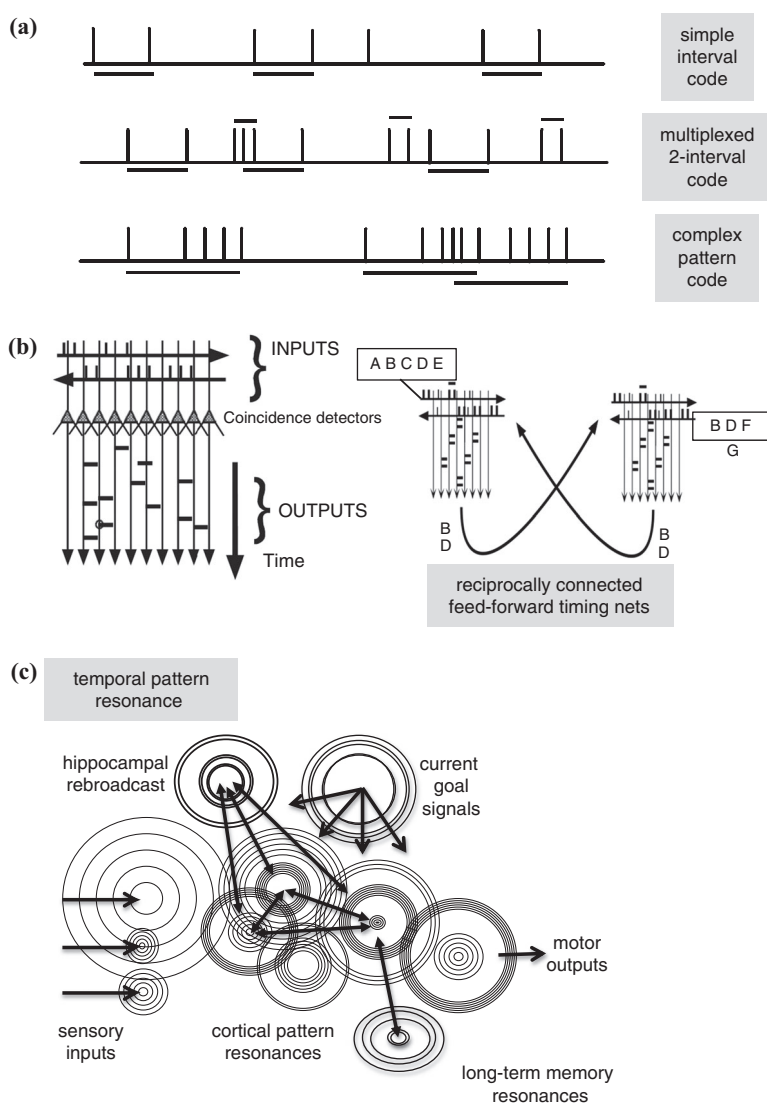
The basic structural plan of animal nervous systems (e.g. Swanson, 2012) consists of a relatively small number of component subsystems that subservise different types of informational functions: sensing (receptors), effecting (muscles), analysing sensory patterns (in mammals, primary and secondary sensory cerebral cortex), object-recognition (multimodal cortex), action-planning (premotor cortex), sequence generation (motor cortex), fine timing control (cerebellum), task-dependent steering systems for gating attention and motor switching (basal ganglia), spatial-relational processing (parietal lobe), regeneration of working memory and memory consolidation (hippocampus), and anticipatory reward prediction and correction systems (midline dopamine circuits). Autonomic systems regulate body functions, with interoceptive sensory organs providing information related to body states (satiety, pain). Limbic analyzers of global internal state provide general dispositions for action (emotions).

Temporal codes and computations

Informational distinctions are mediated through specific patterns of neural activity (neural codes Boring, 1942; Uttal, 1972, 1973; Rieke *et al.*, 1997; Cariani, 1995). In terms of internal, on-going dispositional states and overt behaviours, these are “differences that make a difference”. Neural codes can be divided into channel codes and temporal codes: in channel codes, activation of particular subsets of neurons (channels) convey distinctions (e.g. through across neuron firing rate profiles), whereas in temporal codes particular temporal patterns of spikes convey distinctions.

Connectionist theory adopts the assumption that the central codes operant in brains are firing rate channel codes, whereas the neural timing net theory outlined here posits that these are complex temporal pattern codes. Although channel coding has generally been adopted in the neurosciences as the conventional, default neural coding assumption, throughout the history of neuroscience temporal codes have always been proposed alongside them as alternatives (Boring, 1942). We have previously discussed many of the relative merits of these two kinds of coding schemes (Cariani, 1995, 1999, 2001, 2004).

In simple temporal codes, one temporal parameter conveys one perceptual distinction (Figure 1(a)). For example, in the early auditory system distributions of times between spikes (interspike intervals) produced by the same neurons subservise pitch perception (Cariani, 1995, 1999; Cariani and Delgutte, 1996). The pitch that is



Notes: (a) Simple and complex temporal codes; (b) left, feed-forward timing net (FFTN); right, reciprocally connected FFTNs; (c) visual depiction of pattern-resonance processes, showing signal interactions, mutual reinforcement and competition, goal-driven facilitation, hippocampal rebroadcast, and interactions with long-term memory

Figure 1.
Temporal codes and
computations

heard corresponds to the most common set of related interspike intervals that are produced in the auditory nerve. Binaural auditory localization in the horizontal plane utilizes sub-millisecond spike timing differences produced by corresponding neurons in neural pathways that originate in the two ears. Analogous examples exist in nearly every sense modality (Cariani, 2001b).

Complex temporal pattern codes can be formed from combinations of simple temporal pattern primitives (Figure 1(a)). The appearance of a particular temporal pattern in an ensemble of neurons functions as an independent primitive feature. Combinations of temporal patterns that are present at any given time form a feature-vector. The various patterns can be interleaved or embedded in other patterns of spikes, permitting signal multiplexing (concurrent transmission of multiple types of signals over the same neuronal transmission lines). A complex temporal coding scheme that was proposed in the past for multiple cutaneous sensory qualities (Emmers, 1981) provides a concrete example of how such codes might be organized.

A neural code must convey two types of information – the type of distinction the signal conveys (e.g. pitch vs perceived location) and the attribute distinction itself (e.g. particular pitches or locations). In channel codes, the identity of the channel (which neuron, as determined by its place in the network, its interconnectivities) conveys informational type, whereas patterns of channel activations convey different attribute values. For channel-coding schemes, neural channel-identities maintained via specific interconnections are absolutely critical for function. A neural firing rate is meaningless to the rest of the system without the identity of the neuron that is firing. In contrast, because temporal schemes encode the type of the signal in the form of the message, highly specific interneural connectivities and signal transmission paths are no longer essential for function. Temporal codes thus permit “signals to be liberated from wires” and this in turn enables broadcast modes of signal distribution. Neuronal assemblies downstream can be selectively tuned such that they respond to particular temporal patterns embedded in their inputs. Broadcast, multiplexing, and selective tuning enable decentralized communications in which neural assemblies can respond only to those incoming signal patterns that are relevant to their functional roles. Some codes may be restricted to local neuronal populations (e.g. restricted cortical regions) that handle specific types of information, whereas others may be propagated more globally, re-broadcast by the hippocampus, and then consolidated into long-term memory.

Temporal codes with sub-millisecond precisions can be found in a wide range of sensory systems (Cariani, 2001b). In general, as one proceeds up ascending sensory pathways, away from receptor surfaces, stimulus-related fine timing information becomes successively less apparent, though not completely absent (Cariani, 1999). In the auditory system, despite some progress, cortical representations for basic auditory attributes such as pitch and loudness are still poorly understood (Cariani and Micheyl, 2012), and in lieu of strong coding hypotheses, it is difficult either to confirm or entirely rule out prospective candidate codes. If complex temporal codes exist in central circuits that subservise the representation of all simple sensory attributes associated with events (e.g. the timing, duration, loudness, pitch, and timbre of a single musical note), they may involve longer delays with coarser temporal precisions or precise timing patterns that are difficult to observe because they are distributed across neurons.

These difficulties notwithstanding, temporal patterns of neuronal response associated with the discrete sensory and motor events themselves are very prominent in the cerebral cortex. Central temporal patterns related to temporal sequences of salient sensory events, such as musical rhythms and flashing lights, that occur on relatively coarse timescales ($< 10/\text{sec}$) are widely observed in evoked electrical and magnetic activity at many recording sites (Thatcher and John, 1977; John, 1967). Temporal pattern correlates of musical rhythmic expectancies are also observed (Zanto *et al.*, 2006; Fujioka *et al.*, 2012; Nozaradan, 2014). This evidence argues for temporal coding of musical rhythm at the cortical level. Stimulus-driven temporal response patterns encode the beats that are heard,

whereas stimulus-induced temporal patterns encode beats that are imagined or expected but not present acoustically and not heard. Coarse rhythmic patterns (<10 Hz) are supramodal, with widely distributed neural temporal responses that may explain how musical rhythm can provide a cross-modal temporal scaffold for movement and memory (Thaut, 2005). It should be noted that these stimulus-driven and stimulus-induced temporal patterns are distinct from the more widely studied endogenous brain rhythms that reflect neuronal population dynamics (Buzsáki, 2006). The relation between these neural dynamics and informational functions such as neural coding and grouping processes (Bullock, 1997; John, 1967; Giraud and Poeppel, 2012) remains an open question to this day. One possibility is that neuronal oscillations set the durations of temporal processing windows for interpreting latency-based temporal codes.

There also exist many classical examples of neuronal “assimilation of rhythms” in which neural assemblies internalize the temporal structure of their inputs during conditioning and then once internalized, produce those temporal patterns when activated (John, 1967; Morrell, 1967). Conditioning studies (Miller and Barnet, 1993) and anticipatory neural temporal prediction mechanisms (Schultz *et al.*, 1997) suggest that timelines of all events that lead up to reward are assimilated. If drive states (unmet goals) during conditioning are also broadcast as characteristic temporal patterns mixed in and assimilated with those of other internal events, then the resulting temporal memory trace can contain a representation of the nature and timing of goals pursued as well as specific event sequences and the rewards or punishments that ensued. Such a direct temporal tape-recorder-like representation, activated by similar sets of circumstances and encoded or read-out in faster-than-real-time can make prediction about the occurrence, timing, and likely hedonic consequences of future events.

Temporal processing architectures

We posit a universal temporal coding framework that can potentially handle all kinds of informational distinctions in the nervous system, matched universal short- and long-term memory mechanisms that can store and retrieve such distinctions (John, 1967), and a relatively small number of canonical neurocomputations that operate on temporal patterns. The basic mechanisms for coding, memory, and temporal processing are likely to be phylogenetically ancient. Most brain theories assume short-term reverberatory (echoic, working) memory coupled with long-term fixation. Temporal patterns could be regenerated by more local reverberatory loops over short time spans, re-broadcast by the hippocampus over intermediate spans, and encoded in molecular and synaptic connections over much longer terms. A universal coding system coupled with a universal memory system could provide a common language of distinctions for the brain that would parallel the general-purpose role of the genetic code in the cell.

Neural coding assumptions heavily influence our conceptions regarding the nature of neural information processing architectures. Channel codes lead directly to switchboard-like connectionist architectures that regard neurons as spike count (firing rate) integrators. In contrast, time codes lead to correlation theories of neural signal processing that are based on neurons as temporal coincidence detectors.

Temporal processing architectures take the form of neural time-delay networks (Licklider, 1959; MacKay, 1962), oscillatory networks (Greene, 1962; Buzsáki, 2006), axonal pulse computation trees (Pratt, 1989), synfire chains (Abeles, 2003), polychronous networks (Izhikevich, 2006), wave-interference networks (Heinz, 2010), and timing nets (Cariani, 2001a; Thatcher and John, 1977; John, 1967; Longuet-Higgins, 1989). Many

decades ago Karl Lashley envisioned wavelike, neuronal interference patterns as holograph-like, nonlocal alternatives to switchboard-type theories (Lashley, 1951; Orbach, 1998), and his successors proposed spatial and/or temporal mass-statistical mechanisms for implementing memory storage systems (Freeman, 1975; Pribram, 1971; Thatcher and John, 1977; John, 1967).

As a general rule, neurons in the central nervous system are organized into loops: brains are, first and foremost, “nets with circles” (McCulloch and Pitts, 1943) that have combinatorially large numbers of possible recurrent multisynaptic pathways, each with its own specific delay time. As a rule, regions of cerebral cortex are connected to their corresponding thalamic areas and to other (neighbouring and distant) cortical regions by reciprocal sets of projections that form re-entrant pathways. Another set of recurrent delay-paths can be found in the hippocampal formation, which is often regarded as a spatial, autoassociative memory. In this theory, temporal patterns of spikes circulate through neuronal loops, with the informational contents of the loops being related to the particular temporal patterns that are present. Through the senses and through internal pattern-generators, temporal patterns can be impressed on parts of the system and actively regenerated. The active delay loops that propagate spike patterns function as complex pattern-oscillators. The temporal pattern signals interact in local and global loops, mutually reinforcing or interfering with each other, eventually settling into stable, steady informational, dispositional states that determine and guide action.

Neural timing nets and temporal pattern-resonances

Neural timing nets are information processing architectures that operate entirely on temporal pulse patterns (Cariani, 2001a, 2002, 2004). A neural timing net model assumes representations and operations that stay in the time domain. Whereas connectionist architectures are “connection-centric” (all informational function depends on particular synaptic connection-weightings), neural timing networks are “signal-centric” (action lies in interactions between signals).

Both inputs and outputs of timing nets are temporal patterns of pulses that are processed through arrays of delay lines and pulse coincidence detectors. Feed-forward timing nets (FFTNs) consist of delay-coincidence arrays where input lines cross at many relative delays (Figure 1(b), left). Recurrent timing nets (RTNs) consist of coincidence arrays with delay loops that build up repeating temporal patterns within the loops (such as those produced by rhythmic musical stimuli). FFTNs implement cross-correlation-like operations, RTNs autocorrelation-like ones. Delays can be either monosynaptic (recurrent collaterals) or polysynaptic (delay-paths through networks), with synapses being either fixed or spike timing dependent (inhibited/facilitated by recent spike correlation history). Timing-dependent synapses support competition between signals and winner-take-all dynamics (facilitation of one set of signals inhibits others), as well as the possibility of regenerative, self-facilitating “synfire cycles”.

In timing nets, signals directly interact with each other, by selecting and mutually amplifying sub-patterns they have in common (“pattern-resonances”). A visual metaphor is shown in Figure 1(c). By acting as temporal pattern sieves, they can extract particular sub-patterns from mixtures, enabling signal combinations to be demultiplexed into their primitive components, operations critical for representational compositionality. Some of these basic operations, as applied to auditory features, are presented in (Cariani, 2001a, 2002).

The temporal signal-processing supports vector representations and operations that can potentially subserve Gestaltist grouping processes (Cariani, 2001a, 2004) and as well

as concept-network dynamics (Widdows, 2004). If we regard the constituent temporal patterns in the two spike trains as independent vector dimensions, then FFTNs multiply the two pattern vectors and output only those patterns that are common to the two inputs. The result is that the common sub-patterns in reciprocally connected local FFTNs resonate with each other, causing their multiplicative amplification. Ensembles of signals in different local regions (A, B, C, D, E and B, D, F, G) reinforce only those pattern-dimensions (B, D) that they share in common (Figure 1(b), right). Subsets of such mutually interacting signals will build up those feature primitives that their members have in common and this becomes a basis for perceptual grouping and conceptual coherence.

Timing networks also support content-addressable memory, by permitting high-dimensional representation spaces (Kanerva, 1988) to be searched in parallel. If a temporal probe pattern is presented to a reciprocally connected FFTN with fixed synapses, then that pattern will return if and only if the probe pattern is present in the inputs to the target FFTN. If correlated inputs can facilitate synapses, then injection of a temporal pattern into a timing network leads to its successive recurrent amplification and build up. If the facilitations extend beyond individual synapses to whole neurons, then other delay-paths are also facilitated. These kinds of dynamics can support priming of all neural assemblies that produce the injected pattern, which in turn permits content-addressable search. For example, an injected signal related to a particular attribute (“green”) or object (“elephant”) or goal (“how to satisfy thirst?”) resonates with all other neural assemblies that share the attribute or its components, amplifying their signal-sets, thereby “bringing them to mind”.

The signal primitives activated include associated motor programs for action that have followed goal presentations in the past, such that a search for addressing some particular goal prepares the system to act to achieve that goal. By directly including goal- and action-signals in neural representations, when a goal becomes urgent and its characteristic signal is injected into the rest of the system, pattern-resonance with the goal signal brings forth possible goal-directed actions. This kind of pragmatic, goal-directed content-addressable indexing is evident in animal and human minds, but is almost completely absent from digital computer search systems (which tend to index attributes of objects rather than their manifold possible uses).

The signal productions of a given neural assembly can be regarded as activation of a concept node, with pattern-resonances causing spreading activation (priming) of related concept nodes. Those nodes that have the most signals in common are activated first. Those neural assemblies with similar temporal patterns (encoded features) will mutually stabilize each other and suppress the signal productions of dissimilar patterns.

In cognitive science, feature and vector-based models of concept networks have been developed for lexical semantics (Schreuder and Flores D’arcais, 1989; Widdows, 2004). Many of these exhibit spreading activation through networks on the basis of similarity metrics and stabilization of mutually consistent meanings. There are also tantalizing analogies with Pask’s Conversation Theory, which describes how networks of concepts may be stabilized through mutual resonances and constructive processes. Pask’s theory of concept dynamics provides a “second-order” cybernetic explanation for how the concept-systems of actor-participants can evolve through convergent communicative interactions (Pask, 1996).

Although his theory is rather abstract and formal, it is evident that Pask had concrete, physical and neural implementations of concepts in his mind. His paper on his self-organizing electrochemical device was, after all, entitled “Physical analogues to the

growth of a concept” (Pask, 1959; Cariani, 1993). In other papers, one sees glimpses of how Pask (1980) thought his concept networks might be realized in brains and analog devices, using coupled oscillatory elements (pp. 371-375).

Working along similar lines in the 1960’s, Silvio Ceccato and his colleagues at the Italian Operational School used pulse oscillators to develop a mechanistic signal-processing cybernetic model of concept-based semantic operations (Von Glasersfeld, 2007). Ceccato regarded semantic compositions by observer-actors as concrete constructivist acts in and of themselves and considered their many second-order cybernetic epistemological implications (Parini, 2011). The current research programme in this intellectual lineage strives to identify primitive operations of cognitive information processing (“mind operational semantics”) and to develop a neutrally grounded implementations of these operations (“operational architectonics”) (Benedetti *et al.*, 2010). In a similar spirit, the theory proposed here seeks to explain concept-dynamics in terms of interacting temporal pattern signals that in effect carry out correlation operations on high-dimensional feature vectors.

There are other parallels with Pask’s concept networks as well. In the 1980’s, Paul Pangaro developed a digital computer programme in LISP named THOUGHTSTICKER to implement concept networks and their mechanics (Pangaro, 2001). The interactive programme, which preceded the advent of the World Wide Web and operated under very limited computational constraints, implemented cross-indexed hyperlinks into all other nearby, relevant nodes within a high-dimensional feature and concept space, much the same way that in this timing net theory spreading trajectories of pattern-resonances are conceived to activate successive neural assemblies and their signal productions (concept nodes).

Lastly, some account is needed of how new concepts (categories, perceptual symbols) might be created. Concept-formation is important for constructivist theories of mind and for modelling communication processes in which interacting minds coevolve their own meanings. New neural assemblies can potentially be formed by changing synaptic weights associated with sets of time delays such that a new temporal patterns is emitted when a particular combination of input features and goal signals are presented. The new, emergent temporal pattern would function as a “tag” that a particular combination of features with specific meaning to the system is present (Cariani, 2012). Such “perceptual symbols” (Barsalou, 1999) thus indicate a categorical distinction or concept that goes beyond an arbitrary combination of features.

It is conceivable that the aforementioned neuronal assimilation of rhythms is related to the formation of a new neural assembly. The neural assembly might generate this new tag from the composite pattern of the characteristic features combined with a training, reward signal. The operation should be reversible: by presenting the tag pattern, one should be able to weakly evoke the signals that generated it. A time-domain correlation mechanism for convolution and deconvolution operations that could fulfil this role has been proposed (Longuet-Higgins, 1989). The operation allows for the recovery of constituent features from concept-tags that would be generated via convolution.

Brains can be regarded as powerful, self-organizing content- and purpose-addressable search engines. Questions such as “what color is an elephant?” can be answered by presenting the concept-tag-signal that connotes elephant to cortical regions holding visual memories, thereby evoking imaginary images that weakly produce signals related to the colour grey which in turn activate the lexical node “grey” and the motor assemblies needed to utter the answer). Presentation of the tag-signal to auditory areas weakly

evokes their sounds, to olfactory areas, their smells. By generating a higher level tag pattern and presenting it to a local neural assembly, then seemingly abstract concepts can produce particulars. Through the dynamics of these temporal signal interactions, temporal codes, and timing nets may be able to realize the entailment meshes and concept-logics that are needed for thought and language.

Neurophenomenology

Finally, in addition to accounting for informational functions that subserve behaviour, a full theory of brain function should also seek to explain the structure of subjective experiences that are produced by these systems. Such a theory should provide bridge laws that predict states of conscious awareness and their specific experiential contents (neurophenomenology). The best current hypotheses for the neural correlates of awareness involve recurrent patterned neural activity in global neuronal workspaces that subserve working memory (Dehaene, 2014). Those sets of signals that are actively regenerated in the global loops determine the experiential contents of conscious awareness, whereas the ability itself to coherently regenerate neural signals is held to be the organizational requisite for waking consciousness. The unitary nature of awareness is attributed to multimodal integration of neural information in a “global workspace” (Baars, 1988). Alternate states of consciousness (sleep, hypnosis, meditation, trance) involve different dynamical modes of local and/or global regeneration.

Current hypotheses about the neuronal basis of conscious awareness differ in their (usually implicit) neural coding assumptions. This is the question of how the specific contents of conscious awareness are encoded, i.e. precisely what aspects of neuronal activity patterns are regenerated. Connectionist theories assume that particular subsets of neurons are differentially activated via elevated or depressed firing rates, such that it which ensembles are active determines the contents of subjective experience (Rose, 2006). In this neural timing theory, the signals are circulating temporal patterns, such that circumstances that disrupt the coherent global regeneration of temporal patterns should abolish awareness entirely (anaesthesia, coma, seizure). In both kinds of theories awareness can be disrupted by suppressing (silencing) particular neuronal populations or by rendering incoherent neuronal patterns of activity (scrambling the messages) such that neuronal signals cannot be effectively regenerated (Cariani, 2000). In the temporal theory, neuronal spiking that is not structured such that can be interpreted as part of a code is effectively ignored by the system. In this respect, because it depends on the coherence of neuronal activity, the temporal theory is perhaps closest to E.R. John’s (2002) “hyperneuron” concept of correlated neural activity.

Organizational closure is a fundamental requisite for consciousness in a number of theories. In contrast to hypotheses that posit neural states must attain a threshold informational complexity for awareness (Tononi, 2005), the timing net model posits that the ability of the system to maintain steady informational states through coherent signal regeneration is key (i.e. closing an organizational loop rather than requisite complexity). Organizational closure is also a central requirement for other theories that rely on synchronized mass-oscillatory activity (Varela *et al.*, 2001; Thompson and Varela, 2001; Rudrauf *et al.*, 2003), re-entrant signalling (Edelman, 1992), thalamocortical self-selection of inputs (Llinas and Ribary, 1994), loops anchored in parietal first-person self-space maps (Pollen, 2011), or formal closure of process (Pask, 1979, 1981).

Organizational closure leads to informational autonomy and to the self. Those circular-causal processes generated from within are experienced as self-generated

thoughts, whereas those contingent sensory inputs that switch neural activity patterns from without are experienced as external sensations. Those autonomous sensorimotor routines that come to effectively control some aspect of the outer world, thereby eliminating contingency, become unconscious automatisms. The functional and phenomenal boundaries for the self, which inform our perceptions of agency in others and of our own sense of our selves, may flow directly from these domains of internal vs external causation (what our brains reliably control and what they do not control).

Conclusions

The timing net theory outlined here provides a general cybernetic, neural model of information processing in brains that utilizes temporal pattern pulse codes and temporal pulse coincidence computational operations. The timing theory provides an alternative to connectionist models of brain function that are based on average firing rates and specific interneural connectivities (synaptic weights). A universal, complex temporal pulse pattern coding scheme is proposed that permits multiplexing of neural signals in pulse trains of individual elements and the pulse-pattern statistics of ensembles of elements. A neural architecture consisting of tapped delay lines, delay elements, and pulse coincidence detectors with spike timing dependent plasticity operates on the complex temporal pulse patterns.

Reciprocally connected ensembles of these delay-coincidence arrays build up those temporal patterns that are common to both ensembles (pattern-resonance). Those sets of temporal pattern signal productions that are mutually reinforcing build up, circulate, and prevail in the network of loops formed from interconnected ensembles (an autopoiesis of neuronal signals). The set of signals circulating in the network at a given time constitute the functional state of the system and predispose (prime) the system for subsequent incoming neuronal signals (attention, context) and actions. The forms of the circulating signals that have been actively regenerated by the network beyond a threshold signal-to-noise ratio constitute the contents of conscious awareness at any moment (neurophenomenological bridge laws).

The theory as it stands is in a highly tentative, formative state. Further elaboration, refinement, and eventual empirical testing of several key elements is needed: universal temporal coding schemes (neural coding), pattern-regenerative processes (organizational stability), perceptual symbol (concept) formation, and reversible compositional operations (combinatorial meaning).

The neural coding problem for this theory entails formulation of a universal framework within which all internal distinctions can be expressed. Universal temporal coding schemes permit distinctions related to different informational functions (e.g. sensory attributes, cognitive representations, goal states) to be processed using the same analysis, storage, and retrieval operations. If all internal distinctions can be expressed in terms of complex pulse patterns (e.g. complex spike latency patterns), then one canonical set of temporal neurocomputational operations can suffice to realize all informational functions.

The theory holds that the functional state of the brain (i.e. a mental state) is determined by which sets of temporally coded signals are being actively regenerated in neural circuits at any given time. Exactly how such temporal patterns might be actively regenerated in networks with realistic neuronal parameters is an open problem. Its solution would entail demonstration of how spike pattern statistics of neuronal ensembles could be maintained over time, and thus how short-term temporal pattern memories could operate.

Temporal operations for perceptual symbol formation are needed to produce emergent tag patterns that signify grouped features and meaningful associations. The operation should be partially reversible: the symbolic tag pattern should be able to weakly elicit production of the lower level features that were originally associated. Reversible compositional operations are needed for combinatorial representational systems (concept combinations, language). Ideally perceptual symbol formation and compositional operations should be realizable through signal interactions (mechanics of high-dimensional temporal pattern vectors).

Despite its heterodox neural coding assumptions, the theory offers a heuristically useful neurocomputational alternative to connectionist theory that is flexible, purposive, informationally open, organizationally closed, and self-organizing.

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