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Consciousness CLEARS the mind

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Abstract

A full understanding of consciousness requires that we identify the brain processes from which conscious experiences emerge. What are these processes, and what is their utility in supporting successful adaptive behaviors? Adaptive Resonance Theory (ART) predicted a functional link between processes of Consciousness, Learning, Expectation, Attention, Resonance and Synchrony (CLEARS), including the prediction that "all conscious states are resonant states". This connection clarifies how brain dynamics enable a behaving individual to autonomously adapt in real time to a rapidly changing world. The present article reviews theoretical considerations that predicted these functional links, how they work, and some of the rapidly growing body of behavioral and brain data that have provided support for these predictions. The article also summarizes ART models that predict functional roles for identified cells in laminar thalamocortical circuits, including the six layered neocortical circuits and their interactions with specific primary and higher-order specific thalamic nuclei and nonspecific nuclei. These predictions include explanations of how slow perceptual learning can occur without conscious awareness, and why oscillation frequencies in the lower layers of neocortex are sometimes slower beta oscillations, rather than the higher-frequency gamma oscillations that occur more frequently in superficial cortical layers. ART traces these properties to the existence of intracortical feedback loops, and to reset mechanisms whereby thalamocortical mismatches use circuits such as the one from specific thalamic nuclei to nonspecific thalamic nuclei and then to layer 4 of neocortical areas via layers 1-to-5-to-6-to-4.

Keywords: Consciousness; Learning; Expectation; Attention; Resonance; Synchrony; Gamma oscillations; Reset; Cortical layers; Thalamus; LAMINART

1. Introduction

Adaptive Resonance Theory (ART) proposes that there is an intimate link between an animal's conscious awareness and its ability to learn quickly about a changing world throughout life. In particular, ART points to a critical role for "resonant" states in driving fast learning; hence the name *adaptive resonance*. These resonant states are bound together, using internal top-down feedback, into coherent representations of the world. In particular, ART proposes how learned bottom-up categories and learned top-down expectations interact to create these coherent representations. Learned top-down expectations can be activated in a data-driven manner by bottom-up processes from the external world, or by intentional top-down processes when they prime the brain to anticipate events that may or may not occur. In this way, ART clarifies one sense, but not the only one, in which the brain carries out predictive computation.

When such a learned top-down expectation is activated, matching occurs of the top-down expectation against bottom-up data. If the bottom-up and top-down patterns are not too different, such a matching process can lead to the focusing of attention upon the expected clusters of information, which are called *critical feature patterns*, at the same time that mismatched signals are suppressed. A resonant state emerges through sustained feedback between the attended bottom-up signal pattern and the active top-down expectation as they reach a consensus between what is expected and what is there in the outside world.

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ART predicts that all conscious states in the brain are resonant states, and that these resonant states can trigger rapid learning of sensory and cognitive representations, without causing catastrophic forgetting. This prediction clarifies why it is easier to quickly learn about information to which one pays attention. ART hereby proposes that one reason why advanced animals are intentional and attentional beings is to enable rapid learning about a changing world throughout life.

Psychophysical and neurobiological data in support of ART have been reported in experiments on vision, visual object recognition, auditory streaming, variable-rate speech perception, somatosensory perception and cognitive-emotional interactions, among others. Some of these data are summarized below. Others are reviewed in Carpenter and Grossberg (1991), Grossberg (1999b, 2003a, 2003b, 2003c), and Raizada and Grossberg (2003). In particular, ART mechanisms seem to be operative at all levels of the visual system, and it has been proposed how these mechanisms are realized by laminar circuits of visual cortex as they interact with specific and nonspecific thalamic nuclei (Grossberg, 2003b; Grossberg & Versace, submitted for publication; Raizada & Grossberg, 2003; Versace & Grossberg, 2005, 2006). These laminar models of neocortex have been called LAMINART models because the laminar anatomy of neocortex embodies the types of attentional circuits that were predicted by ART (Grossberg, 1999a). Most recently, it has been proposed how a variation of these laminar neocortical circuits in the prefrontal cortex can carry out short-term storage of event sequences in working memory, learning of categories that selectively respond to these stored sequences, and variable-speed performance of the stored sequences under volitional control (Grossberg & Pearson, submitted for publication; Pearson & Grossberg, 2005, 2006). These examples from vision and cognition show how both spatial and temporal processes can be carried out by variations of the same neocortical design, and point the way towards a general theory of laminar neocortex that can explain aspects of all higher-order intelligent behavior.

1.1. What vs. where: Why procedural memory is not conscious

Although ART-style learning and matching processes seem to be found in many sensory and cognitive processes, another type of learning and matching is found in spatial and motor processes. Spatial and motor processing in the brain's Where processing stream (Goodale & Milner, 1992) obey learning and matching laws that are often *complementary* (Grossberg, 2000b) to those used for sensory and cognitive processing in the What processing stream of the brain (Mishkin, Ungerleider, & Macko, 1983; Ungerleider & Mishkin, 1982). Whereas sensory and cognitive representations use attentive matching to maintain their stability as we learn more about the world, spatial and motor representations are able to forget learned maps and gains that are no longer appropriate as our bodies develop and grow from infanthood to adulthood.

These memory differences can be traced to complementary differences in the corresponding matching and learning processes. ART-like sensory and cognitive learning occurs in an approximate *match* state, and matching is *excitatory*, which enables it to realize a type of excitatory priming. Spatial and motor learning often embodies Vector Associative Map (VAM) circuits (Gaudiano & Grossberg, 1991; Guenther, Bullock, Greve, & Grossberg, 1994) that occur in a *mismatch* state, and matching is realized by an *inhibitory* process. These complementary differences clarify why procedural memories are unconscious; namely, the inhibitory matching process that supports spatial and motor processes cannot lead to resonance.

1.2. A new way to compute: Digital and binary, feedforward and feedback, analog coherence

The LAMINART models (e.g. Fig. 1) are not merely anatomically more precise versions of previous ART ideas. They represent a breakthrough in computing that identifies new principles and processes that embody novel computational properties with revolutionary implications. LAMINART models embody a new type of hybrid between *feedforward* and *feedback* computing, and also between *digital* and *analog* computing (Grossberg, 2003b) for processing distributed data. These properties go beyond the types of Bayesian models that are so popular today. They underlie the fast but stable self-organization that is characteristic of cortical development and lifelong learning.

The synthesis of feedback and feedback processing can be understood from the following example: When an unambiguous scene is processed, the LAMINART model can quickly group the scene in a fast feedforward sweep of activation that passes directly through layer 4 to 2/3 and then on to layers 4 to 2/3 in subsequent cortical areas (Fig. 2(c) and (e)). This property clarifies how recognition can be so fast in response to unambiguous scenes; e.g. Thorpe, Fize, and Marlot (1996). On the other hand, if there are multiple possible groupings in a scene, say in response to a complex textured scene, then competition among these possibilities due to inhibitory interactions in layers 4 and 2/3 (black cells and synapses in Fig. 2) can cause all cell activities to become smaller. This happens because the competitive circuits in the model are *self-normalizing*; that is, they tend to conserve the total activity of the circuit. This self-normalizing property is related to the ability of the shunting on-center off-surround networks that realize the competitive circuits to process input contrasts over a large dynamic range without saturation (Douglas, Koch, Mahowald, Martin, & Suarez, 1995; Grossberg, 1973, 1980; Heeger, 1992).

In other words, these self-normalizing circuits carry out a type of real-time probability theory in which the amplitude of cell activity covaries with the certainty of the network's selection, or decision, about a grouping. Amplitude, in turn, is translated into processing speed and coherence of cell activities. Low activation slows down the feedforward processing in the circuit because it takes longer for cell activities to exceed output threshold and to activate subsequent cells above threshold. In the model, network uncertainty is resolved through feedback: Weakly active layer 2/3 grouping cells feed back signals to layers 6-then-4-then-2/3 to close a cortical feedback loop that