Cortical and subcortical predictive dynamics and learning during perception, cognition, emotion and action

Stephen Grossberg*

Center for Adaptive Systems, Department of Cognitive and Neural Systems, Center of Excellence for Learning in Education, Science and Technology, Boston University, 677 Beacon Street, Boston, MA 02215, USA

An intimate link exists between the predictive and learning processes in the brain. Perceptual/cognitive and spatial/motor processes use complementary predictive mechanisms to learn, recognize, attend and plan about objects in the world, determine their current value, and act upon them. Recent neural models clarify these mechanisms and how they interact in cortical and subcortical brain regions. The present paper reviews and synthesizes data and models of these processes, and outlines a unified theory of predictive brain processing.

**Keywords:** complementary cortical streams; invariant recognition learning; cognitive–emotional dynamics; adaptive timing; working memory; laminar cortical circuits

1. INTRODUCTION: LEARNING AND PREDICTION BY COMPLEMENTARY CORTICAL PROCESSING STREAMS

Advanced brains have an extraordinary capacity to autonomously learn in real time from changing environmental conditions. Accumulating theoretical and empirical evidence suggests that this is accomplished using complementary cortical processing streams that embody different predictive and learning mechanisms (Grossberg 2000b). As summarized in figure 1, perceptual/cognitive processes in the ‘what’ ventral cortical processing stream often use excitatory matching and match-based learning to create predictive representations of objects and events in the world. Match-based learning can occur quickly without causing catastrophic forgetting, much as we quickly learn new faces without forcing rapid forgetting of familiar faces. Complementary spatial/motor processes in the ‘where’ dorsal cortical processing stream often use inhibitory matching and mismatch-based learning to continually update spatial maps and sensory-motor gains as our bodily parameters change through time. As noted in more detail below, these ‘what’ and ‘where’ processes need to work together: the ‘what’ stream learns spatially invariant object categories while the ‘where’ stream learns spatial maps and movement gains. ‘What’–‘where’ interstream interactions enable spatially invariant object representations to control actions towards desired goals in space. No less important, perceptual and cognitive learning provide a self-stabilizing front end to control the more labile spatial/motor learning that enables changing bodies to effectively act upon recognized objects in the world.

The present paper reviews and synthesizes data and models of these processes, and outlines a unified theory of predictive brain processing.

2. LEARNING OF INVARIANT RECOGNITION CATEGORIES IN THE ‘WHAT’ CORTICAL STREAM

Learning in the ‘what’ cortical stream leads to recognition categories that tend to be increasingly independent of object size and position at higher cortical levels. The anterior inferotemporal cortex (ITa) exhibits such invariance (Tanaka et al. 1991; Bar et al. 2001; Sigala & Logothetis 2002; Zoccolan et al. 2007), which helps to prevent a combinatorial explosion in the memory of object representations at every size and position. Such categorization processes have been predicted to achieve fast learning without experiencing catastrophic forgetting (figure 1). How is this accomplished? Adaptive Resonance Theory, or ART, predicted how ‘what’ stream categorization processes integrate properties of consciousness, learning, expectation, attention, resonance and synchrony (CLEARs, Grossberg 1980). Subsequent experiments have supported this prediction (see Grossberg (2003) and Grossberg & Versace (2008) for reviews).

Predictive ART matching uses a top-down learned expectation that causes an excitatory resonance when it matches consistent bottom-up input patterns (figures 1 and 2). The match focuses attention on a critical feature pattern of matched object features that resonates synchronously with the recognition category that reads out the top-down expectation. The resonance drives fast learning that incorporates the critical features into the category prototype. Predictive ART learning hereby joins excitatory matching, resonance, synchrony, attention, and match-based learning.
These processes together solve the **stability–plasticity dilemma** (Grossberg 1980); namely, they enable the brain to learn quickly without experiencing catastrophic forgetting. They also clarify why many animals are intentional beings who pay attention to salient objects, why *all conscious states are resonant states*, and how brains can learn both *many-to-one maps* (representations whereby many object views, positions and sizes all activate the same invariant object category; see §13) and *one-to-many maps* (representations that enable us to expertly know many things about individual objects and events; see Carpenter & Grossberg (1992)).

**ART** predicted that all brain representations which solve the **stability–plasticity dilemma** use variations of **CLEAR S mechanisms** (Grossberg 1978a, 1980). Synchronous resonances are therefore expected to occur between multiple cortical and subcortical areas. Recent data have supported this prediction (e.g. Engel et al. 2001).

### 3. Expectations and Biased Competition: Modulatory On-Centre, Off-Surround Network

How are ‘what’ stream top-down expectations computed? Carpenter & Grossberg (1987) mathematically proved that the simplest network which solves the stability–plasticity dilemma is a **top-down, modulatory on-centre, off-surround network**, which provides excitory priming of features in the on-centre, and driving inhibition in the off-surround. The modulatory on-centre emerges from a balance between the top-down excitation and inhibition. Subsequent modelling studies provide additional evidence for such a circuit (e.g. Gove et al. 1995; Grossberg & Myers 2000; Grossberg et al. 2004; Dranias et al. 2008), and laminar cortical models predict identified cell types (Grossberg 1999; Raizada & Grossberg 2003; Grossberg & Pearson 2008; Grossberg & Versace 2008). Many anatomical and neurophysiological experiments support this prediction (e.g. Downing 1988; Sillito et al. 1994; Steinman et al. 1995; Bullier et al. 1996; Hupé et al. 1997; Caputo & Guerra 1998; Reynolds et al. 1999; Somers et al. 1999; Mounts 2000; Smith et al. 2000; Vanduffel et al. 2000), which is more qualitatively called ‘biased competition’ (Desimone 1998; Kastner & Ungerleider 2001).

### 4. Imagining and Planning Ahead: Prediction Without Action

A top-down expectation is not always modulatory. The excitatory/inhibitory balance in the modulatory on-centre of a top-down expectation can be modified by volitional control from the basal ganglia. If, for example, volitional signals inhibit inhibitory interneurons in the on-centre, then read-out of a top-down expectation from a recognition category can fire...
cells in the on-centre prototype and thereby enable mental imagery, thinking, and planning ahead to occur. If these volitional signals become tonically hyperactive, then top-down expectations can fire without overt intention, leading to properties such as schizophrenic hallucinations (Grossberg 2000a). The ability to imagine and plan ahead thus risks having hallucinations, and all these properties follow from using top-down expectations to stabilize predictive learned memories.

5. COMPLEMENTARY ATTENTIONAL AND ORIENTING SYSTEMS: EXPECTED VERSUS UNEXPECTED EVENTS

How does a brain learn about unexpected and unfamiliar events, such as novel objects to recognize, without causing catastrophic forgetting? Within ART, this is achieved by a memory search, or hypothesis testing process that discovers the recognition category that best matches an event or object. Figure 2 illustrates how this process that discovers the recognition category that best achieved by a memory search, or hypothesis testing causing catastrophic forgetting? Within ART, this is events, such as novel objects to recognize, without predictively prime events whose future occurrence is sought.

6. SPIKES, SYNCHRONY AND ATTENTIVE LEARNING BY LAMINAR THALAMOCORTICAL CIRCUITS

The synchronous matching ART (SMART) model (figure 3) predicts that finer details about the CLEARS processes may be realized by multiple levels of brain organization. SMART provides a unified functional explanation of single-cell properties, such as spiking dynamics, spike-timing-dependent plasticity and acetylcholine modulation; detailed laminar thalamic
and cortical circuit designs and their interactions; aggregate cell recordings, such as current source densities and local field potentials; and single cell and large-scale inter-areal oscillations in the gamma and beta frequency domains. Figure 3 summarizes how these circuits embody the ART matching rule and thereby allow laminar circuits of multiple cortical and thalamic areas to carry out attentive visual learning and information processing.

One of the new SMART predictions concerns how brain oscillations contribute to predictive learning. SMART predicts that matches cause gamma oscillations that support attention, resonance, learning and consciousness, whereas mismatches inhibit learning by causing slower beta oscillations during reset and hypothesis testing operations (figure 2) that are initiated in the deeper cortical layers. Three kinds of recent data support this prediction:

(i) Buffalo et al. (2004) have reported beta oscillations in deeper cortical layers,
(ii) Buschman & Miller (2007) have reported beta oscillations during partial attention shifts; and
(iii) Berke et al. (2008) have reported beta oscillations during hippocampal place cell learning in novel environments.

Place cells can develop within seconds to minutes, and can remain stable for months (Thompson & Best 1990; Wilson & McNaughton 1993; Muller 1996; Frank et al. 2004). Place cell learning thus seems to have solved the stability–plasticity dilemma.
Are place cells learned using ART dynamics? The Berke et al. (2008) data are consistent with this hypothesis: paradoxically, beta power was very low as a mouse traversed a lap for the first time, grew to full strength on the second and third laps, became low again after 2 min of exploration, and remained low on subsequent days. Beta oscillation power also correlated with the rate at which place cells became spatially selective.

These data can be explained as follows (Grossberg submitted). Gorchetchnikov & Grossberg (2007) modeled how place cell receptive fields may be learned in an ART system wherein hippocampal place cells categorize multiple scales of entorhinal grid cells (Hafting et al. 2005). In any ART system, top-down adaptive weights are large before learning occurs, so that they can match whatever input pattern first initiates the learning of a new category (Carpenter & Grossberg 1987). Weights are pruned on subsequent learning trials to match the emerging critical feature pattern during mismatch-based reset events. The low beta power on the first lap of exploration can be explained by the initial top-down match. Beta power on subsequent laps can be explained by mismatch events that correlate with the rate at which place cells become spatially selective.

7. COGNITIVE–EMOTIONAL INTERACTIONS ENDOW PREDICTIONS WITH VALUE CONSTRAINTS

Invariant recognition categories can be activated when objects are experienced, but do not reflect the emotional value of these objects. An invariant object category can, however, be readily associated through reinforcement learning with one or more drive representations, which are brain sites that represent internal drive states and emotions. Activation of a drive representation by an invariant object category can trigger emotional reactions and motivational decisions that can motivationally modulate the object representations. Recognized objects can hereby trigger the choice and release of actions that realize valued goals in a context-sensitive way.

In figure 4a,b, visually perceived objects are called conditioned stimuli (CSs). The invariant object categories that they activate are called sensory representations (S\text{CSs}\text{)}\text{), which, in turn, activate drive representations (D). Figure 4a summarizes how predictive behaviour can be constrained by such external sensory options and internal emotional and motivational requirements.

The amygdala is a drive representation (e.g. Aggleton 1993; LeDoux 1993). Reinforcement learning (figure 4a,b) can convert the event or object (say CS\text{)}\text{) that activates an invariant object category (S\text{CSs}\text{)}\text{) into a conditioned reinforcer by strengthening the associative links from the category to the drive representation (D), e.g. learning in inferotemporal-to-amygdala pathways. The invariant object category can also send excitatory projections to the regions of prefrontal cortex (S\text{CSs}\text{)}\text{), such as orbitofrontal cortex. The amygdala (D) also sends projections to orbitofrontal cortex (Grossberg 1975, 1982; Barbas 1995). Reinforcement learning can hereby strengthen amygdala-to-orbitofrontal pathways, which provide incentive motivation to the orbitofrontal representations. Orbitofrontal representations fire most vigorously when they receive convergent inputs from inferotemporal categories and amygdala incentive motivation (Baxter et al. 2000; Schoenbaum et al. 2003).

Orbitofrontal cells (S\text{CSs}\text{)}\text{) send top-down feedback to sensory cortex (S\text{CSs}\text{)}\text{) to enhance sensory representations that are motivationally salient (figure 4b). Competition among inferotemporal categories chooses those with the best combination of sensory and motivational support. An inferotemporal–amygdala–orbitofrontal feedback loop triggers a cognitive–emotional resonance that supports the basic consciousness of goals and feelings (Grossberg 1975, 2000; Damasio 1999), and releases learned action commands from prefrontal cortex (S\text{CSs}\text{)}\text{) to M) to achieve valued goals.

The CogEM, or cognitive–emotional–motor, model that is schematized in figure 4a,b predicted and functionally explained these processes with increasing precision and predictive range since its introduction in Grossberg (1972a,b, 1975, 1982). CogEM top-down prefrontal-to-sensory cortex feedback is another example of ART matching, one that clarifies data about attentional blocking and unblocking (Pavlov 1927; Kamin 1969; Grossberg 1975; Grossberg & Levine 1987). When this CogEM circuit functions improperly, symptoms of various mental disorders result. For example, amygdala or orbitofrontal hypoactivity can lead to symptoms of autism and schizophrenia (Grossberg 2000c; Grossberg & Seidman 2006).

The MOTIVATOR model (Dranias et al. 2008; Grossberg et al. 2008) further develops the CogEM model, just as SMART further develops ART (figure 4c). In addition, MOTIVATOR unifies the
CogEM and TELOS models (Brown et al. 1999, 2004). TELOS proposes how the basal ganglia trigger reinforcement learning in response to unexpected rewards (Schultz 1998), and gates selection and release of actions that are learned through reinforcement learning. In vivo, the basal ganglia and amygdala work together to provide motivational support, focus attention, and release contextually appropriate actions to achieve valued goals. MOTIVATOR clarifies how this interaction happens. The model simulates properties such as food-specific satiety, Pavlovian conditioning, reinforcer devaluation, simultaneous visual discrimination, saccadic reaction times, CS-dependent shifts, emotional rebounds and exploratory behaviours.

8. ADAPTIVELY TIMED PREDICTIONS: DISTINGUISHING EXPECTED VERSUS UNEXPECTED DISCONFIRMATIONS

Reinforcement learning must be adaptively timed, since rewards are often delayed in time relative to actions aimed at acquiring them. On the one hand, if an animal or human could not inhibit its exploratory behaviour, then it could starve to death by restless moving from place to place, unable to remain in one place long enough to obtain delayed rewards there, such as food. On the other hand, if an animal inhibited its exploratory behaviour for too long while waiting for an expected reward, such as food, then it could starve to death if food was not forthcoming. Being able to predict when desired consequences occur is often as important as predicting that they will occur. Indeed, to control predictive action, the brain needs to coordinate the ‘what’, ‘why’, ‘when’, ‘where’ and ‘how’ of desired consequences by combining recognition learning, reinforcement learning, adaptively timed learning, spatial learning and sensory-motor learning, respectively.

Adaptive timing requires balancing between exploratory behaviour, which may discover novel sources of reward, and consummatory behaviour, which may acquire expected sources of reward. A human or animal needs to suppress exploratory behaviour and focus attention upon an expected source of reward when the reward is expected. The spectral timing model (Grossberg & Schmajuk 1989; Fiala et al. 1996; Grossberg & Merrill 1992, 1996; Brown et al. 1999) accomplishes this by predicting how the brain distinguishes expected non-occurrences, or disconfirmations, of rewards, which should not interfere with acquiring the delayed goal, from unexpected non-occurrences, or disconfirmations, of rewards, which can trigger consequences of predictive failure, including the reset of working memory, attention shifts, emotional rebounds and exploratory behaviours. The name ‘spectral timing’ signifies that a population ‘spectrum’ of cell sites with different reaction rates can learn to match the statistical distribution of expected delays in reinforcement over time.

9. SPECTRAL TIMING IN CEREBELLUM AND HIPPOCAMPUS: TIMED ACTION, ATTENTION, AND AUTISM

Adaptive timing occurs during several types of reinforcement learning. For example, classical conditioning is optimal at a range of positive interstimulus intervals (ISIs) between the conditioned stimulus (CS) and the unconditioned stimulus (US) that are characteristic of the animal and the task, and is greatly attenuated at zero and long ISIs. Within this range, learned responses are timed to match the statistics of the learning environment (Smith 1968). Although the amygdala is a primary site for emotion and stimulus–reward association, the hippocampus and cerebellum have also been implicated in adaptively timed processing of cognitive–emotional interactions. For example, Thompson et al. (1987) distinguished two types of learning that go on during conditioning of the rabbit’s nictitating membrane response: adaptively timed ‘conditioned fear’ learning that is linked to the hippocampus, and adaptively timed ‘learning of the discrete adaptive response’ that is linked to the cerebellum.

A unified explanation of why both hippocampus and cerebellum use adaptively timed learning is given by the START (Spectrally Timed ART) model (figure 5), which unifies the ART and CogEM models (Grossberg & Schmajuk 1987; Grossberg & Merrill 1992, 1996; Fiala et al. 1996). CogEM predicts how salient conditioned cues can rapidly focus attention upon their sensory categories (S) via a cognitive–emotional resonance with their associated drive (D) representations (figure 4). However, what then prevents the actions (M) that they control from being prematurely released?

The cerebellum is predicted to adaptively time actions in a task-appropriate way by using a spectrum of learning sites, each sensitive to a different range of delays between the CS and the US. Learning selects those sites whose reaction rates match the ISIs between the CS and the US. Adaptively timed long-term depression (LTD) learning at parallel fibre/Purkinje cell synapses depresses the tonically active output from cerebellar Purkinje cells to cerebellar nuclei. LTD hereby disinhibits target cerebellar nucleus sites that read out adaptively timed learned movement gains at around the time when the US is expected.

Fiala et al. (1996) modelled how the metabotropic glutamate receptor (mGluR) system may create the spectrum of delays during cerebellar adaptively timed learning. Subsequent experiments confirmed a role for...
calcium signalling and mGluR in cerebellar adaptive timing (Finch & Augustine 1998; Takechi et al. 1998; Ichise et al. 2000; Miyata et al. 2000). This model simulates both normal adaptively timed conditioning data and premature responding when cerebellar cortex is lesioned (Perrett et al. 1993). Autistic individuals with cerebellar malfunction also demonstrate prematurely released behaviours (Sears et al. 1994; Grossberg & Scidman 2006).

Cerebellar adaptive timing hereby reconciles two potentially conflicting behavioural properties: fast allocation of attention to motivationally salient events via cortico-amydala feedback versus adaptively timed responses to these events via cortico-cerebellar adaptively timed responding.

In order for adaptively timed responding to be effective, motivated attention needs to persist long enough to support the read-out of adaptively timed motor commands, and to prevent irrelevant events from prematurely resetting these commands. The START model (Grossberg & Merrill 1992, 1996) proposes how hippocampal dentate-CA3 circuits can do this (figure 5). Without these hippocampal mechanisms, a novel event could easily reset motor commands prematurely. Indeed, if a top-down prototype and bottom-up sensory input mismatch too much for resonance to occur, then the orienting system can be activated and reset active categories (figure 2). The hippocampal system and non-specific thalamus are proposed to be part of this mismatch-activated orienting system A. The thalamo-cortical and corticocortical mismatches that activate hippocampus or non-specific thalamus are not, however, sensitive to whether the novel event that caused the mismatch is task relevant. The START model clarifies how mismatches may be modulated by task relevance in an adaptively timed way.

In particular, figure 5 suggests how adaptively timed activity (T in figure 5) can inhibit A during an interval wherein a valued and predictable goal is being acted upon. T models adaptively timed activity in hippocampal dentate-CA3 cell firing during the rabbit nictitating membrane response (Berger et al. 1986).

In summary, the START model enables three key properties to simultaneously coexist.

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**Fast motivated attention.** Rapid focusing of attention on motivationally salient cues occurs from regions such as the amygdala to prefrontal cortex (pathway $D \rightarrow S^{(2)}$ in figure 5). Without further processing, fast activation of the CS-activated $S^{(2)}$ sensory representations could prematurely release motor behaviours (pathway $S^{(2)} \rightarrow M$ in figure 5).

**Adaptively timed responding.** Adaptively timed read-out of responses via cerebellar circuits (pathway $M$ in figure 5) enables learned responses to be released at task-appropriate times, despite the fact that CS cortical representations can be quickly activated by fast motivated attention.

**Adaptively timed duration of motivated attention and inhibition of orienting responses.** Premature reset of active CS representations by irrelevant cues during task-specific delays is prevented by adaptively timed inhibition of mismatch-sensitive cells in the orienting system of the hippocampus (pathway $T \rightarrow D \rightarrow A$ in figure 5). This inhibition is part of the competition between consummatory and orienting behaviours (Staddon 1983). Adaptively timed incentive motivational feedback ($D \rightarrow S^{(2)} \rightarrow S^{(1)}$ in figure 5) simultaneously maintains the CS...
activation in short-term memory, so that the CS can continue to read out adaptively timed responses until they are complete. The contingent negative variation event-related potential is predicted to be a neural marker of adaptively timed motivational feedback. Many additional data have been explained using these circuits, including data from delayed non-match to sample experiments wherein both temporal delays and novelty-sensitive recognition processes are involved (Gaffan 1974; Mishkin & Delacour 1975). Similar adaptive timing mechanisms seem to operate in basal ganglia (Brown et al. 1999).

10. LAMINAR CORTEX DYNAMICS OF WORKING MEMORY, LIST CHUNKING AND PERFORMANCE

The above mechanisms do not explain how the brain responds selectively to sequences of events. Predictive behaviour depends upon the capacity to think about, plan, execute and evaluate such event sequences. In particular, multiple events in a specific temporal order can be stored temporarily in working memory. As event sequences are temporarily stored, they are grouped, or chunked, through learning into unitized plans, or list chunks, and can later be performed at variable rates under volitional control. Here, the term ‘working memory’ is used to describe brain processes that temporarily store the temporal order of several events, not merely persistence of individual events.

Grossberg (1978a,b) introduced a model of working memory and list chunking, which proposed how the working memories are designed to enable list chunks to be stably learned and remembered. Inputs to this working memory are unitized item categories of individual events or objects (§2) that have enough adaptively timed, incentive motivational support (§7) to be persistently stored and transferred into the working memory. Item representations are stored in the working memory as a temporally evolving spatial pattern of activity across working memory cells. The relative activity of different cell populations codes the temporal order in which the items will be rehearsed, with the largest activities rehearsed earliest; hence, the name Item and Order working memory for this class of models. A more recent name is competitive queuing (Houghton 1990). The LIST PARSE model (Grossberg & Pearson 2008) built on this foundation to predict how laminar circuits in ventrolateral prefrontal cortex embody a cognitive working memory and list chunk learning network that interacts with a motor working memory in dorsolateral prefrontal cortex and a basal ganglia adaptively timed volitional control system. Accumulating neurobiological data support the view that visual and verbal object categories may be learned in temporal and ventromedial prefrontal (e.g. orbitofrontal) cortex, with the latter responding to combined item and motivational signals, followed by the loading of these item representations into a sequential working memory that codes temporal order information in ventrolateral and/or dorsolateral prefrontal cortex (e.g. Goldman-Rakic 1987; Barbas 2000; Petrides 2005; Ranganath & D’Esposito 2005). These temporally evolving working memory patterns are, in turn, categorized by list chunks, or sequential plans, which can be used to predict subsequent expected events.

A full review of the LIST PARSE model goes beyond the scope of this paper. Here, it suffices to note that LIST PARSE unifies the explanation of cognitive, neurophysiological and anatomical data from humans and monkeys concerning how predictive, sequentially organized behaviours are controlled. Its laminar organized prefrontal circuits are variations of laminar circuits in visual cortex (§6). Thus, both vision and cognition seem to use variations of a shared laminar cortical design to rapidly learn stable categories with which to predict a changing world. In particular, LIST PARSE quantitatively simulates human cognitive data about immediate serial recall and immediate, delayed and continuous-distractor free recall, as well as the monkey neurophysiological data from the prefrontal cortex obtained during sequential sensory-motor imitation and planned performance. It hereby clarifies how both spatial and non-spatial working memories may share the same laminar cortical circuit design.

11. BALANCING REACTIVE VERSUS PLANNED BEHAVIOURS: BASAL GANGLIA GATING

Complementary orienting versus attentional systems search for and learn new recognition codes (§5). They are subsumed by a larger complementary brain system that balances reactive versus planned behaviours. Rapid reactive movements, such as orienting movements, facilitate survival in response to unexpected dangers. Planned movements, which involve focused attention, often take longer to select and release. How does the brain prevent premature reactive movements towards objects in situations where a more slowly occurring planned movement is more adaptive?

Movement gates (cf. §9) can inhibit a reactive movement command until a planned movement can effectively compete with it. Then, a planned command can open its gate and launch its movement. The basal ganglia carry out such a gating function. Movement gates overcome a potentially devastating problem: a movement gate must be opened to release any movement. How does the brain know that a plan is emerging before it is fully formed, so that it can inhibit the gate that would otherwise have prematurely released a faster reactive movement? The TELOS model (Brown et al. 2004) predicts how frontal–parietal interactions prevent a reactive movement command from opening its gate before a planned movement command is ready, yet also allows a reactive movement command to open its gate quickly when no planned movement command is being formed. TELOS predicted that a frontal–parietal resonance occurs when this competition is resolved, and lets the appropriate gate open. Such a resonance has recently been reported (Buschman & Miller 2007). Miller’s laboratory has also reported the expected timing of frontal and basal ganglia activations (Pasupathy & Miller 2002).
12. SPATIALLY INVARIANT RECOGNITION CODES CONTROL SPATIALLY PRECISE ACTIONS

Conditional movements towards valued goal objects cannot be made until goal objects are recognized and selected, and their spatial locations specified. As noted in §1 and figure 1, the ‘what’ stream learns object representations that are increasingly independent of object position and size, whereas the ‘where’ stream represents the object positions and how to move. ‘What’–‘where’ stream interactions overcome these complementary informational deficiencies to generate movements towards recognized objects.

Whereas object representations in posterior inferotemporal cortex (ITp) combine feature and positional information, object representations in ITa are more positionally invariant. These two types of representations are linked by reciprocal learned connections, as described by ART. ITp representations also project to the posterior parietal cortex (PPC) as the target locations of an object. Consider what happens when multiple objects in a scene all try to activate their corresponding ITp and ITa representations. Suppose that a particular ITa category represents a valued goal object in that situation. As noted in §7, the ITa representation can get amplified by an inferotemporal–amygdala–orbitofrontal resonance. When this happens, the amplified ITa representation can better compete for object attention, and can send larger top-down priming signals to its ITp representations. The ITp representation that corresponds to the valued object is thereby selectively amplified, and sends an amplified signal to the parietal cortex, where its target location can win the competition for where the next movement will go (figure 6). This scheme can help to solve the ‘Where’s Waldo’ problem.

13. LEARNING VIEW- AND POSITION-INvariant OBJECT CATEGORIES USING ATTENTIONAL SHROUDS

How are positionally invariant and view-invariant categories learned by the brain? To understand how this happens, several basic questions need to be answered: what is an object? How does the brain learn what an object is under both unsupervised and supervised learning conditions? How does the brain learn to bind multiple views of an object into a view-invariant and positionally invariant object category while scanning its parts with eye movements?

To answer these questions, one also needs to solve the following problem: as eyes scan a scene, two successive eye movements may focus on different parts of the same object or on different objects. How does the brain avoid erroneously classifying views of different objects together, even before the brain knows what the object is?

The ARTSCAN model (figure 7) clarifies how the brain uses scanning saccadic eye movements to learn view-invariant object categories (Fazl et al. 2009). The discussion about ART above considered only object attention (Posner 1980) in the ‘what’ cortical stream. ARTSCAN explains how object attention works with spatial attention (Duncan 1984) in the ‘where’ cortical stream to direct eye movements that explore object surfaces. As the eyes move around an object surface, multiple view-specific categories are learned of the object (e.g. in ITp) and are associated with an emerging view-invariant object category (e.g. in ITa).

How does the brain know which view-specific categories should be associated with a given view-invariant category?

ARTSCAN predicts that a pre-attentively formed surface representation activates an attentional shroud (Tyler & Kontsevich 1995), or form-fitting distribution of spatial attention, even before the brain can recognize the surface as representing a particular object. This shroud persists within the ‘where’ stream during active scanning of an object. The shroud protects the view-invariant category from getting reset, even while view-specific categories are reset, as the eyes explore an object. The shroud does this by inhibiting the ITa reset mechanism (figure 7).

How does the shroud persist during active scanning of an object? A surface-shroud resonance arises owing to feedback interactions between a surface representation (e.g. in area V4) and spatial attention (e.g. in PPC), and focuses spatial attention upon the object to be learned. When the shroud collapses as the eyes move to another surface, its view-invariant object category is reset as well. Many paradoxical data are explained by these concepts, including how spatial attention can increase the perceived brightness of a surface (Carrasco et al. 2000; Reynolds & Desimone 2003), and what sort of category invariance can be learned (Zoccolan et al. 2007).

14. INHIBITORY MATCHING AND MISMATCH LEARNING OF SENSORY MOTOR MAPS AND GAINS

As noted in §§1 and 2, learning of object representations in the ‘what’ stream uses excitatory matching and match-based learning to solve the stability–plasticity dilemma. ‘Where’ stream learning, by contrast, often uses inhibitory matching and mismatch-based learning. Inhibitory matching is often between brain representations of a target position and the present position of a motor effector. Inhibitory matching computes a difference vector that represents the distance and direction of an intended movement. The difference vector is volitionally gated (see §11) by a GO signal that determines when and how fast the movement will occur (Bullock & Grossberg 1988; Bullock et al. 1998). During motor learning, a difference vector can also generate error signals when the same target position and present position are encoded but not properly calibrated. These error signals eliminate the source of the mismatch through time by recalibrating system maps and gains. Neural models predict how mismatch learning may tune spatial representations and adaptive motor gains in basal ganglia, cerebellum, motor cortex, parietal cortex and prefrontal cortex (Guenther et al. 1994; Fiala et al. 1996; Brown et al. 1999, 2004; Grossberg & Paine 2000).

In summary, perceptual/cognitive processes often use excitatory matching and match-based learning to create stable predictive representations of objects and
events in the world. Complementary spatial/motor processes often use inhibitory matching and mismatch-based learning to continually update spatial maps and sensory motor gains. Together, these complementary predictive and learning mechanisms create a self-stabilizing perceptual/cognitive front end for activating the more labile spatial/motor processes that control our changing bodies as they act upon objects in the world.

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