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The Working Mind

Meaning and Mental Attention in Human Development

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11 The Working Mind Inside a Working Brain: Functional Dimensions in Brain Semiotics

We use the constructivist framework of the book to interpret semantic dimensions and functional networks of the brain. The focus is on seven semantic systems or networks: (1) operative/procedural versus figurative/declarative processing and learning (anterior vs. posterior lobes); (2) dorsal-attention versus ventral-attention networks (frontal and parietal dorsal vs. ventral); (3) symbolic or effortful mode of problem solving/learning (left hemisphere) versus signalic or automatic (right hemisphere); (4) levels of reductive abstraction in the brain; (5) functional hierarchies of operative symbolic streams; (6) mental-attentional activation and inhibition brain mechanisms; and (7) representational streams. We also briefly discuss cortical arousal, neurotransmitters, and the limbic-system's role in cognition.

Reality is best construed as a universe of resistances to the subject's goal-directed activity (praxis)—both positive (Gibson's affordances) and negative (encumbrances or obstacles to praxis). Construction of experienced reality and novelty in performance are explained by the persons' capacity to synthesize, represent, and re-represent to themselves patterns of coactivation (and activation sequences) of their own schematic processes (which tend to express, directly or indirectly, Reality resistances). Reflective abstraction is Piaget's name for this important way of synthesizing flexible hierarchical levels of abstraction (see chapters 1, 5, and 10). To facilitate learning processes, the brain comes prepared by evolution with distinct architectural locations or sites, often specialized for distinct modes of processing. To determine performance, these modes of processing tend to suppress (i.e., inhibit) one another when in competition (e.g., Walsh & Pascual-Leone, 2003).

Before proceeding further, we should comment on the difference between resting-state network "maps," which express cofunctional and often coactivated (usually well-learned) functional connections existing in the cortex (schemes/schemas linking these sites), and the semantic brain "mapping" of our constructivist constructs. Resting-state network configurations may be found because their linking processes are innate (hard wired, causing joint oscillations of connected regions), or they are well learned/

overlearned, or they have been recently used and remain coactivated. The cortical functional relations we investigate in this book stem from a developmental-constructivist interpretation of brain growth and functioning. This developmental-constructivist functionality may lead to patterns of coactivation, learning, and overlearning, eventually expressed in resting state brain patterns. However, unless it is innate, well learned, or overlearned, developmental constructivist functionality may not be expressed in resting-state networks. We now discuss functional modes (and sites) particularly relevant for our theory (Pascual-Leone, 1995).

Operative/Procedural versus Figurative/Declarative Learning

We believe that schemes stored in the frontal lobe (i.e., anterior to the central or Rolando's fissure/sulcus) are operative or transformational schemes. Schemes stored posterior to this central sulcus (in the parietal, temporal, or occipital lobes) are, we believe, figurative-state processes. The latter often are representational declarative schemes standing for physical or mental objects, and simple or complex signalic/symbolic patterns, which include numbers and their interrelations. The *operative mode of processing* (referred to by neurologists as motor) includes mentation directed to external or internal acts of local transformation, or procedures of any sort. For instance, executive schemes (according to our definition) are operative, so they appear in relation with prefrontal activity. From this site, they coordinate activation or inhibition power of mental/endogenous attention, applying it to activate (or inhibit) task-relevant (or misleading) action schemes elsewhere in the cortex. The *figurative mode* consists of schemes standing for signalic or symbolic states (i.e., objects of any sort) or adjunct operative information (schemes—parameters—prescribing how an operative scheme should be applied). To clarify the functional significance, we use “operative versus figurative” in lieu of neurology's terms “motor” versus “sensorial” processes. We do so because “most of the brain's neurons are, strictly speaking, neither sensory nor motor” (Nauta & Feirtag, 1986, p. 38), but intermediate/associative components of the cortex.

To explicitly represent change, the human brain (mathematical calculus illustrates that well) proceeds to model dynamic flow of change by using sequences of idealized state-descriptions (i.e., figurative schemes or momentary-state models), sequencing representation moments of this flow. Each state-description is reached by applying idealized transformational/procedural units (i.e., operative schemes, operators, or action models) to the previous figurative state. These sequences can then be abstracted or mapped into sequence-representing schemes, which we call *fluents*, because they embody the flow

of temporally structured experience (Johnson, Fabian, & Pascual-Leone, 1989; Pascual-Leone, 1984). Fluent schemes can function as either figurative (perhaps task parameters) or operative processes, depending upon the context, and they may be stored in higher complexity-abstraction areas (tertiary or quaternary, i.e., high tertiary). As Kant and other classic rationalists (Hegel, Bergson, Cassirer) emphasized, temporal structures (our fluents) are essential for coordinating or constructing complex mental schemas.

An intuitive illustration of this function of temporal-process structuring is offered by construction of complex spatial structures. Spatial schemas use as data the step-by-step products of visual scanning or mental representation; products that are effortlessly (automatically) coordinated into not-yet-learned intuitive spatial schemas, via temporal-structuring processes (possibly in medial temporal brain regions, our *T*-operator). Only after these sequentially acquired components have been brought together by the working mind can mental attention (Matt) and Schemes' Overdetermination of Performance (*SOP*) synthesize here-and-now spatial schemas/structures encompassing the functional totality (which may generate, for instance, a spatial mental map of our city). Neuroscientists recognize this constructive function of temporal structuring. For instance, Alvaro Pascual-Leone, distinguished behavioral neurologist from Harvard University, believes that these temporal factors (coded by patterns of brain oscillations) must be considered together with spatial structures in various levels of processing (primary, secondary, tertiary, quaternary). For him (personal communication, August 2019) temporal constructive factors of complex spatial-temporal organizations serve as "fingerprints," which highlight activity (agency/praxis) needed to construct complex schemas.

Cortical control of operative/procedural versus figurative/declarative processes can be seen in language, in the contrasted cortical-control location of verbs versus nouns. Verbs clearly are linguistic expressions of operative schemes (fluent schemes in the mind of trained speakers), but nouns express figurative schemes. Shapiro, Pascual-Leone, Mottaghy, Gangitand, and Caramazza (2001) conducted "virtual-lesion" experiments with rTMS (repetitive transcranial magnetic stimulation), which produces temporary changes that result in transitory interruption of local cortical processing. These experiments showed that participants voiced their grammatical answers rapidly for nouns (e.g., singular vs. plural form: song, songs) when rTMS was applied to the prefrontal cortex (midfrontal gyrus anterior and superior to Broca's area, Brodmann areas [BA] 44 and 45). They were significantly slowed, however, when asked instead to give the third-person singular or plural of a verb (e.g., sings, sing). Related findings about verb versus noun processing have been reported using functional magnetic resonance imaging (fMRI) and lesion research (e.g., Damasio & Damasio, 1994).

Dorsal-Attention versus Ventral-Attention Networks in the Cortex

Piaget described two self-propelling modes of functioning in schemes: the assimilation and accommodation tendencies that are important to explain adaptive cognitive and developmental change. Assimilation is the tendency of schemes (i.e., neuronal assemblies or brain circuits) to apply and produce performance, whether mental or behavioral. It induces performance to follow the schemes' constraints for response and expectations. Accommodation is a tendency of schemes to adapt by incorporating to them new aspects/features of the situation or ongoing dominant process, when relevant for affective goals of the organism. These functional modes may be innately prepared, since they appear semiotically (semantic-pragmatically) expressed by two distinct brain networks also found in monkeys and apes. These are, respectively, the dorsal-attention versus ventral-attention networks—both basically frontal and parietal (Austin, 2009, 2010; Corbetta, Patel, & Shulman, 2008; Corbetta & Shulman, 2002; Sara & Bouret, 2012; Stöttinger et al., 2015). Functional complementarity of these two networks is well studied.

The dorsal-attention network carries out top-down two sorts of activity: it pursues endogenous cognitive goals for the intended praxis and explores unexpected and salient, not-task-relevant, exogenous aspects of situations. The ventral-attention network notices, bottom-up, task relevant (or affectively relevant) aspects of the situation (part of this network overlaps with the “salience network,” Seeley et al., 2007); it appraises mismatches with the intended praxis. Corbetta and Shulman (2002, p. 208) described this contrast as follows: “Neurophysiological studies indicate that the dorsal frontoparietal network, which is recruited for top-down selection, is also modulated by the bottom-up distinctiveness of objects in a visual scene.” They subsequently added (p. 210), “[T]he ventral frontoparietal network is modulated by detection of unattended or low-frequency events, independent of their location, sensory modality of presentation or response demands. These stimuli reorient attention, but not necessarily spatially.” Stöttinger et al. (2015, p. 119) clarified further the function of this ventral-attention pathway: “a more plausible assumption is that the observed [ventral-attention] network is involved in processing alternative options after a mismatch has been detected. In order to update a mental representation...one has to flexibly decide either to stay with the current model [representation] or to explore new, alternative options.” Waters and Tucker (2013) pointed out that the functioning in these dorsal versus ventral areas may relate, respectively, to Piaget's assimilation versus accommodation.

Without reviewing data, we note that the ventral-attention pathway tends to strongly use the right hemisphere, whereas the dorsal-attention pathway predominately uses the left hemisphere, where executive network and mental attention dominate (Austin,

2010; Corbetta et al., 2008; Corbetta & Shulman, 2002). Thus, one could say that the mode of assimilation, in Piaget's sense, is best expressed in the brain by the dorsal-attention pathway of the left hemisphere, whereas accommodation is expressed by the ventral-attention pathway and the right hemisphere (accommodation must adapt previously automatized or well-learned schemes—neuroplasticity). These are two functional systems of brain representation in continuous dialectical interaction that interrupt one another as needed (Corbetta et al., 2008). These approaches and their interaction are necessary in science and life (e.g., “top-down” versus “bottom-up” thinking, “field-independent” versus “field-dependent” attitudes).

In two meta-analyses Yuan and Brown (2015) contrasted cortical activity (activation likelihood estimation) during adults' drawing and writing. This study is important for us, because (as Piaget emphasized) drawing largely involves accommodation, but writing involves assimilation. Consistent with this interpretation, Yuan and Brown found that drawing showed a tendency to activate the ventral parietal region (inferior parietal lobe, BA 40), whereas writing tended to activate the dorsal parietal region (BA 7), although they share many sensorimotor networks. Because the brain systems are innately prepared, so should be Piaget's assimilation versus accommodation modes. The complementarity and intertwining of assimilation and accommodation is a key developmental-learning characteristic of neuropsychological schemes.

LM (Symbolic or Effortful, Left Hemisphere) versus LC (Signalic or Automatic, Right Hemisphere) Learning

LM and *LC* are two distinct but nonexclusive modes of processing (see chapter 5, Pascual-Leone, 1995, 1996b, 2000b; Pascual-Leone & Johnson, 2005, 2011). *LM* is logical-structural learning caused by effortful use of mental attention; it is relational-symbolic. *LC* learning is relational-associative, forming logical-structural content schemes due to repetition. These two modes are at times conflated by researchers with the modes mentioned above (figurative or declarative/representational vs. operative or procedural learning). Such conflation may explain why researchers often claim that declarative memory is always explicit (which *LM* mode tends to be), whereas procedural and other nondeclarative memory processes are implicit (e.g., Fuster, 1995; Nelson & Webb, 2003), as *LC* learning often is. We think this correlation is correct only as a tendency (i.e., not categorically), because there are operative (procedural) processes that turn explicit after being implicit, and there are figurative processes that begin implicit (*LC*) but eventually become explicit (*LM*). For example, Alvaro Pascual-Leone, Grafman, and Hallett (1994) studied development of implicit and then explicit knowledge

in a visuomotor learning task (organized as a serial reaction time task). Participants were regularly probed verbally about their location knowledge of a repeated (twelve-item) sequence of stars that appeared on a computer screen, to which they responded by pressing suitable buttons. Implicit knowledge was reflected in decreasing response times. Explicit knowledge, when it appeared, was shown in participants' expressed anticipation of the screen position of the star next to come. Transcranial magnetic stimulation (TMS) was performed repeatedly during the experiment, showing that the cortical motor-output map of muscles involved in the task became progressively larger during implicit learning but returned to usual topography and size when knowledge became explicit, although improvement in performance continued.

It is well established that linguistic and conceptual tasks tend to involve the left hemisphere, whereas visuospatial tasks often involve the right hemisphere (Kolb & Whishaw, 2003; Trevarthen, 1990). This difference may be due to lateralization of distinct modes of processing likely to intervene in the domains in question. Processing done in the left hemisphere (LH) is usually described as analytic, logical, categorical, abstract/conceptual, digital, sequential, and serial. In contrast, the right hemisphere (RH) is seen as specialized in holistic, global, coordinating, parallel, analog processing (Gazzaniga, Ivry, & Mangun, 1998; Goel, Shuren, Sheesley, & Grafman, 2004; Kosslyn, 1994; Pascual-Leone, 1976b; Stephan et al., 2003; Vartanian & Goel, 2005). In a similar vein, it has been suggested that the LH is better in processing spatial high-frequency information and thus finds it easier to notice parts and details in a pattern (or notice fast changing ones), whereas the RH is better with low-frequency information, noticing overall patterns and perhaps missing details in visuospatial figures (Kitterle, Christman, & Hellige, 1990; Piazza & Silver, 2017; Wolford, Miller, & Gazzaniga, 2000).

From our constructivist developmental viewpoint (Arsalidou, Pascual-Leone, Johnson, Morris, & Taylor, 2013; Arsalidou, Pawliw-Levac, Sadeghi, & Pascual-Leone, 2018; Pascual-Leone, 1995), propensities fostered by LH may be characterized as problem-solving analytical (using endogenous mental-attention and executive-driven), often within misleading novel situations. This formulation agrees with the "abstract/conceptual" (LH) versus "perceptual" or overlearned (RH) distinction offered by Stevens, Kahn, Wig, and Schacter (2012); the characterization "explanation/inferential" (LH) versus "conflict detection" and "context monitoring" (RH) given by Marinsek, Turner, Gazzaniga, and Miller (2014); and novel relational reasoning versus more global and perhaps overlearned concrete reasoning, as offered by Vendetti, Johnson, Lemos, and Bunge (2015). It also is congruent with Goel's (2019) model of LH as a top-down interpreter or problem solver versus an RH as a bottom-up analyst in (often facilitating)

situations that are perceptually clear and well learned or very unclear or indeterminate as life can be. Such lateralization of modes of processing may result from prewired differences in microneuroanatomy (e.g., Gazzaniga et al., 1998). A case in point is the anatomical finding that RH (when compared with LH) has greater functional connectivity with the brain as a whole (e.g., Gotts et al., 2013) and can therefore more easily abstract holistic general patterns, in facilitating contexts, and automatize them.

Sherman, Seth, and Kanai (2016) have shown, using fMRI and a perceptual processing experiment, that top-down expectancies can be evaluated against sensorial experience to reach decisions or perceptual confidence. Top-down perceptual expectations (expressed in orbito-frontal cortex activity) and bottom-up sensory inputs (perhaps expressed by activity in BA 17) are then contrasted (match/mismatch processing), yielding subjective evaluation of confidence. Prefrontal lobe of the RH may play a decision-making role in this appraisal.

Our model says that effortful *LM* learning processes (which involve mental-attentional control, or *M*-operations) usually take place in the LH (Arsalidou et al., 2013, 2018; Pascual-Leone 1989, 1995). *LM* processes can produce symbols and can explicitly engage in symbolic processing. In contrast RH seems more able to store signalic *LC* processes (logical learning of content-schemes, a form of chunking), although it may also store automatized *LM*-schemes (which we call *LCLM* learning; see chapter 5). *M*-operations and *LM* learning may explain the higher aptitude of LH to interpret sequences of events that predict outcomes (Wolford et al., 2000).

When mental demand of the task at hand is greater than mental capacity of the person (*M*-power smaller than *M*-demand), left-hemisphere *LM*-schemes may not be able to cope with the task. Right-hemisphere *LC*-schemes may then be used, tacitly seeking help from automatized processes. This is consistent with Goel (2015, 2019; Goel & Grafman, 2000), who found that mentally demanding, ill-defined or indeterminate cognitive problems often engaged the RH in adults. For a similar reason, early language learning, prior to 17 months of age, takes place in the RH (Mills, Coffey-Corina, & Neville, 1993; Molfese, Wetzel, & Gill, 1993; Thal et al., 1991). The LH becomes dominant in language only after the age of 20 to 35 months, when growth of *M*-capacity permits language-learning to form *LM*-schemes, driven by mental attention. Analogously, amateurs can process music mainly in the RH, but professional musicians process it predominantly in the LH (Bever & Chiarello, 1974; Ohnishi et al., 2001). Note that the examples of language in infants and music in professionals argue against a common idea (e.g., Goel, 2019): that language localization in LH may cause the top-down interpretive problem-solving powers in LH.

The functional distinction RH/LH has a long historical record: for Hughlings Jackson (1915), a founder of modern clinical neurology, the LH was involved in volitional/conscious aspects of language, but both hemispheres contributed to automatic language. Other recent theoreticians of brain lateralization have expressed related views: Eccles (1980) thought that the “conscious self” is in LH, and Gazzaniga and others (Marinsek et al., 2014; Goel, 2015, 2019) believe that the LH contains a creative causal “interpreter” of felt experiences, whereas the RH instead appraises issues (Goel’s, 2015, 2019, “indeterminacy”) to notice contradicting interpretations. The two hemispheres interact and share task processing. To summarize (see table 10.1), the LH is dominant in misleading problem-solving situations that it can handle, to produce analytical and often conscious processes. The RH (globally experiential) predominates in either of two circumstances: (1) when the intended performance is more or less automatized, or (2) when the mental-attentional demand of the task is too high for the LH to cope with it alone, so help from the RH’s automatized schemes could be useful.

Levels of Reductive Abstraction: Experiential versus Conceptual and Complex Episodic Processes

The modes of processing (functional dimensions of variation) we have described as reflective abstraction (i.e., levels of abstraction-complexity, see Table 5.2) can be examined from a semantic meaning-reduction perspective: some schemes are more concretely particular, whereas others are abstract and more generic (Goldstein & Sheerer, 1941). The amount of meaning reduction that takes place to ensure effective complexity of schemes varies with personal style and circumstances. For this reason, *reductive abstraction* is a distinct dimension of variation that is subject to individual differences. This dimension expresses how much meaning is reduced (or eliminated) when reflective abstraction changes from concrete, local, global schemes, to more generic and analytical schemes—schemes that often have greater scope and semiotic complexity but are more abstract. This meaning-reduction perspective marks the dimension of variation called experiential versus conceptual. Conceptual learning, broadly defined (e.g., Pascual-Leone, 1995; Pascual-Leone & Irwin, 1998), is a constructive (comprehensive) or reductive (actively selective) abstraction of aspects of any sort (e.g., perceptual, semantic, functional), found in represented objects or individuals during experience in situations. As Cassirer, quoting Burkamp, put it, “If I understand a new mechanical contrivance, it is a concept for me, even if I do not give it a name. The functional relation, transferable to an indetermined manifold [as functional invariant], is a concept” (Cassirer, 1929/1957, p. 328). The word *manifold* in this quote refers to Kant’s sense,

which means the collection of distinct sorts of particular relations to/from which the concept is applicable or is inferred, inducted, or abducted. Cassirer referred to the concept as a functional relation. It is a relation, because the concept does not preserve any particulars, but it abstracts generically some functional/descriptive relation(s) critical to the activity of the person who introduced or uses the concept.

Particulars also can be extracted from experience (i.e., constructed, construed) contingent to an implicit decision of relevance, but they are not concepts. Particulars are abstracted from much more narrowly defined types of situations and emerge as packages of functional invariances from here-and-now perception or mentation; that is, they are always situated. Piaget called *infralogical* the most concrete manner of extracting particulars from the here-and-now of experience. We use the term *infralogical* in this sense: the subrepertoire of schemes that embody and stand for particulars: that is, the here-and-now purely concrete things or actions of experience during agency/praxis. In contrast, concepts are generic, constructive/reductive abstractions from coordinated *infralogical* schemes (extracted across types of situations).

Starting from *infralogical* processing (which is virtually the sole mode of processing until about 8 months of age) conceptual processing, at first implicit and practical, emerges progressively following the stages of Piaget and Case summarized in figure 7.2. The greater the number of essential or necessary and distinct types of situations from which a given concept is abstracted, the higher will be the concept's level. With reflective abstraction, two very different, but complementary, modes of processing develop, although the first mode takes precedence during the sensorimotor period. These are the *mereological/intuitive* (more or less generic but not verbal) versus the *logological/linguistic* (verbal particular or generic and later propositional) modes of knowledge modeling. These two modes are prepared in the brain by phylogenetic evolution, and they occur in neurologically distinct brain locations. The three key modes of reductive abstraction (i.e., *infralogical*, *mereological*, *logological*¹, see table 5.2) are dialectically intertwined and collaborate in developing knowledge. The *infralogical* mode is the *final referential domain* (the ultimate source of semiotic referents) for the *mereological* and *logological* modes (with language included as part of the latter).

The *mereological* mode refers to part-whole relations found in objects or collections of objects (e.g., the body has "arms" and "a head"). Its modeling is based on intuitive spatial-temporal, at times causal, representations, action procedures, and so forth that reflect intuitive part-whole relations found in *infralogical* particulars (i.e., low-level schemes), within experience and across situations. Episodic memory is a product of *mereological* complex schemes (schemas) that capture details of life experiences with their sequencing and experiential flow. As also happens with language-based *logological*

schemes, mereological schemes could express complex high-level abstractions (schemes of schemes of schemes of greater scope—schemas), while tending to preserve generic details from the actual here-and-now experiences (with less richness than infralogical schemes).

We call logological a mode that Piaget, among others, called “logical” (“logic” here stands for analytically essential functional structures). We say “logo” because this constructive/reductive abstraction produces, and is aided by, language. Properly speaking, all meaningful schemes, even infralogical ones, express the semiotics (semantics, pragmatics) of experiencing and knowing situations.

Language is common but not essential for complex conceptual abstraction, as suggested by Cassirer’s quote mentioned earlier. Abstraction of concepts can also be done mereologically, by using intuitive/imaginal (e.g., visual, auditory, motor) quasi-representations and feelings, which may constitute mental/internal models (Johnson-Laird, 2010; Kosslyn, 1994). The latter in turn can be expressed in language. For instance, one develops language-based concepts of complex distal objects (abstracted entities) of the world-as-represented, such as supermarkets, universities, airports, and organizations, including their sociocultural aspects. These are mereological entities when first abstracted: the city has, among other aspects, houses, streets, hydro power, and underground water mains. When both figurative and operative processes are coordinated into complex mental/internal models, they become tools for intuitive causal abstraction and effective agency/praxis.

Brain Areas Serving Modes of Reductive Abstraction

The brain has distinct processing levels, from information about particulars to progressively more complex concepts. These developmentally emerging hierarchies of levels are stored in functionally nested brain areas (simplifying: primary, secondary, tertiary, or high tertiary/quaternary—maximally polymodal) that may incorporate temporally structured (fluent) schemas. The mereological mode involves, among others, interactions among prefrontal, frontal, lateral parietal, and temporal lobes. The logological mode involves (among others) interactions between the prefrontal, frontal, and temporal lobes. Left hemisphere prefrontal, frontal, or temporal areas, such as Broca (BA 44, 45) and Wernicke (BA 22, 39, 40), often intervene in logological or language-based abstraction. In contrast, middle, inferior, and medial parietal areas, plus other temporal and occipital areas, are involved in intuitive mereological abstractions (often within the right hemisphere, if they are suitably automatized or too complex). The spiral of levels of abstraction is represented within hierarchies of nested primary, secondary, and polymodal (i.e., tertiary or quaternary) areas. These levels are often attained, we

speculate, by using the mental-attentional system of operators (i.e., *E, M, I, F*) located in the prefrontal lobes (see chapters 5 and 7).

Neuroscience and cognitive science tend to collapse the various intertwined modes of processing into two polar extremes: *semantic* (conceptual, logological) processes supported by language and often using reductive abstraction versus *episodic* (experiential and temporally structured, mereological, or infralogical) processes, which often retain some of the here-and-now fluent concreteness of experience. Either of these processes could vary from high-level cognition to low-level cognition.

Because experiential processes are also semantic, and episodic processes could reach an effective complexity as high as logological-linguistic processes (produced by complex mereological schemas—explicit internal mental models), we can reduce these dimensions to two developmental mode categories (i.e., experiential vs. conceptual processes) and two corresponding modes of learning. Experiential learning (infralogical or low mereological) tends to be descriptive of life experience and often occurs in facilitating situations. Under these conditions it can be achieved by means of *LC* learning (which may occur predominantly in the RH), because learning in this case is data driven. Complex or misleading conceptual (logological or high mereological) learning is a very different case. Reductive abstraction often causes schemes not to be descriptive of concrete situations, making situations misleading or harder to grasp; this may occur due to situation-elicited unwanted schemes. Thus, people may mobilize executive-driven mental attention (i.e., *Matt*, with inhibition/interruption) to achieve logological or high-mereological learning. In such case, *LM* learning (LH) should be involved. Teachers, coaches, and trainers could minimize tasks' mental-attentional demand by changing these learning situations to render them more facilitating. After practice, logological and high-mereological learning could mostly use global strategies that are automatized or well-learned (*LC* learning) and stored in the RH.

Complexity Levels in Operative Symbolic or Executive Streams

The vast literature on the prefrontal brain shows that prefrontal lobes are decisive links between limbic system's affective priorities or implicit values (i.e., affective goals) and the person's actual performance—whether in internal mental processing (i.e., mentation) or external/overt responses of the organism (perceptual, motor; i.e., within the brain-interpreted environment and its causal texture, Tucker, 2001). Adaptation of performance to serve affective goals in situations is accomplished by the prefrontal lobe using the currently dominant set of activated and compatible executive schemes with their executive function (which we call *E-operator*), as well as other hidden operators

like those of mental attention (see chapters 4, 5, and 7). Current literature often subsumes these constructs under executive processes, organized in flexible hierarchies in term of their effective complexity (Badre, 2008; Christoff & Gabrieli, 2000; Christoff, Keramatian, Gordon, Smith, & Mädler, 2009; Miller & Cohen, 2001). Executive schemes (*E*) control “central” activatory or inhibitory functions, helping to coordinate pathways. Researchers distinguish at least five prefrontal cortex (PFC) regions, where mental operative activities take place: *ventrolateral* (BA 44, 45, 47, 47/12), *dorsolateral* (BA 9, 46, 9/46), *frontopolar* (BA 10), *orbital or orbito-frontal or anterior insula* (BA 11, 12, 13, 14), and *medial* (BA 25, 32, which are part of the anterior cingulate region). If we consider the fronto-medial region as distinct, we must add other structures closely interconnected with the prefrontal lobe: the *anterior and posterior cingulate gyri* (BA 24, 32, 33, and BA 23, 31). Anterior cingulate is a major constituent of the limbic system that is also part of the neocortex (e.g., Allman, Hakeem, Erwin, Nimchinsky, & Hop, 2001), and it could be seen as transforming affective goals (limbic and frontomedial processes) into cognitive goals (prefrontal/frontal processes), as we have proposed (Arsalidou & Pascual-Leone, 2016; Arsalidou et al., 2018; Pascual-Leone, Pascual-Leone, & Arsalidou, 2015).

Christoff and Gabrieli (2000), elaborating on Petrides’ theory (Owen, Evans, & Petrides, 1996; Petrides, 1994), proposed a flexible nested hierarchy of processing levels in the prefrontal lobes, constituted by (1) ventrolateral PFC, (2) dorsolateral PFC, and (3) frontopolar PFC. They saw this cumulative hierarchy of levels as being caused by, and indexing, task complexity (which increases from areas 1 to 3). Our neuropsychological model (supported by task analyses of neuroscience research) suggests that this hierarchy depends on both the tasks’ mental demand (the need to mobilize and allocate mental attention) and the executive demand. This possibility may not have been recognized, or not fully embraced, by Christoff and Gabrieli (2000). As readers of this book know, by mental attention (**Matt**) we mean the system $\langle E, M, I, F \rangle$. Let us restate this model: (**Matt.1**) Matt has a currently activated set *E* of executive schemes (carriers of executive function), possibly generated or stored in ventrolateral, dorsolateral, or frontopolar areas of PFC, which controls allocation of attentional “energy” (mental activation capacity) and attentional interruption (inhibition). (**Matt.2**) It has a mental-attentional “energy” or capacity (*M*-operator) driven at the prefrontal lobe to boost activation of task-relevant schemes elsewhere in the cortex, and this serves perceptual/automatic attention or symbolic attention-demands of tasks. (**Matt.3**) It has mental-attentional inhibition or interruption, an attentional inhibition utility that we call *I*-operator. (**Matt.4**) Its dynamic syntheses are helped by local lateral-inhibition processes (found in layer four of cortical sites) that we identify with an internal “field factor” or *F*-operator. This *F*-factor, in coordination with the Schemes’ Overdetermination

of Performance (*SOP* principle, a winner-takes-all principle of brain functioning) causes dynamic syntheses of nonautomatized novel performances.

All cognitive goals are prompted by implicit or explicit affective goals (Pascual-Leone & Johnson, 2004; Pascual-Leone et al., 2015). For as long as performance is novel (in problem solving) and is not automatized, operative mental-attentional streams should be needed to cause performance. Monitored by the anterior cingulate gyrus (which brings about a conversion of affective goals to cognitive goals) these mental-attentional pathways serve to synthesize (with help from the *F-SOP* operator, i.e., lateral inhibition) intended novel performances.

To emphasize the relations of both affective/limbic system and mental-attentional demand with the cognitive-complexity hierarchical model of Christoff and Gabrieli (2000; Christoff et al., 2009), we propose to expand their model by distinguishing four different complexity levels—related, we think, with Sanides' (1970) three evolutionary differentiation-trend systems. Following Goldberg (1985), Tucker (2001), and others, we call these PFC evolutionary systems paleocortical (level one), archicortical (levels two and three), and neocortical (level four).

Complexity Level One

Level one of complexity processing is constituted by the *ventrolateral PFC and comes from the paleocortical system* (evolutionarily taking origin in the insular cortex, and related to the piriform—olfactory—cortex). It often is used in facilitating situations relative to internal needs (which the insula possibly synthesizes—Arsalidou et al., 2018; Damasio, 2012; Sescousse, Caldú, Segura, & Dreher, 2013) whether instinctive, affective, or cognitive. The ventrolateral PFC system mediates emotion-arousal, perhaps in interpersonal situations (Rolls, 1999). It also appears to participate in control of response inhibition of cognitive tasks that are already practiced (*LC* learned) and/or are relatively easy (Aron, Robbins, & Poldrack, 2004; Levy & Wagner, 2011).

Complexity Level Two

Level two of complexity processing is constituted by *medial PFC*. It belongs to the *archicortical system* (evolutionarily taking origin in the cingulate cortex, and related to the hippocampus). This level we add to Christoff and Gabrieli's three cognitive complexity levels to highlight a task-complexity level when anterior cingulate and inferior lateral but not dorsolateral PFC are activated—tasks with some interference but not complex or too misleading. It is used, in addition to level one, when inhibitory control processes are needed—in intersubjective, partly automatic but somewhat conflicting, situations—often during instinctive, feeling/emotive, interpersonal, or reward/

punishment exchanges (e.g., Bechara, Tranel, & Damasio, 2000; Stuss, Gallup, & Alexander, 2001). These initial two levels can serve more or less holistic or automatized (instinctual, feeling/emotive, empathic, cognitive) goals, by engaging in perceptual attention (external processing) and figurative (object-based) motivation in the context of not-too-complex tasks (Goel & Vartanian, 2005; Tucker, 2001).

These first two complexity levels often are driven by the lateral limbic system, the amygdala being a key source for motivation (the amygdala may set up positive or negative criteria of relevance, or priority, for the motivation in current situations; see Pascual-Leone et al., 2015; Sander, Grafman, & Zalla, 2003). The orbitofrontal cortex (OFC) is the site where lateral-limbic affective goals are appraised in terms of external circumstances relative to organism values, in interaction with amygdala, ventrolateral, and medial PFC. The inhibitory control of the orbital cortex is well recognized (Drevets, 1999; Rolls, 1999). When goals are to be turned into motivated action, the link of OFC with the ventral striatum (nucleus accumbens) may help to regulate choice of performance relative to affective goals (e.g., the amygdala's criterion of relevance for events/experiences, and possibly actions).

Complexity Level Three

Level three of processing is associated with the *dorsolateral PFC*, which evolutionarily belongs to the *archicortical system*; it is activated in situations that are relatively complex and often misleading. It can also be activated, however, in less complex situations (that promote the inferior lateral PFC) if some misleadingness occurs. There are neurons in the dorsolateral prefrontal cortex (e.g., Fuster & Alexander, 1971) that remain active during the interval between presentation of a task-relevant piece of information (e.g., a cue, a location, or identity of a stimulus) and the later use of this information in performance (e.g., execution of a contingent response). This is an expected property if the task's executive constraints (*E-schemes*) are to be sustained for as long as needed. The unique property of these PFC neurons is their capacity to actively maintain a task-relevant representation despite intervening distractions (Bunge, Hazeltine, Scanlon, Rosen, & Gabrieli, 2002; E. Miller & Cohen, 2001). In contrast, sustained activity of neurons in the inferotemporal or posterior parietal cortex is easily disrupted by distractors (Petrides, 2000).

Complexity levels three and four are driven by the medial limbic system. In this system the anterior cingulate cortex (ACC) is a site where affective goals are converted into cognitive goals, and performance errors relative to these goals are detected (Bush, Luu, & Posner, 2000; Luu, Tucker, Derryberry, Reed, & Poulsen, 2003). This ACC cognitive-goal control often occurs within complex misleading or conflict situations that

demand mental-executive, not just perceptual/automatic attention (Albright, Jessell, Kandel, & Posner, 2001; Kerns et al., 2004).

Complexity Level Four

This level of processing is constituted by the *frontopolar (rostrolateral prefrontal) cortex*, BA 10. Christoff and Gabrieli (2000) contrasted their level-two region (complexity level three for us) with the frontopolar region (level three for them, complexity level four for us), in the following way. The dorsolateral cortex tends to be engaged in tasks strongly anchored in externally generated information, such as word recognition tasks, or cued-recall of paired associates, or Petrides' self-ordered pointing task (Petrides, Alivisatos, Evans, & Meyer, 1993), or matching visible properties of objects (Christoff et al., 2009). In contrast, the frontopolar cortex (supported by dorsolateral cortex) is engaged in more complex (but not necessarily more difficult) mentally demanding tasks anchored in internally generated information. Examples are an updating n-back task (Christoff & Gabrieli, 2000) or judging whether the inferred dimension of change from one object to another corresponds to the dimension of change between two other objects (Christoff et al., 2009).

The evolutionary origin of the frontopolar cortex (neocortical) is different and more recent than the paleocortical and archicortical levels of complexity processing just described (Goldberg, 1985; Sanides, 1970). This suggests that frontopolar cortex has a more complex or refined function than dorsolateral cortex. Consistent with the qualitative interpretation of Christoff and Gabrieli (i.e., "internally generated information") there is evidence suggesting that frontopolar cortex, greater in humans than in other apes, is the highest level of self-reflective consciousness (e.g., Stuss & Levine, 2002). Evolutionary qualitative differences of this sort may, however, be side effects of deeper complexity-processing differences in mental-attentional capacity and its executive-processing capacity—which limits tasks' *M*-demand and *E*-demand (Case, 1998; Morra, 2000; Pascual-Leone, 2000a, 2000b; Pascual-Leone & Johnson, 2004, 2017). To examine this possibility more closely, at the end of chapter 10 we contrasted task analyses of two functionally related tasks: one that induces activity restricted to our level-three (i.e., dorsolateral PFC; Petrides' self-ordered pointing task) and another that is related to activity of our level-four frontopolar PFC (the n-back updating task, e.g., Christoff & Gabrieli, 2000; Owen, McMillan, Laird, & Bullmore, 2005). We refer readers to chapter 10.

Two remarks about this heterarchical organization (i.e., paleocortical level one, archicortical level two, archicortical level three, and neocortical level four) are necessary. First, some PFC structures are functionally close to the limbic system and can be seen as belonging to the paralimbic cortex (Mesulam, 2003); examples are the orbitofrontal

or cingulate gyrus (but also temporal regions like temporopolar cortex, insula, BA 13, parahippocampus complex). They are very densely interconnected among each other, including extensive connections with tertiary and quaternary areas (as Edelman [1987] would say, they are polymodal). In contrast, association (isocortex) areas such as the ventrolateral, dorsolateral and frontopolar PFC, and more so the primary cortical areas, are progressively more isolated and specialized in modality-specific processing of figurative/representation or operative/motor performance (Mesulam, 2003; Tucker, 2001). This architecture functionally unifies the four PFC levels for the control of cortical processes during fluent praxis and mentation.

Second, all four main specific arousal systems (indexed by their distinct neurotransmitters, discussed below) are in dynamic interaction with the PFC complexity levels just described; each neurotransmitter contributes its own qualitatively different sort of processing. Indeed, acetylcholine and dopamine are involved predominantly in cognitive-act processing, that is, processes geared, mediately or immediately, to operative praxis (goal-directed intentional activities, often anticipating near or distant future events or outcomes), with the participation of striatum and cerebellum when action is to be implemented or when complex operative schemes should be coordinated (Cotterill, 2001; Goel & Vartanian, 2005). In dialectical complementarity with those neurotransmitters, norepinephrine and serotonin (also dopamine) are involved in affective processes, that is, the vital (organismic, life-oriented) evaluation of situations, which assigns here-and-now motivation value to objects and figurative representations (we call *figurative motivation* these situation-induced evaluations, very often driven, we think, by the amygdala).

Operative praxis and figurative motivation are important in the PFC functioning. Although PFC complexity levels one and two contribute more to the latter, and complexity levels three and four to the former (Tucker, 2001), operative praxis and figurative motivation are intertwined: all neurotransmitter pathways and all prefrontal systems cooperate. Such cooperation is nowhere clearer than in the case of language, in conceptual development and mental life, or even in the production of meaningful movement sequences. It is now well recognized (Arbib, 2005; Leonard, 2003) that language shares the ventrolateral PFC sites BA 45 and 44 (Broca area) with symbolic meaning-carrying motor sequences (e.g., reaching for and grasping a given object, or imitation).² These sites contain special neurons, the “mirror neurons,” that become activated whenever meaning-carrying sequences of actions are either observed in others or are performed by the subject him- or herself (such equivalence of others with self explains the “mirror” name, but see Hickok, 2014 for “the myth” of mirror neurons). This unique mirroring function suggests to us that what is being expressed here are functionally invariant

(probabilistically recurrent) and relevant (motivated and meaningful) temporally structured sequences of actions, irrespective of who makes them or with what.

For example, in the case of grasping, “the trajectory of the relation of parts of the hand to the object rather than the visual appearance of the hand” is expressed (Arbib, 2005). The same actions performed meaninglessly (e.g., reaching without grasping an object) would not activate these special neurons. Rizzolatti, Arbib, and others (see Arbib, 2005) claim that these mirror neurons in prefrontal (BA 45, 44), inferior parietal (BA 40, 39), and superior temporal sulcus (all quaternary areas) are involved in intentional grasping, complex imitation, symbolic performance (e.g., pantomime), and the emergence of language. Notice that there is also an operative (PFC) fluent/temporal stream for relating, interpreting, and producing (rather than perceiving or representing) sequences of operative schemes. This stream is located in BA 44, 9, 8, 6 (e.g., Leonard, 2003). Fuster (1995, 2004) and Luria (1973, 1962/1980) are earlier researchers who recognized the importance of prefrontal lobes for fluent/temporal structuring of operative plans and procedures. To serve these and other cognitive functions, the temporal and parietal lobe pathways, are, respectively, intertwined with the paleocortical and the archicortical PFC, as we discuss next.

How Mental-Attentional Activation (*M-Operator*) and Inhibition (*I-Operator*) Are Expressed in the Brain

In this section we discuss how our complex system of constructs for mental endogenous attention ($Matt = \langle E, M, I, F \rangle$), and in particular the *M*- and *I*-operators, may be expressed in the brain. This dialectical-constructivist model of mental attention explicates common cognitive psychology constructs such as executive function, working memory, and cognitive inhibition processes. These constructs often are subsumed under the label *executive function* and currently are used as central explanatory constructs, with claims at times that one or another construct is not necessary to explain the data (Buss & Spencer, 2014). In the literature these three complex information-processing constructs are often unclear, however, and their systemic coordination must be clarified. The key issues seem to be three: (1) Can the *M*-capacity component of mental attention (often wrongly equated with working memory) explain the apparent cognitive inhibition performances of children and adults, or do we also need separate constructs for attentional inhibition? (2) If an attentional-inhibition construct is necessary, will one suffice, or do we need to distinguish effortful inhibition versus automatic inhibition? (3) Can the attentional inhibition construct(s) function independently, or are they functionally

intertwined within a mental-attention (Matt) complex system endowed of activation and inhibition operators?

Howard, Johnson, and Pascual-Leone (2014) reviewed the pertinent psychological literature (which we omit here) and tested these and other hypotheses with a set of relevant differential tasks, using confirmatory factor analysis. Their analyses support our Theory of Constructive Operators (TCO) by confirming that mental attention is necessary, including distinct psychological activation (M) and inhibition (I) processes. The factor-analytical model with only inhibitory processes was inferior to one with intertwined activation and inhibition processes. The modeling also supported two distinct inhibitory mechanisms: effortful interruption/inhibition (I_e) and automatic interruption/inhibition (I_{au}). However, there was support as well for a single inhibitory factor, which agrees with our claim that I_e and I_{au} are two distinct-but-complementary functions of a unified complex inhibitory/interruption construct I (Johnson, Im-Bolter, & Pascual-Leone, 2003; Pascual-Leone, 1984; Pascual-Leone & Johnson, 2005, 2011). They differ in that I_e is slower and attentionally effortful and can be very selective in its application, whereas I_{au} is fast, effortless, and its application is global and not discriminating (excluding all that is not being attended to).

Here, we interpret the M and I constructs within the brain, an exercise in scientifically informed speculation. M and I emerge developmentally in concurrent interaction (complementary functions, a dialectical pair). They serve to control and regulate one another, both using executive schemes as controls. Constituents of mental attention, $\langle E, M, I, F \rangle$, can be mapped in the working brain (as Luria, 1973, may have intuitively felt). We first address mechanisms of general (affective and/or cognitive) arousal.

fMRI shows mental attention as the activation/inhibition of neural energy (Arsalidou et al., 2013). This mental energy is conjointly produced, in our model, by three distinct and complementary sources of activation regulated in part by the PFC. **(Source 1)** First is the *brainstem arousal system*, with nonspecific and specific sources (each specific source related to one of the four main slow neurotransmitters). A nonspecific fast-neurotransmitter source is now regarded as most important to cause cortical arousal; this is the glutamatergic activation input from the basal forebrain, which has as inhibitory source the fast neurotransmitter GABA (Fuller, Sherman, Pedersen, Saper, & Lu, 2011; Saper & Fuller, 2017). The specific networks and their corresponding slow neurotransmitters (dopamine, norepinephrine, serotonin, acetylcholine) are now regarded as modulators of arousal within specific sorts of situations. Activation is brought to the cortex via glutamatergic circuits, which reformulates the up-to-now standard model of a reticular ascending system (RAS) of activation. **(Source 2)** Second there are *three pathways* that relate PFC, basal ganglia (BG), and thalamus: the direct pathway (this

is, we think, the BG-link that enables production of mental power/energy— Mp); the BG indirect pathway (i.e., the mediator of effortful attentional interruption, I_e); and the BG hyperdirect pathway (i.e., automatic, unspecific attentional interruption, I_{au}). (Source 3) Third is the *corticocortical connections from PFC* to the relevant site for the task in question, as well as other cortical-loop connections with the thalamus, cerebellum, and other parts of the brain. Our model assumes that this cumulative series of three activation/inhibition sources occurs in the order described (1, 2, 3), and the amount of initiating energy needed by each source decreases in the order of mention, although the specificity of this effect (specific vs. global) increases with the order mentioned.

We will discuss specific arousal (RAS) network processes (source 1) below, when we examine our model for the four key neurotransmitters. We now discuss in more detail the BG-source of attentional activation/inhibition (source 2). We hypothesize that M and I are expressed in the brain (within the second, BG, source) by a complex network of connections that relate anterior cingulate gyrus (ACC), prefrontal lobes (PFL), and pre-supplementary motor areas (preSMA), to the basal ganglia (BG) and/or subthalamic nucleus (STN), which are linked to the thalamus. Thalamic nuclei regulate strength and variety of information (the information-bearing schemes or circuits) that at any time can reach the cortex. According to reviews by Cockburn and Frank (2011), Greenhouse, Swann, and Aron (2011), and Holroyd and Yeung (2012), there are three distinct pathways, which we relate to our constructs: BG's *direct pathway* (our M), *indirect pathway* (our I_e), and *hyperdirect pathway* (our I_{au}).

These pathways are schematized in figure 11.1, which elaborates on a figure from Cockburn and Frank (2011). The figure represents functional anatomy of the BG circuit. The *direct pathway* (M), originates in dopaminergic-D1 (GO-D1) receptor units in the striatum (BG) as they receive excitatory activation from the cortex (PFC and presupplementary motor area [preSMA]); it then gives a neural inhibitory input to the internal globus pallidus (GPi—part of BG). GPi has a permanent tonic inhibitory link with the thalamus (Thal) that suppresses/reduces the messages from Thal to cortex (Cx). Thus, inhibition of GPi weakens the inhibitory GPi-Thal link and consequently boosts communication between Thal and Cx, which facilitates afferent cortical reception of thalamic messages—a psychological-processing activation boost. By negating a negation, the direct pathway has a positive effect, boosting selectively Thal-Cx links as required by the prefrontal lobes and preSMA. Notice however that “disinhibiting thalamic units only permits those units to become active if those same units also receive top-down excitation from cortex” (Cockburn & Frank, 2011, p. 317). This is the neurological effect that may underpin the executive-driven psychological boosting that M -operator achieves. Notice further that (under this interpretation) psychological inhibition and neurological

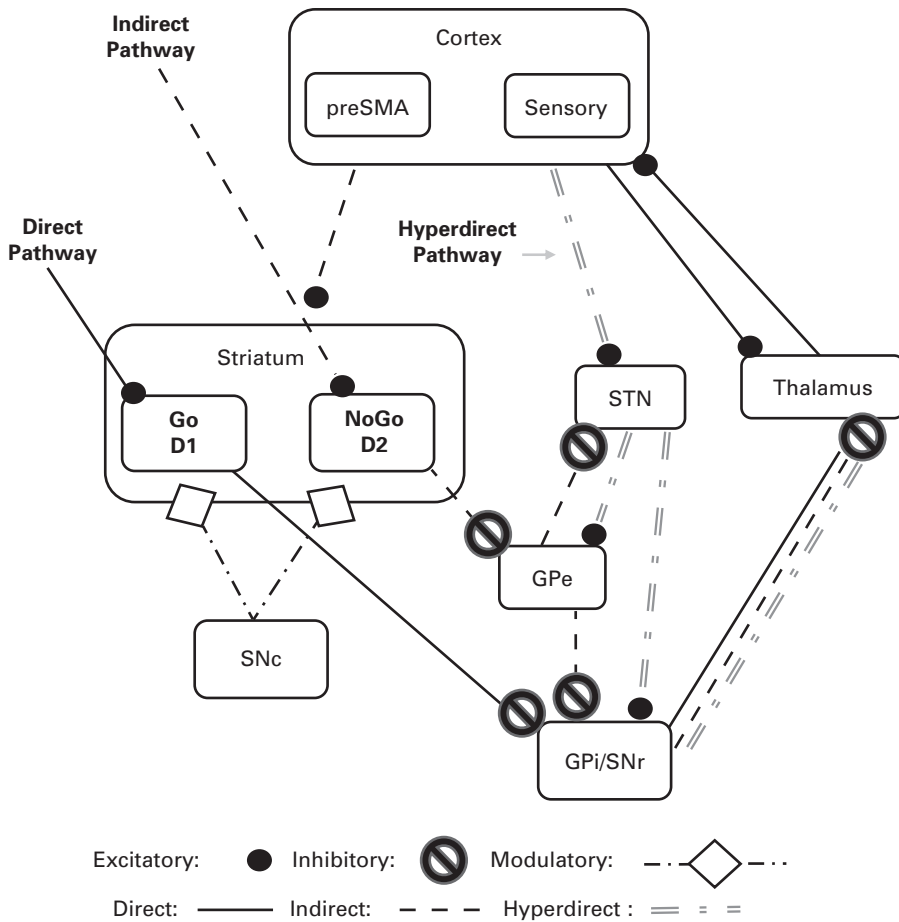


Figure 11.1

Functional anatomy of the basal ganglia (BG) circuit. (Adapted from Cockburn, J., & Frank, M.J. [2011]. Reinforcement learning, conflict monitoring, and cognitive control: An integrative model of cingulate-striatal interactions and the ERN. In R. Mars, J. Sallet, M. Rushworth, & N. Yeung [Eds.], *Neural basis of motivational and cognitive control* [p. 316]. MIT Press. Copyright 2011 by MIT Press. Adapted with permission.)

inhibition are distinct and different functions, which should not be confused. BG modulates only processes that originate in the cortex. Other competing figurative or operative schemes are then immediately suppressed in the cortex by lateral inhibition. This lateral inhibition is the process of *F-SOP* resolution that we explained in chapter 10 using Edelman's model. The currently active executive cortex (*E*-operator in our theory) may select its own action/scheme options in misleading situations with the help of this BG direct pathway (this would be a neuroscience aspect of *M*-operator's power capacity).

The indirect pathway (which psychologically expresses I_e —effortful attentional interruption) goes from PFC and preSMA, via dopaminergic-D2 receptor units in the striatum (BG), which give direct and selectively specific inhibitory input to external globus pallidus (GPe—part of BG). Thus, GPe weakens (in a selective, specific manner) its usual inhibitory input of GPi, weakening selectively the link of GPi on Thal. Here the negation of a negation (disinhibition) of GPi produces positive enhancement of GPi's inhibitory power over the thalamus, causing stronger (neurological and psychological) selective inhibition, which reduces the flow of thalamocortical activity. Dynamic balance between the direct pathway (our *M*-operator) and this indirect pathway (our *I*-operator) “determines the probability that the action [or figurative process] in question is gated” (Cockburn & Frank, 2011, p. 317). This neural connectivity aspect is congruent with our hypothesis that *M* and *I* constitute a functionally intertwined dialectical pair (Howard et al., 2014).

The hyperdirect pathway (which psychologically expresses automatic attentional interruption I_{au}) originates in the cortex and goes through the subthalamic nucleus (STN), bypassing the striatum (BG). STN receives excitatory input from the cortex and forwards excitatory input to the GPi, which inhibits further the thalamocortical activity. The projections of STN on GPi are diffuse, and so STN provides a “global no-go” signal to the thalamus, providing nonspecific inhibition to the thalamocortical pathway (Cockburn & Frank, 2011).

The hyperdirect pathway, the indirect pathway, and the direct pathway work in coordination and also in a proactive manner: if there are several alternative specific responses (schemes) in competition, and one has been chosen by the direct pathway (*E* and *M* processes), the STN hyperdirect pathway (I_{au}) will dynamically acquire greater strength to inhibit globally the unwanted schemes. The latter is aided by the indirect pathway (I_e) that modulates and contributes specificity to the inhibitory action (congruently with the neurological model of Cockburn & Frank, 2011; Greenhouse et al., 2011). If we translate these neurofunctional patterns into dialectical constructivist psychology, this means (as we theoretically implied above and in chapters 5 through 7) that the brain mechanisms for hidden operators *E*, *M*, I_e , and I_{au} are functionally

intertwined, constituting a dialectical quartet in continuous coordination. The dorso-lateral prefrontal cortex seems to do this coordination (Greenhouse et al., 2011), particularly when the task is complex or misleading.

Consider now the *corticocortical connections* (**source 3**), as well as other corticothalamocortical connections and loops via the cerebellum. We cannot review this considerable literature and will not appraise our hypothesis here. We posit that there are corticocortical connections from PFC to cortical sites relevant or irrelevant for the task at hand, which will add to excitatory/inhibitory activation that comes from the two sources of activation/inhibition mentioned above (i.e., **1** and **2**). This effect may be reinforced by corticothalamocortical connections and (to ensure coordinating operative balance) loops with the cerebellum. When **source 3** so defined applies, task-relevant sites may (or may not) have already been activated by sources of activation **1** and **2**, but with the three sources cumulating, the effect of this selective **3** corticocortical excitation can finally complete the cumulative process of activation/inhibition in the specific directions intended by the prefrontal processes (the executive *E*-operator).

This full effect of mental attention's activation (*Mp*) and effortful inhibition (*I_e*) may have the complex neuroscientific foundation just described, but there is another important aspect to *M*-capacity: the conjoint coactivation of schemes that could co-exist in the internal focus of mental centration without interfering with one another. This aspect, closer to the intuition of a working memory, also requires (we think) that the coactivated scheme processes in question, which carry the information (in an electroencephalogram [EEG] this may appear as fast waves, e.g., gamma waves), be protected from interfering with one another. Such protection often is achieved (as we explain in more detail later on) by the coupling of these gamma waves (the coactivated schemes) with theta waves. This coupling of gamma with theta waves would prevent interference among coactivated but distinct gamma waves and allow their effective concurrent coactivation with *M*-capacity. This coupling of EEG waves is further discussed in the next section. We will comment on the mental-attention **source 1** (i.e., the brainstem arousal system with nonspecific excitatory processes, together with specific modulator processes each with one of the four main neurotransmitters) in the section Arousal, Neurotransmitters, and the Limbic System's Role in Cognition.

Representational (Figurative) Streams

The posterior cortex is involved in processing figurative schemes/schemas (e.g., representations of objects, events, situations), as well as semantic relations holding among them (logological/linguistic or mereological/experiential relations). The causal texture of the environment is psychologically made by these internal/mental models and their

cognitive/truth relations (e.g., Johnson-Laird, 2010). Mental models are constructively and reductively abstracted from probabilistic invariants internalized from experience. Relations holding among objects, and objects themselves, cannot therefore be absolute but relative to goals, agency, or praxis—consciously intended agency (Gonseth, 1936/1974; Johnson-Laird, 2010; Pascual-Leone, Escobar, & Johnson, 2012). In this respect, Leibniz was right in the eighteenth century, maintaining against Newton/Clarke (Alexander, 1976, p. xxv) that space is “the order of coexistent phenomena.” In our terms, space is a constructed referential framework formed by relations of coexistence (caused by our innately prepared hidden *S*-operator) among agency-related schemes/schemas stored within the organism. Likewise, Leibniz took the view that time is “the order of successive phenomena” (Alexander, 1976, p. xxv). That is, time is a constructed referential framework formed by the flow of sequential relations—in our model caused by a hidden Time (*T*-) operator among schemes and schemas. Kant thought that space and time thus defined were purely transcendental³ categories of intuition. This is what we today would describe as *natural* dimensions of experiential variation (prepared in the brain connectivity, partly innate, partly constructed). Against these natural dimensions we organize our, initially mereological, synthesis of experience that internalizes Reality resistances. This is important, because sensorial experience reaches us only through a vast collection of perceptual snapshots that must be synthesized into cognitive schemes during our reflective abstraction process.

Neuroscience has confirmed a modern version of the idea that Leibniz and Kant initially introduced: it has been shown that there are two innate streams of processing usually called representational, dorsal (occipito-parietal) stream and ventral (occipito-temporal) stream. They constitute, respectively, neuroscience’s current version of the Leibniz-Kant space and time (a historical connection often not recognized). An alert human organism can recognize, without much effort and at times automatically, the flow of sequences of processes induced by experience. The various sensorial channels are mapped topographically and serially onto the brain, preserving dynamically basic relations of coexistence and sequencing among sensorial traces. Spatial and temporal relations can be meaningfully constructed with little effort, relating actual resistances that express these particular dimensions among/within packages of external resistances. Relations of coexistence may be constructed from meaningful pragmatic (in the sense of goal-directed, praxis-driven) sequences and interrelations among experienced resistances, relative to situations (context sensitive). They are pragmatic, because they express relations among resistances that emerge in agency or praxis.

The representational ventral stream is, in our view, the *figurative-representation temporal stream*.⁴ It is often thought (perhaps too restrictively) as a perceptual or

object-identification stream, because it answers questions about the “what” or “how” of experience (i.e., What is this? How to do it?; Atkinson & Braddick, 2003; Milner & Goodale, 1995).⁵ Its location is occipito-temporal. In our theory, this is a site of fluent-schemes created by the *T*-operator, an automatic flow- or sequence-reader and learning factor. In addition to visual centers (e.g., for shape, color, or orientation), it involves the inferotemporal region, temporal lobe, and superior temporal sulcus. These centers send information to the perirhinal cortex (BA 35, 36), which adds its own processing (perhaps sequential patterning, although the nature of this processing may not be clear). Then, information is transferred to the entorhinal cortex (BA 28)—medial temporal cortex. The entorhinal cortex is a “major zone of convergence, both for object information arriving from the perirhinal cortex and for spatial information arriving from the parahippocampal cortex” (Suzuki, 2002, p. 294). Suzuki points out that entorhinal neurons signal memory for objects and spatial information in similar ways: “they respond selectively to particular objects or cued spatial locations (i.e., stimulus-selective response), and memory is signaled by enhancing or suppressing these stimulus-selective responses” (Suzuki, 2002, p. 294). In turn, the entorhinal cortex is in close bilateral connection with the hippocampus, which abstracts a higher-level, spatiotemporal, representation (Suzuki, 2002). This is a representation of a here-and-now environmental “context” intertwined with internal action processes (Jiang, Brashier, & Egner, 2015; Pribram, 1991).

The role of hippocampus in the explicit sequential structuring of navigational learning has been shown by Ruediger, Spirig, Donato, and Caroni (2012) using individual mice learning to navigate a water maze. The mice learned sequentially the steps of the track, and these steps were explicitly and sequentially represented in distinct (progressively engaged, as learning proceeded) sites in the hippocampus (H): from ventral-H (in humans anterior-H), to intermediate-H, to dorsal-H. Ruediger et al. (2012, p. 1570) put it in these words: “We provide evidence that maze navigation involves a stereotyped sequence of subtasks that involve learning at distinct hippocampal subdivisions.” This discovery in mice is important, because it shows how the brain could register temporal-sequence scheme learning (the constitution of fluent schemes) that we hypothesized when positing the existence of a *T*-operator.

There is also indirect evidence that this sort of mechanism may be found in humans. For instance, according to Olsen et al. (2015, p. 5342) “The hippocampus may be necessary when the item elements need to be bound within and across episodes, to form a lasting representation that can be used flexibly.” They investigated this idea by studying a young woman with developmental amnesia and bilateral hippocampus damage, as well as some control participants, with a series of cards reproducing a face taken from

different changing perspectives versus a series of faces from a fixed perspective. Despite repeated presentations, the patient could not learn to recognize the face presented with changing perspectives, but she could learn the fixed perspective face. This is consistent with our model: whereas the former must be learned by retaining the face features and coordinating them (sequentially and spatially as one distal object) via the flow of temporally situated scanpaths (sequences), the latter could be learned as a complex pattern or template (a spatial proximal object). Thus *T*-operator would be needed only in the former. As the quote shows, these authors are coming very close to our idea: the hippocampus is necessary for reductively abstracting (as a probabilistic invariant) the common face structure across the face-episode sequence, when the changing perspectives prevent a simpler pattern-learning.

A problem remains, however: how can this spatial-and-temporal structure, this analytical sequential totality, be communicated (preserving the distinctiveness of sequential parts) across the brain, from one brain center to the other? Buzsaki (2006) and Lisman and Jensen (2013) suggest that the brain could do this by using a neural code that intertwines theta (or alpha—*slow EEG wave frequencies*) with *fast frequency waves*, which carry information—for example, gamma rhythms of activity (theta or alpha waves would serve to frame and mark the sequencing of gamma or beta waves). These interlocked (“multiplexed”) rhythms embody the temporal sequencing of segregated gamma units, because this fast (gamma) rhythm is sequentially ordered and temporally framed by the slow theta or alpha waves. This framing with slow waves is found in the hippocampus and transferable elsewhere. Such multiplexed rhythms may be an essential substratum for our *T*-operator.

As Buzsaki (2006) suggests, slow wave framing of fast waves (which, we add, carry experienced information—schemes) may also be essential to explain in part the magical number 7; that is, the maximum capacity of mental attention (i.e., capacity of our *M*-operator), which Buzsaki calls working memory. As Buzsaki (2006, p. 352) says, “The number of items that can be stored by the multiplexed gamma-theta model is identical with the magical number 7 (+/-2).” A theoretical micro-analysis of mental-attentional knowing (in both perception and mentation) suggests this intertwining of *T*-operator and *M*-operator: most knowledge acquisition (using scanning, focal attention) occurs sequentially. Then the schemes/events experienced during this sequential processing are dynamically synthesized into a single mental centration compound (i.e., simultaneous attention points within the focus of working memory, whose number, when appropriate tasks are used, is our measure of *M*-capacity). According to Buzsaki (2006) the theta period can encompass seven to nine items multiplexed on successive gamma cycles, “However, in the case of the faster alpha oscillator [alpha rhythm], the span is

shorter, with a capacity limit of four or five nested cell assemblies in a single alpha wave" (p. 353).⁶ Thus, the maximum or reserve mental-attentional (*M*-) capacity of adults (which generally is seven) may be fixed by the encompassing capacity of these theta waves, but the well-known commonly exhibited, functional *M*-capacity of normal adults (which is four or five) may be fixed by the encompassing capacity of their alpha wave cycles.

Hippocampus, however, may not be essential for all sorts of processing in the ventral pathway (Atkinson & Braddick, 2003). This ventral stream is closely connected with the ventrolateral areas (paleocortical system), predominantly BA 45 and 12, but also BA 47, 11/12, 13, 8. We think of this pathway as a figurative-temporal (sequence-patterning) stream that synthesizes distal objects of praxis out of interrelated proximal objects of perception. In addition to synthesizing meaning for objects, the ventral pathway may participate in the learning of sequences of appropriate responses and rewards or outcomes, which would lead to the formation of expectancies (fluent schemes). These are perhaps good reasons to claim that these fluent schemas are critical for neural representation, serving as spatiotemporal "fingerprints" (Alvaro Pascual-Leone, personal communication, August 2019).

The temporal lobe has other important streams, which are neurologically and semantically different, but also involve sequences, all of which could perhaps be subsumed under the concept of a figurative-temporal (*T*-) operator. This hidden *T*-operator is temporal, because it can (effortlessly) capture the flow of events, by synthesizing dynamic sequence-structuring schemes that can be learned as fluents.⁷ This *T*-operator works cognitively in coordination with space (*S*-operator) by the mediation of the hippocampus. From this perspective one may perhaps say that receptive language is precisely "located" on the left superior-and-posterior temporal lobe (Wernicke area, posterior BA 22), because language processing shares with the ventral pathway the need to abstract and retain meaningful sequences—sequences of words in language. Arbib, Rizzolatti, and others (see Arbib, 2005) proposed that language derives evolutionarily from imitation, gesture, communication, and pantomime (all fluent spatiotemporal activities), and this processing is facilitated by special neurons that sustain their activation to mediate the processing of sequences and fluent representations. These are, for instance, mirror and canonical neurons, located in the prefrontal lobe (BA 45, 44) but also in temporal-parietal regions such as superior temporal sulcus, entorhinal cortex, or intraparietal sulcus (Arbib, 2005; Hickok, 2014; Suzuki, 2002). Similar arguments about abstraction of sequences can be made with reference to sound patterns and music. Music processing seems to occur (besides the auditory centers) in the superior and anterior temporal lobe—anterior BA 22 (Zatorre & Peretz, 2001).

In dialectical complementarity with this ventral (figurative-temporal) stream, and richly interconnected with it (e.g., Stiles, 2001), is the *representational dorsal stream*. This is a space-structuring pathway, which constructively abstracts relations of coexistence (our hidden *S*-operator) at the service of operative processing (e.g., goal-driven activity). It (along with the prefrontal lobe when mental attention is needed) represents the location of objects in space from an egocentric perspective, that is, the perspective of the persons' goal-directed action or praxis, suggesting "how" to proceed (Milner & Goodale, 1995). From studies in monkeys (Suzuki, 2002) we know that, along with numerous visual-processing sites, this stream includes several temporal/spatial sites: middle temporal area (MT—also called V5), the dorsal bank of superior temporal sulcus (STS), posterior superior temporal gyrus, inferior or posterior parietal areas (BA 40, 39, 7), and lateral intraparietal region (LIP). The STS, BA 40, 39, and LIP are polymodal (high tertiary or quaternary) areas that may contain the special mirror and canonical neurons mentioned above (Arbib, 2005; Hickok, 2014). These dorsal centers converge toward the parahippocampal cortex along with input from the insula and the cingulate gyrus. Superordinate to both perirhinal cortex (ventral stream) and parahippocampal cortex (dorsal stream), the entorhinal cortex synthesizes the complex information prepared by these two pathways (Damasio & Damasio, 1994; Suzuki, 2002) and brings it to the hippocampus, which is the apex of this heterarchy. The hippocampus may be the site where sequences of events (schemes) are organized into a *causal context of the environment*, a "cognitive map" of relations of coexistence (in space and/or time) among the various identified objects. This well-known context-generating function of the brain expresses our space/time intertwining processes, also necessary for figurative (declarative memory) and relational learning (Shimamura, 2002).

As mentioned above, the hippocampus is a major structure of the medial (archicortical) limbic system, maintaining bilateral connections with prefrontal neocortical structures such as the dorsolateral prefrontal area (BA 46). Whenever a visuospatial task is complex or is misleading enough to demand mental attention, this prefrontal cortex is activated.

Arousal, Neurotransmitters, and the Limbic System's Role in Cognition⁸

The arousal mechanism helps to modulate readiness of neuronal synapses to fire; this mechanism relates to our lateralization neuropsychological model of activation/inhibition mentioned above and in chapter 10. The brainstem's mesencephalic reticular formation (MRF—also called the reticular ascending/activating system, or RAS) functions largely as a modulator for cortical and subcortical processes driven also by glutamatergic

circuits, as mentioned before. It regulates arousal level by means of (direct and indirect) reciprocal connections that are activatory or inhibitory. For instance, connections that MRF sends to the reticular nucleus (NR) of the thalamus are inhibitory; the NR acts as a gate that filters sensory input arriving at the thalamus on the way to the cortex. This is done by inhibiting the thalamic relay nuclei that transmit sensory input to the cortex. Thus, the inhibitory connection from MRF to NR opens (or regulates) the gate by inhibiting (or releasing) this inhibition. The prefrontal lobe can regulate activity of MRF by directly activating it also via the mostly activatory prefrontal connection with NR nucleus (Mesulam, 2003). J. Skinner and Yingling (1977), who pioneered discussion of the NR-gating mechanism, interpreted their data as meaning that the MRF-NR link participates in causing tonic arousal, and the prefrontal-NR link in modulating attention. Modulation here means regulating effects of other sources of activation/inhibition so that they together codetermine outcomes (this is part of the functional infrastructure for *SOP* organismic dynamics, i.e., the “winner takes all” brain principle already mentioned, e.g., chapter 10).

This unspecific function of attention is further modulated by four specific pathways that together with the MRF system constitute an ascending reticular activating system (ARAS—Mesulam, 2003; also called RAS). These pathways have neurotransmitters that mediate synaptic transmissions within them (Kolb & Whishaw, 2003; Robbins & Everitt, 1995; Stahl, 2000). We will mention four neurotransmitters: acetylcholine (cholinergic or ACh system), norepinephrine (noradrenergic or NE system—also called NA system), serotonin (serotonergic or 5-HT system), and dopamine (dopaminergic or DA system). Each has a specific function and is compatible with the others: “These reticular systems are simultaneously active in varying degrees, to optimize processing capacity and facilitate response output” (Robbins & Everitt, 1995, p. 715). The four of them intervene in attention by serving as modulators (neuromodulators) of cortical activity. Even though more research is needed to clarify their psychological significance (Richards, 2003; Stahl, 2000; Ullsperger, 2011), we believe that they can be understood in their interactions as part of dynamic meta-function controls (different from hidden operators) that can reset the brain for specialized ways of functioning. Ullsperger (2011) seemed to be asking for this sort of theoretical effort: “This clearly calls for models that try to integrate more than one neuromodulator” (p. 43). Our process-analytical constructivist model for these neurotransmitters (sketched in table 11.1) highlights their functional significance as *slow* (from many milliseconds to seconds) and *often sustained neuromodulators of arousal* (Stahl, 2000). Lack of space prevents discussion of the vast, relevant and (when interpreted) supportive, empirical evidence.

Table 11.1

A physiological interpretive model of the extrinsic arousal neurotransmitters

	Facilitating Situations	Misleading Situations
Perceptual/Automatic Attention	ACETYLCHOLINE: Habitual processes; mediates the body's parasympathetic system. Pribram's arousal and Posner's orienting.	NOREPINEPHRINE: Novel affective orienting reactions; mediates the body's sympathetic system. Pribram's activation and Posner's alerting.
Mental/Effortful Attention	SEROTONIN: Related to well-being and active interruption (inhibition) of irrelevant processes and negative affects. Regulates norepinephrine and dopamine systems.	DOPAMINE: Related to agency, value assignment (reinforcement), and praxis (reward anticipation, etc.). Pribram's effort and Posner's executive attention.

Note:

Cognitive Processes: Basal ganglia, etc. relate to operative praxis	Affective Processes: Amygdala, etc. relate to figurative motivation
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We describe each neurotransmitter in terms of three dimensions of variation, or categories of processing, which characterize temporary effects on neurons that each neurotransmitter may promote (see table 11.1). The three dimensions are (1) perceptual/automatic attention versus mental/effortful attention (see chapters 6 and 7 and below); (2) facilitating situations versus misleading situations (a distinction explained repeatedly in this book); and (3) cognitive processes (important in operative agency/praxis) versus affective processes (important in figurative motivation; see chapter 5). The first dimension concerns the type of attention, perceptual versus mental. Perceptual/automatic attention involves cognitive processes applied to information entering through sensorial receptors. It is the activity Posner (Petersen & Posner, 2012; Rothbart & Posner, 2001) assigned to his orienting and alerting networks. This may involve activity in the posterior parietal lobe, the frontal eye area (BA 6, 8), the right frontal lobe (superior BA 6), right parietal lobe, and the brainstem locus coeruleus (a main source of the NE system). Perceptual attention is closely related to the classic orienting reaction, which leads the animal to attend automatically whenever some novel event happens in its perceptual field (Kahneman, 1973; Pribram, 1971, 1991). We speculate that the ACh system (acetylcholine) and the NE system (norepinephrine) intervene as a pair of complementary and dialectically interacting arousal processes in perceptual/automatic attention. ACh

is released with respect to cognitively facilitating aspects of situations. In this context mental “cool” arousal (which we interpret as *M*-activation) is potentiated by ACh. Also, during sleep, dreams (REM sleep) are enabled by the cholinergic network (Platt & Riedel, 2011). NE, in contrast, is released in response to affectively misleading (disturbing, surprising, confusing, emotion arousing) aspects of situations and causes its own different form of (“hot”) arousal, which possibly also activates *M*-capacity; NE activity interrupts sleep, including REM sleep.

Mental attention involves activation and control of arousal to enable thinking, planning, goal-directed activity, conflict resolution, and other activity. These are internally mediated (i.e., mental) processes that the brain maintains in relative autonomy from the perceptual input. Posner and others call this sort of attention “executive attention” or executive-control network (Heitz, Unsworth, & Engle, 2005; Petersen & Posner, 2012; Rothbart & Posner, 2001). As mentioned in chapters 3 and 7, we prefer the term *mental* instead of *executive*, because mental-attentional processes already exist in children of 2 to 3 months of age, when “executives” have not yet appeared. The cingulate gyrus and midline frontal areas (e.g., anterior cingulate gyrus, supplementary motor area in BA 6), prefrontal cortex, and basal ganglia often are involved in mental attention (as contrasted with perceptual/automatic attention, e.g., Rothbart & Posner, 2001). We speculate that in “cool” (i.e., not affectively loaded) mentation and complex cognition, mental-attentional processes are specially (not exclusively) supported by the DA system (dopamine). The DA system is in dialectical complementarity (mutual regulation) with the serotonin system. In “hot” (affectively loaded) cognition the norepinephrine system may join in or replace the DA system, although serotonin continues to be the complementary or regulating system.

Notice that perceptual/automatic attention is involved predominantly in figurative representation of the input and its affective/emotional appraisal. This emotional appraisal gives affect-values (vital organismic values) to the representation of inputs, values that we call *figurative motivation* and others have called “salience.” Mental (in contrast to perceptual) attention is often involved in intentional/volitional activity (praxis), or in mentation that is preparatory for subsequent or future action/praxis. As Piaget, Vygotsky, and many others have claimed, covert mental processes (mentation) can be interpreted as internalized action, or preparation for action; this is operative activity, whether strictly motor or not. Particularly when applying on novel and suitably complex situations, mental-attentional processes tend to engage left frontal or prefrontal activities. In contrast, perceptual attention (which is more automatized, *LC* schemas) engages predominantly parietal (and temporal) processes, often with right frontal processes. Bilateral processing occurs when tasks are only partly automatized,

or too demanding, for the subject's own mental (M) capacity. The three intertwined dimensions presented in table 11.1 are crossed: each neurotransmitter prepares the organism for specified positions on each of the three dimensions, all at the same time.

Acetylcholine (ACh)

Cholinergic (acetylcholine) mediation occurs in not-too-complex perceptual or cognitive tasks (Störmer, Passow, & Biesenack, 2012) to mobilize arousal and mental attention (Matt, M -capacity). It is mobilized in the context of perceptual attention to relevant aspects of agency/praxis, often within facilitating situations. As Störmer et al. (2012, p. 885) said, "Precisely, most studies using tasks that require orienting processes, such as spatial cueing tasks, reported effects of the cholinergic system. Tasks involving the maintenance or updating of information, on the contrary, have mostly been found to depend on dopaminergic neurotransmission and in some cases on the interaction of the cholinergic and the dopaminergic system."

Robbins and Everitt (1995) described an experiment with rats that illustrates the difference among the four neurotransmitters we are considering. Using a special apparatus, rats were trained to detect brief visual stimuli (brief light flashes) presented unpredictably at one of five locations. Five seconds after the rat obtained its reward, the next stimulus occurred; a session contained one hundred such trials. Rats that had a chemically induced 70% reduction of activity in the cholinergic cortical pathways showed important deficits, relative to normal rats, in detecting the location of randomly presented light flashes. Similar results with a similar task were obtained with patients with probable Alzheimer dementia (who usually exhibit a cortical cholinergic reduction). As happened with the experimental rats, problems of these patients in the task could be reversed if an anticholinesterase (a chemical that retards decomposition of ACh in the tissues) was administered.

Because acetylcholine is the main neurotransmitter in neuronal pathways of the autonomous nervous system, for which the vagus is the key cranial nerve, vagus activity increases whenever the cholinergic system is high in the orbitofrontal cortex (Richards, 2002), causing the heart rate to decelerate. Consequently, a slow heart rate is reliable indicator of sustained perceptual attention and openness to environmental cues (Richards, 2002). Robbins and Everitt suggested that the ACh system "aids the processing of stimuli at the cortical level by enhancing the impact of salient information" (1995, p. 715). This increment in processing efficiency may be caused by the ACh system's enhancement of the cortical lateral-inhibition processes discussed in previous chapters. Cortical lateral-inhibition processes correspond to our F -operator. If

this hypothesis were correct, the ACh system would be one way in which our model's *F*-operator potency is increased, regulated upward.

Also, the ACh system may be able to mobilize mental attention (dopaminergic system) within facilitating situations (Störmer et al., 2012). Intriguing experiments point in this direction. Castro-Alamancos and Gulati (2014) have shown in rats that the ACh system increases cortical activity while increasing activity in the thalamus, which we should expect if the cholinergic system increases openness and sensitivity to facilitating perceptual situations. In contrast, these authors show that the norepinephrine (NE) system increases cortical activity but decreases activity in the thalamus. This should diminish perceptual openness to external stimulation in general—as expected if NE prepares the organism for selective perceptual processing in misleading situations (where misleading perceptual factors should be inhibited).

Norepinephrine (NE System)

Norepinephrine, also called noradrenaline, is a key neurotransmitter for the sympathetic division of the autonomous nervous system. Epinephrine (adrenaline), a close variant, is released into the bloodstream by suprarenal glands in alarm or peak emotional reactions (Richards, 2002, 2003). The NE-system mediates in the brain's orienting reactions (Pribram, 1971, 1991; Sara & Bouret, 2012), that is, reactions to unexpected novelty and good or bad surprising events, and participates in emotions initiated by the amygdala in the limbic organization (Pribram, 1971, 1991; Robbins & Everitt, 1995; Sara & Bouret, 2012). Activation of the NE-system may be accompanied by such reactions as a fast heart rate, a skin conductance response (SCR or galvanic skin response), or pupil dilation. Norepinephrine-sensitive (NE) neurons are best activated by “new, unexpected, nonpainful stimuli in the animal's environment” and “are least active when the animals are not vigilant, just sitting around quietly” (Bear, Connors, & Paradiso, 2001, p. 515). NE can make neurons of the cortex more responsive to salient sensorial stimuli, making the sensory and motor systems more efficient, “improving the ‘signal’ by decreasing the ‘noise’; related to tonic activity of the LC [Locus Coeruleus—key source of the NE system] nucleus” (Howells, Stein, & Russell, 2010, p. 14). Howells et al. further suggest that feeling of mental effort, common in misleading situations, is produced by tonic activity of the norepinephrine system.

In the Robbins and Everitt (1995) experiment described above, rats with a damaged NE-system performed well under normal conditions, but as soon as a distractor or stressor was added (e.g., white noise) their performance collapsed. The problem with NE-damaged rats was distraction, whereas that of ACh-depleted rats was accuracy (Robbins & Everitt, 1995). NE and ACh complement one another: ACh occurs in easy

cognitive processes and facilitating (nonconflictive) situations, whereas NE occurs in affective processes and misleading, conflictive situations. These (and the other two) key neurotransmitters complement each other by adapting the brain function to different sorts of situations and contingencies.

Prefrontal lobes (operative/executive processes) are needed to apply mental attention to misleading or complex—affective or cognitive—situations (as Luria, 1973, early emphasized). The NE system is an important modulator of prefrontal activity, and its activation is possibly counterbalanced by the serotonergic system. This form of arousal corresponds to Posner's alerting (Rothbart & Posner, 2001) and to Pribram's activation. The NE system is involved in highly active affective processes (our *A-operator*) and possibly intervenes in learning driven by affect (*LA-learning*). Organismic affective/cognitive reactions to experience may give (via this NE system) a feeling of mental or affective effort, which, if extreme, could lead to stress with its distinct neurobiological characteristics (Hermans et al., 2011). Under neurobiological stress, or under salient/relevant unexpected circumstances, the NE system can cause a reorienting reaction (Corbetta et al., 2008; Sara & Bouret, 2012) as it changes cortical control of attention from dorsal-attention (frontoparietal) network orientation (involved in focal selective attention and in task-directed activity—analytical alertness with *phasic firing* of norepinephrine neurons) to the ventral-attention network. The latter is characterized by global alertness, *tonic firing* of norepinephrine-sensitive neurons, affect-driven perception, interoception (heightened organismic feelings—resulting from the fronto-insular cortex), and activity in the dorsal anterior cingulate cortex, medial prefrontal cortex, amygdala, and other areas of the brain (Corbetta et al., 2008; Hermans et al., 2011; Sara & Bouret, 2012).

Dopamine (DA System)

Dopamine is implicated in processing rewards and motivated behavior, hunger, thirst, sexual arousal, endogenous (positive or negative) emotions, muscular activity, and so on (Walton, Gan, & Phillips, 2011). In cognition it mediates arousal in misleading situations, which demands mental attention (Matt, working memory). A well-studied domain for these situations is financial appraisal, or economic behavior, in cost/benefit decision making (Treadway et al., 2012). The DA system mediates connections between the basal ganglia (caudate nucleus, putamen, globus pallidus, nucleus accumbens), the thalamus, the prefrontal lobe, and the limbic organization. Via basal ganglia connection with the limbic system, the DA system is involved in “reward” evaluations that reinforce or assign organismic/vital value to (adaptive or nonadaptive) behaviors, energizing relevant circuits and focusing attention when needed (Bear et al., 2001;

H. Fischer et al., 2010; Rolls, 1999). The DA system helps to form *criteria of relevance* for encountered events or mentations with the nonexclusive participation of insula, orbital prefrontal cortex, nucleus accumbens, and amygdala (Bear et al., 2001; Pascual-Leone et al., 2015). Via orbitofrontal, anterior cingulate, and amygdala (etc.) connections, the DA system helps to focus attention and exert praxis on relevant events. DA processes enable mental/executive attention, which is diminished when the DA system decreases in potency either because of old age or because younger people have received some DA-D1 receptor antagonist (H. Fischer et al., 2010; Petersen & Posner, 2012; Pribram, 1991; Sagvolden, Johansen, Aase, & Russell, 2005). The DA system has a well-recognized age-developmental pattern of growth and of decrementation with aging (H. Fischer et al., 2010; S.-C. Li, 2012), possibly related to development of mental-attentional capacity in humans and of individual differences in DA system potency.

The emergence of motivation (both operative—internal, enactive— and figurative—external, contextual) is, as mentioned, related to these neurotransmitters. Motivation may involve a heterarchy of sites that include periaqueductal gray area, anterior insula, orbitofrontal cortex, amygdala (criterion of relevance), and anterior cingulate, which is where affective goals (implicit motives) are converted, we think, into cognitive goals (Arsalidou et al., 2018; Pascual-Leone et al., 2015).

Mental effort, related to mental (*M*) activation and/or mental interruption (*I*), and caused by the NE system's tonic activation, expresses the activity of prefrontal lobes (e.g., lateral, dorsolateral, frontal polar). This function of the prefrontal lobes was recognized by Luria (1973) and is now generally admitted. Such executive planning function of prefrontal lobes is mediated by dopaminergic, cholinergic, noradrenergic, and serotonergic arousal processes (perhaps in that priority order).

Serotonin (5-HT System)

Serotonin is much less understood in its effect on performance control and on thinking, but it appears to be involved in affective regulation, motivational processes, cognitive flexibility, and impulse control (Ullsperger, 2011). Often in interaction with dopamine, it seems to have some controlling effect on such issues as impulsive/aggressive behavior, suicide tendencies, and individuals with borderline personality disorders (Dalley & Roiser, 2012). In our model, we assume a soothing control effect (table 11.1) in more or less facilitating situations that require mental attention and affective processing. Another cognitive function may be the control (reduction) of task-irrelevant, perhaps not misleading, processes. For instance, in the rat's five-choice attentional task already mentioned, the effect of central serotonin loss was a significant increase in premature or impulsive responding without change in the percent correct (Robbins & Everitt, 1995).

The serotonin pathway plays a role in the regulation of mood—emotional behavior such as (in rats, primates, or humans) aggression or anxiety, and regulation of sleep (sleep/awake are controlled by ACh, NE, and serotonin pathways—Bear et al., 2001). Research in primates suggests the serotonin system may control, regulate, or reduce emotive expression of the NE system, simultaneously facilitating social-cognitive interactions with congeners (members of the same species) and improving the mood or social skills in monkeys (Pribram, 1991). In humans, deficiencies in brain serotonin may cause depression (also anorexia nervosa or bulimia). We interpret serotonin as expressing an interruption mechanism (an automatic *I*-operator), often used with affective processes, which is activated independently from, but coordinated with, the effortful mental-attentional operators primed by the DA system. It may be regulated by the prefrontal lobe (e.g., orbitofrontal, medial frontal cortex). Serotonin and dopamine systems seem to interact and complement one another (Benes, 2001).

Brain Expression of Hidden Operators: Summary

We briefly review our hypothesis about how the prefrontal lobe accomplishes the executive activation (or inhibition) of task-relevant (or -irrelevant) areas of the cortex. This explanation complements the one provided earlier in the chapter. Once the criteria of relevance (expressing dominant affective/cognitive goals) are clear in a task or situation (likely accomplished by anterior cingulate gyrus and its connections), the prefrontal lobe induces activation of the mesencephalic reticular formation (MRF), which causes RAS processes (reticular ascending/activating system activity, including specific pathways for the four discussed neurotransmitters). RAS activation reaches relevant regions of the cortex priming or modulating activation, either in a diffuse or a regionally specific manner (in accord with currently dominant neurotransmitters). Complex or misleading cognitive situations need use of mental attention (Pascual-Leone, 2000b, 2019; Pascual-Leone & Johnson, 2005, 2011, 2017). These cognitive situations are controlled by the prefrontal executive network via dopaminergic connections that relate basal ganglia with thalamus (Cockburn & Frank, 2011). This is done via three links: psychological-activatory direct pathway (related to our *M*-operator), psychological-inhibitory indirect pathway (related to our effortful *I*-operator), and psychological-inhibitory hyperdirect pathway (related to our automatic *I*-operator). These three specific sources of activation/inhibition ensure that specific (locally focused) task-relevant areas of the cortex will be further primed, whereas irrelevant areas are inhibited. Because of these subcortical sources of priming, the prefrontal lobe may achieve enough activation of specifically relevant cortical sites by using cortico-cortical connections (possibly mediated by

neurotransmitters glutamate—activatory—and GABA—inhibitory), and other connections, to recruit into action the needed processes (Dunnett & Robbins, 1992; Edelman & Tononi, 2000; Shimamura, 2002).

Congruent with the perceptual/automatic attention versus mental attention distinction (two complementary modes), the limbic organization seems to have two evolutionarily distinct limbic systems. These have reciprocal connections with various parts of the frontal lobe: the lateral (basolateral) circuits versus the medial circuits (Bakchine, 2000; Goldberg, 1985; Pascual-Leone, 1995; Thatcher, 1994; Tucker, 2001). As summarized by Bakchine (2000) and Thatcher (1994), the evolutionarily older (paleocortical) lateral limbic circuit consists principally of the amygdala, dorsomedial thalamic nuclei, orbitofrontal, insular, and temporal-polar cortices, with premotor area connections as their motor link. It also has extensive connections with the dorsolateral prefrontal cortex and posterior parietal association cortex. It processes information concerning the external world, contributing implicit affective evaluation (global affective goals and their bodily manifestations, Damasio's [1999] somatic markers) to here-and-now situations, motivating acts and social-personal interactions. Pribram's (1991) work suggests that this system, centered on the amygdala, defines and emphasizes (somatic markers) the affective importance of subjects or objects within here-and-now experience, helping to constitute a criterion of relevance. Neurotransmitters acetylcholine and epinephrine, with serotonin and dopamine in complex situations, seem important here (see table 11.1).

The evolutionarily recent medial limbic circuit (archicortical cortex) includes the hypothalamus, anterior thalamic nuclei, hippocampus, cingulate gyrus, and related tracks, having as main motor link the supplementary motor areas, and drawing arousal from the brainstem reticular formation (Bakchine, 2000; Goldberg, 1985; Thatcher, 1994). It mediates important aspects of learning, memory, and mental attention. Via hippocampus, it intervenes in representations of space and time, and in relational (*LM* or *LC*) learning, although it cannot alone identify objects. The importance of this medial limbic system is apparent in episodic-memory research (Moscovitch, Cabeza, Winocur, & Nadel, 2016). For Pribram (1991) the hippocampus helps to demarcate the context, not the object, of experience, by construing situations as analytical wholes (a "context"). Fuster (1995) holds related views, interpreting the hippocampus as a convergence zone (Damasio & Damasio, 1994) "involved in the binding—in part through non-cortical neural stations—of widely dispersed representations" (Fuster, 1995, p. 103).

For us the hippocampus complex (including entorhinal, perirhinal, and parahippocampal cortex) can coordinate the replicable activation sequences of schemes (neocortical processes), with their relations of coexistence (e.g., spatial, temporal) and retain

these relational patterns as local dynamic “cognitive maps” at the service of agency/praxis (Pribram, 1991). These spatial-temporal maps internalize the causal texture of the environment (Tolman & Brunswik, 1935). This function of relational-temporal fluent learning (organized by the hippocampus) expresses in our theory the intertwining of *T*-operator (temporal structuring) and *S*-operator (relations of coexistence).

The medial limbic circuit intervenes in representing space-time and is essential for planful, predictive, and appropriate action. In contrast to the here-and-now relevance of the lateral system, this medial system is involved in anticipatory or predictive actions (prospective operative praxis) guided by expectancies of how the world will be in the future (Goldberg, 1985; Thatcher, 1994). Dopamine is a major neurotransmitter in the medial limbic system and helps to define criteria of relevance in complex and misleading situations.

Conclusions

We began the two neuropsychology chapters by outlining a problem of current cognitive neuropsychology: the lack of an organismic (i.e., general and causal) theory or model for psychology—an analytical formulation of neuropsychological processes within high cognition. This organismic model should explain the macro (molar) levels of performance and have a clear (micro-level) neuroscientific interpretation. Further, this organismic model should include methods of process representation and task analysis, to yield causal descriptions of psychological processes interpretable as neurological activity. We suggested how the theory of constructive operators (TCO), its constructs and principles, can serve this purpose. We have discussed how brain research supports developmental neo-Piagetian constructs such as mental attention, which explicates the functional origin of working memory (Pascual-Leone, 2000b; Pascual-Leone & Baillargeon, 1994; Pascual-Leone & Johnson, 2005). The growth throughout infancy and childhood, until adolescence, of mental attentional capacity (our model $\langle E, M, I, F \rangle$) explains emergence of developmental cognitive stages and the growth of learning potential, conceptual abstraction, and language.

In this chapter we have discussed seven major functional dimensions of variation in the cortex: (1) cortically anterior versus posterior lobes; (2) dorsal-attention (frontoparietal cognitive assimilation) versus ventral-attention (frontoparietal cognitive accommodation); (3) left versus right hemisphere; (4) experiential versus conceptual knowing (primary, secondary, tertiary, and quaternary or polymodal areas); (5) functional hierarchies of operative symbolic streams; (6) mental-attentional activation and inhibition brain mechanisms; and (7) representational-dorsal (spatial) versus representational-ventral

(temporal) streams. Coordination of these dimensions clarifies how the brain encodes and expresses meaning (semiotics). Localization separates (to minimize interference) different functional modes of processing that are complementary and collaborate to overdetermine human performance. We have also discussed key neuromodulators (extrinsic neurotransmitters) to show how they contribute to adapt processing to situations and to internal states.

To clarify evolutionary grounding of some functional dimensions, we briefly discussed how neurotransmitters and processes relate to the paleocortical (lateral) and the archicortical (medial) limbic subsystem, perhaps clarifying interactions among cognitive/cortical, affective/limbic, and arousal/neuromodulator processes. We hope to have intimated how the brain can produce affectively “cool” versus “hot” cognitive processes and how it can cope with facilitating versus misleading situations and deal with simple versus complex situations and with figurative (representational) versus operative processes.

We have also intimated how abstract relations of coexistence among schemes (space, dorsal-representational pathways) coordinating with the flow of sequential relations (time, ventral-representations) can constitute the environmental “context” (Pribram, 1991) or “causal texture of the environment” (Tolman & Brunswik, 1935). Our conclusions presented in chapters 10 and 11 are based on task-analyses of neuroscience research findings—research that for brevity we have omitted. Findings discussed are those chosen to illustrate ideas and theoretical analyses of this scientific essay.